Development of High Cu Ratio Nb_3Al and Nb_3Sn CIC Conductors for Superconducting Toroidal Field Coils of JT-60

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JT-60

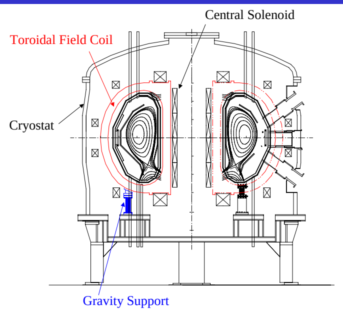
1. Design of Toroidal Field Coil

The JT-60 has been planned to modify as a full superconducting coil tokamak (JT-60SC) toward to a steady state plasma operation.

Requirement for TFC

1. The TFC has to generate B_T=3.8T at R=2.8m.
2. The size of TFC is limited by central solenoid and cryostat.

   Available space for TFC is about 4 m x 6m.



Cross sectional view of superconducting JT-60

Present design parameters of TFC

Coil shape		D-shape
Number of coils		18
Inner diameter	m	3.02x5.22
Outer diameter	m	3.86x6.04
Average circumference	m	14.9
Ampere turn	MAT	53.8
Toroidal filed at R=2.8m	T	3.8
Number of turn for 1 TFC	turn	154
Operational current	kA	19.4
Stored energy	GJ	1.7

#Features of JT-60 conductor

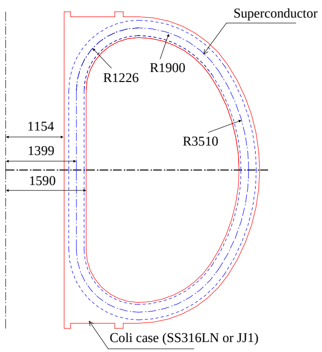
1. Nb_3Al is the one of the candidate materials because of its low strain sensitivity.

   React and Wind technique can be applied indicating that the coil fabrication is easy.

   The reaction time is 1/3 of Nb_3Sn meaning that the lower cost.
2. Stainless steel conduit is adopted, because Incoloy 908 used for ITER requires careful control of the atmosphere during manufacture.

   The thermal strain on superconducting strand becomes higher than the case of the ITER.

   The superconducting strand (Nb_3Al or Nb_3Sn) with relatively high critical currents density (Jc) is required.
3. High Cu/non-Cu ratio strand around 4 is required for stability, because the Jc of 7.4 T is about 3 time larger than 11.8 T (ITER).

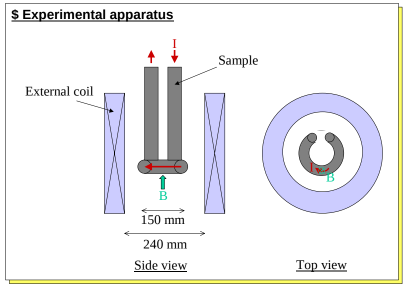


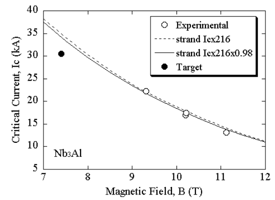
Cross sectional view of TFC

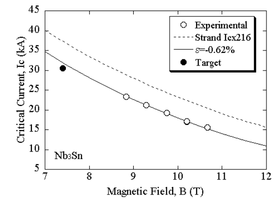
2. One of the optimization result for Cu/non-Cu ratio

5. Critical current (Ic) of full scale conductor

A Ic of full scale conductors were measured using a 240 mm bore-13 T superconducting coil. The perpendicular magnetic field to the sample CIC conductor was from 8.0 to 11.0 T. An appearance of resistance was measured using two pairs of voltage taps whose length was 100 mm and 300 mm. The conductor Ic was defined using 0.1 µV/cm criterion.







External magnetic filed dependence of Ic.

1. The observed Ic values exceed the target value (30.5 kA) at 7.4 T.

   These results indicate that the developed CIC conductors are sufficiently applicable for the TFC of JT-60SC.
2. The measured Ic of Nb_3Al and Nb_3Sn CIC conductors (open circles) were

   Nb_3Al : 98 %

   Nb_3Sn : 79 %

   of strand Ic x 216 (number of strands), because of the thermal contraction effect from the stainless steel conduit.
3. The experimental results (Nb_3Sn) show good agreement with the empirical equation using the same fitting parameters for non-Cu Jc of strand.

   The result indicates that the intrinsic strain of strands was –0.62 %.

   This value is reasonable from the thermal contraction effect between Nb_3Sn and stainless steel conduit.

6. AC loss measurement of full scale conductor

AC losses of full scale conductors were measured by a calorimetric method.
Bubbles generated by AC losses were collected in a FRP chamber.
The volume of bubbles was measured by a liquid helium level indicator in the FRP chamber.

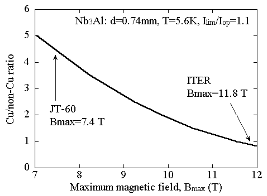
The optimizations of the conductor were performed on the basis of design criteria for ITER. The relation between maximum magnetic field and the Cu/non-Cu ratio was derived from the limiting current (I_{lim}) for stability and the critical current density.

$$I_{op} = \frac{\pi}{4} d^2 n_{sc} \frac{1}{1+r_{cu}} J_{op}$$

$$I_{\lim} = \sqrt{\frac{\pi}{4} d^2 n_{sc} \frac{r_{cu}}{1+r_{cu}} \frac{P_h h}{\rho}\left(T_c - (T_{op}+1)\right)}$$

$I_{lim}/I_{op}=1.1$

Iop: operational current=19.4 kA
d: Strand diameter=0.74 mm
n_{sc}:number of superconducting strand = 216
r_{cu}:Cu/non-Cu ratio
J_{op}:current density at I_{op}
I_{lim} : limiting current
P_h: perimeter=5/6πdn_{sc}
h:Heat transfer 1000W/m^{2}K
ρ: copper resistivity at RRR=120
T_c:critical temperature
T_{op}+1=5.6K

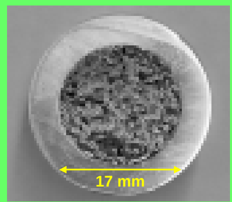


Maximum magnetic filed dependence of Cu/non-Cu ratio.

The allowable Cu/non-Cu ratio of the superconciting strand for JT-60SC was estimated as around 4.

3. Design Parameters of CIC conductor for TFC of JT-60SC

Superconducting material	Nb_3Al or Nb_3Sn
Conduit material	SS316LN
Maximum Magnetic Field	7.4 T
Operating current	19.4 kA
Operating temperature	4.6 K
Number of strand	3×3×3×3×4=324
Number of superconducting strand	216
Cu/Non-Cu ratio	4
Number of copper wire	108
Diameter of strand	0.74 mm
Inner diameter of conduit	17 mm
Void fraction	36%

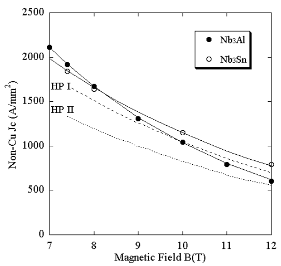


4. Characteristic of developed strand

Major parameters of the developed strand

	Nb_3Al	Nb_3Sn
Outer diameter (mm)	0.74	0.74
Cu/Non-Cu ratio	4.1	3.6
Twist Pitch (mm)	50	8
Jc at 4.2K, 12T (A/mm²)	601	794
Histeresis Loss (±3T) (mJ/cc-nonCu)	1742	425

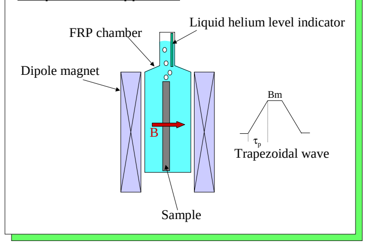
The non-Cu Jc (definition with 0.1 μV/cm) of developed strands were 1914 A/mm² for Nb_3Al and 1843 A/mm² for Nb_3Sn at 7.4 T, 4.2 K. Each non-Cu Jc values were fitted by well-known empirical equation shown as solid lines. The equation of ITER [1] and Ando [2] was used for Nb_3Sn and Nb_3Al, respectively. These empirical equations show the experimental values very well. Therefore, design parameters of TFC can be determined by using these equations.

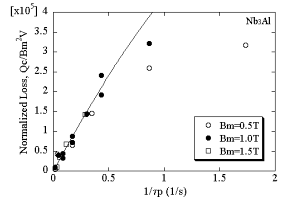


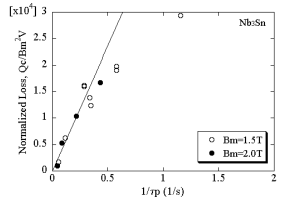
The non-Cu Jc for the developed Nb_3Al (closed circle) and Nb_3Sn (open circle) strands at 4.2 K.

[1]T. Ando et al., IEEE Trans. on Magn. Vol. 32, pp. 2324-2327, 1996
[2] ITER Design Description Document 1.1-1.3, App. C-II. 1997, pp. 1.

$ Experimental apparatus







The inverse of ramping time (τ_p) dependence of normalized Qc of Nb_3Al and Nb_3Sn CIC conductors.

The coupling loss (Qc) was derived from subtraction of the histeresis loss from the total AC loss.The sample length is 440 mm for Nb_3Al and 750 mm for Nb_3Sn.The solid line in Figure are fitting line to reproduce the experimental values.

$$Q_c = 2\frac{Bm^2}{\mu_0}\frac{n\tau_c}{\tau_p}\left[1-\frac{\tau_c}{\tau_p}\left\{1-\exp\left(-\frac{\tau_c}{\tau_p}\right)\right\}\right]V$$

Bm: Flat top magnetic field of trapezoidal wave
τp : ramping time
V: sample non-Cu volume

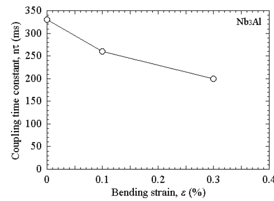
Derived coupling time constant of Nb_3Al was 330 ms.
On the other hand, Nb_3Sn showed the 30 ms. This value is too small compared with the value of Nb_3Sn conductor for CS (240 ms). Heat treatment was conducted without N_2 flow inside conduit for TF conductor. Therefore, the oxidation of Cr plating is considerable reason.

AC loss measurement of bent conductor

In order to reduce the Qc, nτ of bent Nb_3Al conductor was measured.
The nτ was decreased to 250 ms by loading 0.3 % bending strain.

This means that the sintered Cr plating among strands is easily come off by bending.

This result will be efficiently adopted for Nb_3Al conductor for the TFC of JT-60SC, because superconductors of the TFC will be fabricated by react and wind method and bending strain become ±0.4 %.



The results of AC loss measurement of bent conductor.

7. Summary

1. The non-Cu Jc (definition with 0.1 μV/cm) of developed strands were 1914 A/mm² for Nb_3Al and 1843 A/mm² for Nb_3Sn at 7.4 T, 4.2 K. The Cu ratio of Nb_3Al and Nb_3Sn strand is 4.1 and 3.6, respectively. The observed external magnetic field dependence of non-Cu Jc is fitted well by well-known empirical equations.

2. Measurements of Ic of full size conductors were performed. Measured Ic of Nb_3Al and Nb_3Sn CIC conductors were 98% and 79% of Ic estimated from Ic in strands because of the thermal contraction effect from stainless steel conduit. The intrinsic strain of superconducting strand by stainless steel conduit was estimated as –0.62 % by empirical equation. The observed Ic values exceed the design value indicating that the developed conductors are sufficiently applicable for TFC of JT-60SC.

3. The AC loss measurements were also performed using the calorimetric method. Coupling time constants of developed Nb_3Al and Nb_3Sn conductor was 330 ms and 30 ms, respectively. The Nb_3Al conductor with bending strain of 0.3 % showed that the nτ was reduced to 250 ms.