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Breakthrough in Performance Degradation of ITER Central Solenoid Conductors owing to Short-Twist-Pitch Cabling and Suppression of Bending Strain

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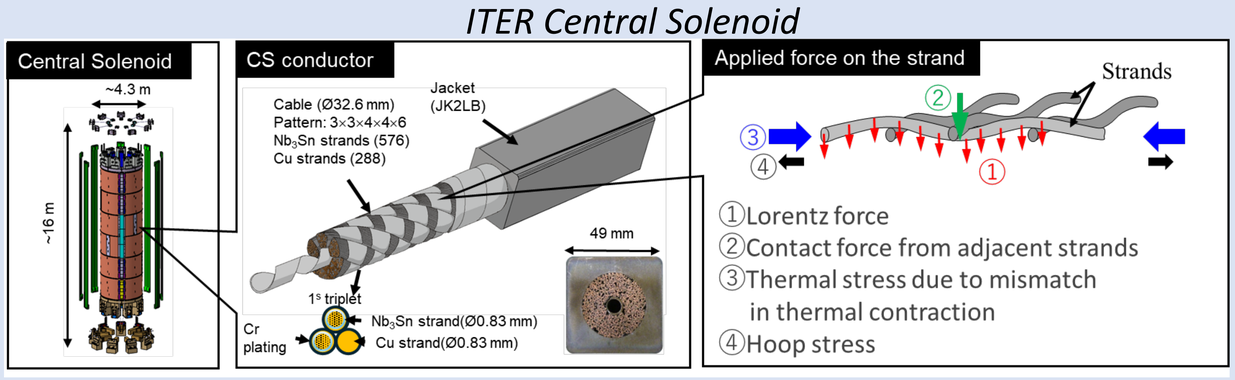
1. ABSTRACT

- In developing the **ITER central solenoid (CS)** conductors, **performance degradation** due to electromagnetic loading cycles was identified as a **critical issue**.
- While this degradation issue has been **resolved** by **short twist pitch** conductor, the mechanism of degradation mitigation remains **unclear**.
- To support the **development** of conductors for DEMO, **strain analysis** was performed to investigate both the **mechanism of degradation mitigation** and the **strain state under actual operating conditions**.

2. BACKGROUND

- The CS conductors are expected to be subjected 60,000 **electromagnetic loading (F_{EM}) cycles** over the lifetime of ITER, because Nb_3Sn strands **degrades** due to **strain** induced by the loading.
- While T_{cs} degradation was observed in the conductors with long twist pitch due to **strand deformation**, **short twist pitch** conductors were developed to **improve cable stiffness** and reduce strand deformation and strain.
- Since the dependence of T_{cs} on the strain state of Nb_3Sn strands in the conductor has **not** been **fully clarified**, **strain analyses** of CS conductors was performed based on the previous test results for future development.

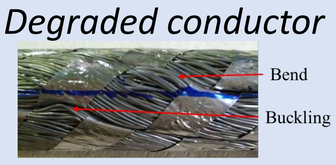
ITER Central Solenoid



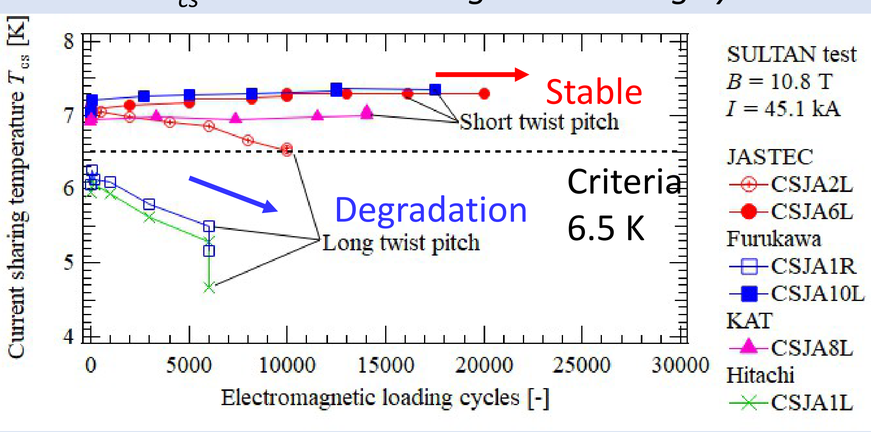
Major Specifications

Twist pitch		Long	Short
Cable Pattern		3×3×4×4×6	
Twist pitch	1st	45±5	20±5
	2nd	85±10	45±5
	3rd	145±10	80±10
	4th	250±15	150±15
	5th	450±20	
Void fraction [%]		33.4	32.4

Degraded conductor



T_{cs} under electromagnetic loading cycles



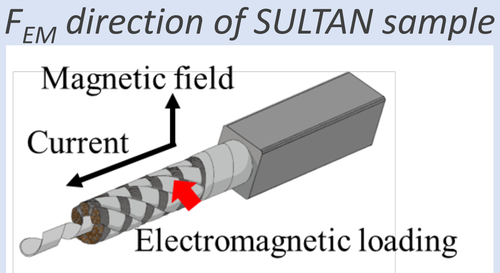
3. Analysis of strain induced by electromagnetic loading

- To investigate the influence of **strain induced by electromagnetic loading** F_{FM} on conductor performance, an **effective strain** analysis was performed.
- Effective strain ε_{eff} was defined as an **equivalent axial strain** that characterizes the T_{cs} caused by:
  - ✓ Compressive thermal strain,
  - ✓ Strain induced by electromagnetic loading F_{FM}.

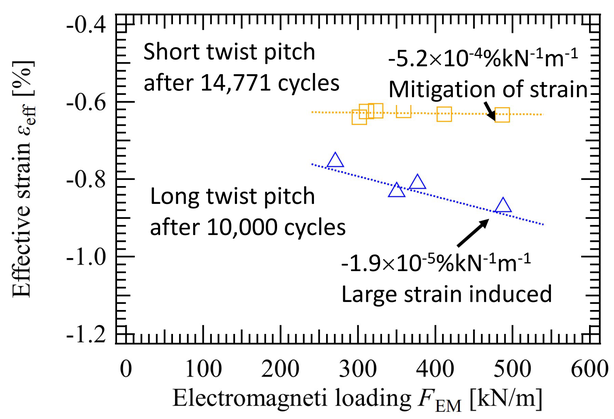
$$E = \frac{E_c}{L_V A}\int\int\left(\frac{I_{op}/N_{SC}}{I_c(B,T,\varepsilon_{eff})}\right)^n dAdz$$

- If strain in the Nb_3Sn strands is induced by F_{EM}, the gradient of ε_{eff} vs. F_{EM} plot become large.
- A small gradient was observed in the **short-twist-pitch** conductor, most likely due to **reduced bending strain** caused by F_{EM}.
- This hypothesis cannot be validated through effective strain evaluation alone, because **axial** and **bending** strain **cannot** be **distinguished**.

F_{EM} direction of SULTAN sample



F_{EM} Dependence of effective strain



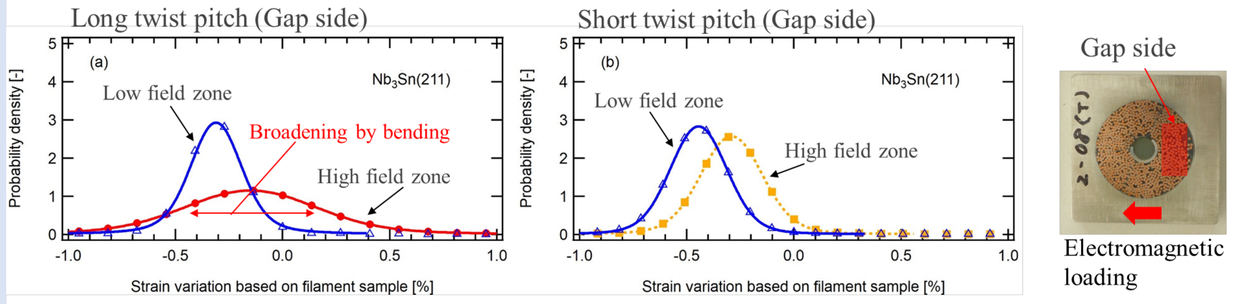
4. Axial and bending strain analysis by neutron diffraction[1]

- To investigate whether short twist pitch **suppresses** bending strain, residual strain measurements using **neutron diffraction** were performed on the conductors after F_{EM} cycles (SULTAN test) at room temperature.
- The **short twist pitch** effectively mitigates permanent bending strain from F_{EM} cycles, resulting in the suppression of T_{cs} degradation.
- **Relaxation of axial strain** may cause the several-percent increase of T_{cs} in the short-twist-pitch conductors after F_{EM} cycles.

Strain variation by F_{EM} cycles

Twist pitch	Strain relaxation	Range of bending strain
Long	0.16%	0.53±0.32%
Short	0.16%	0.10±0.07%

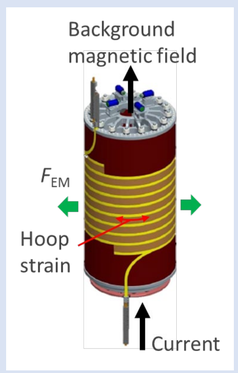
Strain distribution in the CS conductors



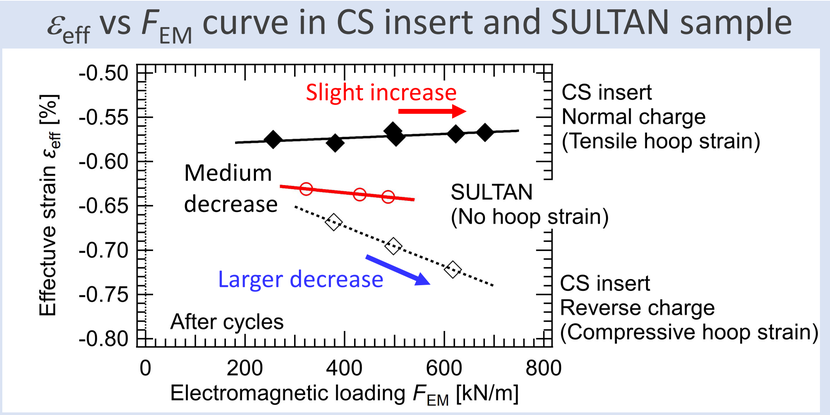
5. Influence of hoop strain under actual operating condition[2]

- To evaluate the impact of **hoop strain** through a **comparison of ε_{eff}**, both a cylindrical **CS insert coil** and a **SULTAN sample** were fabricated from **the same conductor** and tested.
- **Hoop strain** was applied to the **CS insert** in a background magnetic field by CS model coil.
- The difference in the gradient of the ε_{eff} vs. F_{EM} plot may be caused by hoop strain.
  - Normal charge: **Relaxation of thermal compressive strain** due to tensile hoop strain is considered to have exceeded the degradation by F_{EM}. ➡ **slight positive gradient**
  - Reverse charge: Compressive hoop strain is considered to have **added** to the strain. ➡ **larger negative gradient**
- After F_{EM} cycle, T_{cs} of the CS insert (7.7 K) was **higher** than SULTAN sample (7.3 K), which can be explained by **strain compensation** due to **hoop strain**.

CS insert



ε_{eff} vs F_{EM} curve in CS insert and SULTAN sample



6. Advantage of short twist pitch design

- **Reducing bending** strain prevents T_{cs} degradation caused by F_{EM} cycles.
- An **increase** in T_{cs} is expected due to the relaxation of compressive thermal strain due to **tensile hoop strain** in the CS operation.
- **Small gradient** of ε_{eff} **vs** F_{EM} may indicate that degradation is mitigated under higher electromagnetic forces than those in ITER (520 kN/m).

7. CONCLUSION

- The **short-twist-pitch** conductor is expected to **maintain** its performance due to the reduction of the bending strain even under the higher electromagnetic forces in DEMO.
- Since **no hoop stress** is applied to the samples in SULTAN, the results are conservative. However, this test is effective for qualification.
- To quantitatively evaluate the **influence of hoop stress**, testing with a **cylindrical sample like the CS insert** is necessary
- If the correlation between effective strain and actual strain in Nb_3Sn strands is further clarified, future conductors can be developed using effective strain as a benchmark.

REFERENCES

[1]SUWA T., et al., Supercond. Sci. Technol. 38, (2024) 015008. [2]NABARA. Y, et. al., J. Cryo. Super.Jpn. 51 (2016) 102.