Program ID: Thu-Mo-Po4.12-03 [90]
Contribution ID: 1224

MT 26 International Conference on Magnet Technology
Vancouver, Canada | 2019

Development of a 1-T Class Force- Balanced Helical Coils Using REBCO Tapes

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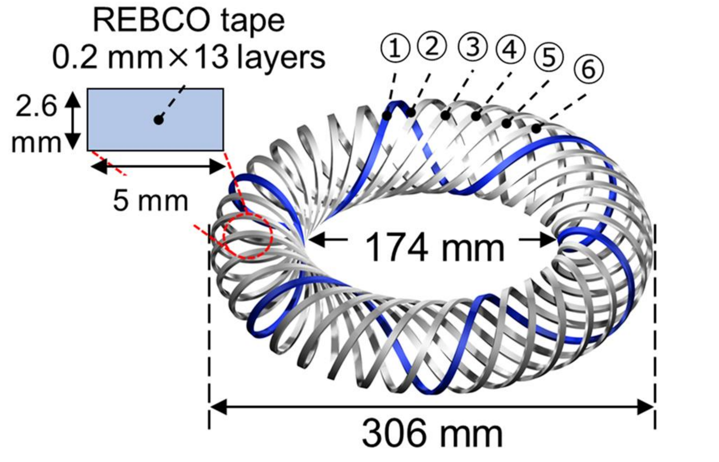
I. Introduction

Applying high-temperature superconducting (hereafter called HTS) tapes to superconducting magnetic energy storage (hereafter called SMES) is expected to improve small sized high magnetic field coils. In developing high field coils using HTS tapes, however, large electromagnetic forces caused by a large current and high field can degrade the critical current of HTS in the winding. To decrease the electromagnetic forces, the authors proposed the force-balanced helical coils (hereafter called FBC) concept as a feasible option for SMES. The authors design and develop a 1-T class helical coils (hereafter called HTS-FBC) based on the FBC concept using REBCO tapes. Although the FBC can minimize the mechanical stresses induced by the electromagnetic forces, the FBC may cause the decrease in the critical current due to three-dimensional complex shapes of the helical windings. In other words, since the tensile strain, the bending strain and the torsional strain simultaneously apply to the REBCO tapes, the critical current of the HTS-FBC decrease.

The objective of this work is to clarify the critical current property of REBCO tapes depending on the applying complex mechanical strain due to the winding process, the winding configuration and the electromagnetic forces through the development of the HTS-FBC.

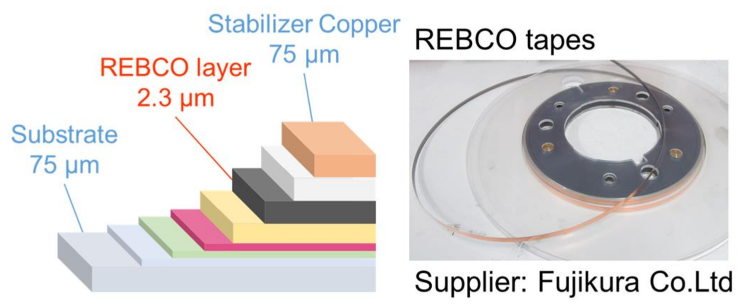
II. Design Parameter of a 1-T Class HTS-FBC

Dimension of the 1-T Class HTS-FBC



■ Design Parameters of the 1-T Class HTS-FBC

Items	Value
Major Radius / Minor Radius	0.12 m / 0.03 m
Winding Structure	6 poloidal turns × 13 layers
Total Poloidal Turns	468 turns (6×13×6 coils)
Operating Coil Current (4.2 K/ 77 K)	1000 A/ 130 A
Maximum Magnetic Field (4.2 K/ 77 K)	1.04 T/ 0.33 T
Self Inductance	2.39 mH
Total Conductor Length	108 m (18 m / 1 coil)



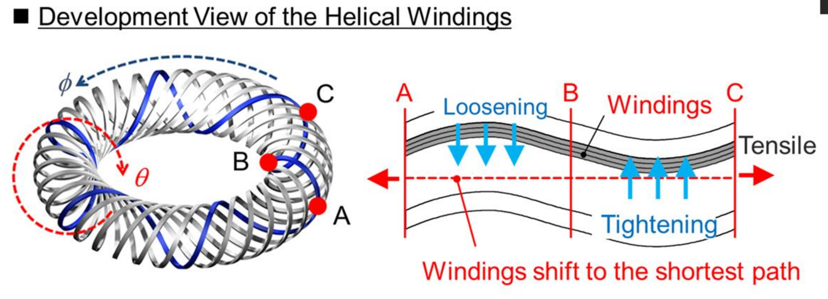
Supplier: Fujikura Co.Ltd

■ Specifications of REBCO Tapes

Items	Value
Critical Current (Ave.)	285 A at 77 K
Tape Thickness / Width	0.2 mm / 5.0 mm
Substrate Thickness	75 μm (Hastelloy C-276)
Stabilizer Thickness	75 μm (Copper)
Allowable Tensile Stresses	< 400 MPa
Allowable Bending Radius	> 30 mm

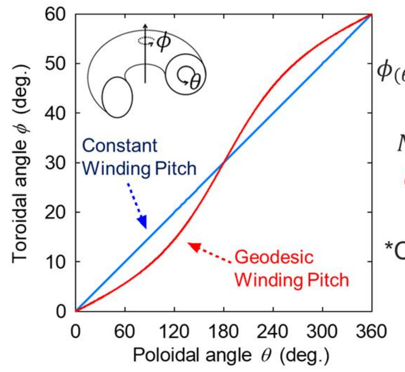
Reduction of the Edgewise Bending Strain in Coil Windings

■ Development View of the Helical Windings



Winding trajectory that fits by applying tension to the helical winding
→Geodesic trajectory

■ Relationship between ϕ and θ



$$\phi_{(\theta)} = \frac{1}{N}\left(\theta + \sum_{k=1}^{\infty} C_k \frac{\sin k\theta}{k}\right) + \phi_0$$

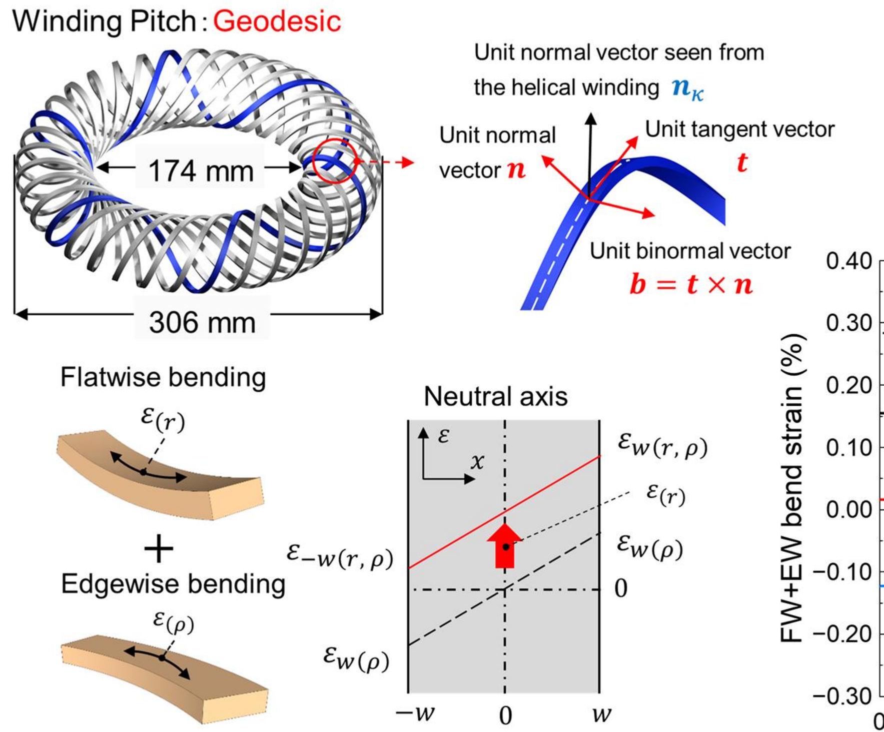
N: the number of helical turns
C_k: winding pitch modulation parameters
*Constant Winding Pitch Helical $C_k = 0$

Feasible solution to the FBC winding technique using REBCO tapes

Reduction of the edgewise curvature by the effect of the geodesic trajectory winding
- Prevention of the decrease in the critical current due to the edgewise bending strain -

III. Critical Current Evaluation for Complex Uniaxial Strain

Complex Uniaxial Strain Distribution in Helical Windings

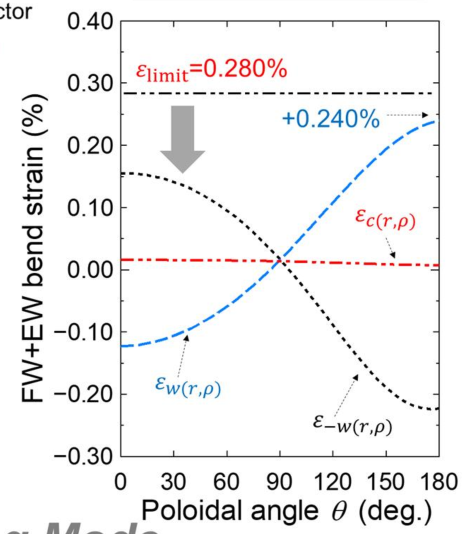


• FW bending Radius
$r_{(\theta)} = |\boldsymbol{n_\kappa} \cdot \boldsymbol{n}|^{-1}$
$\varepsilon_{(r)} = d/r_{(\theta)}$

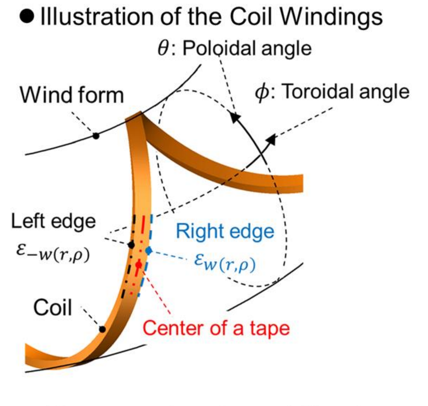
• EW bending Radius
$\rho_{(\theta)} = |\boldsymbol{n_\kappa} \cdot \boldsymbol{b}|^{-1}$
$\varepsilon_{(\rho)} = w/2\rho_{(\theta)}$

■ Complex Uniaxial Strain

$$\begin{cases} \varepsilon_{-w(r,\rho)} = \dfrac{d}{r} + \dfrac{-w}{2\rho} \\ \varepsilon_{w(r,\rho)} = \dfrac{d}{r} + \dfrac{w}{2\rho} \end{cases}$$

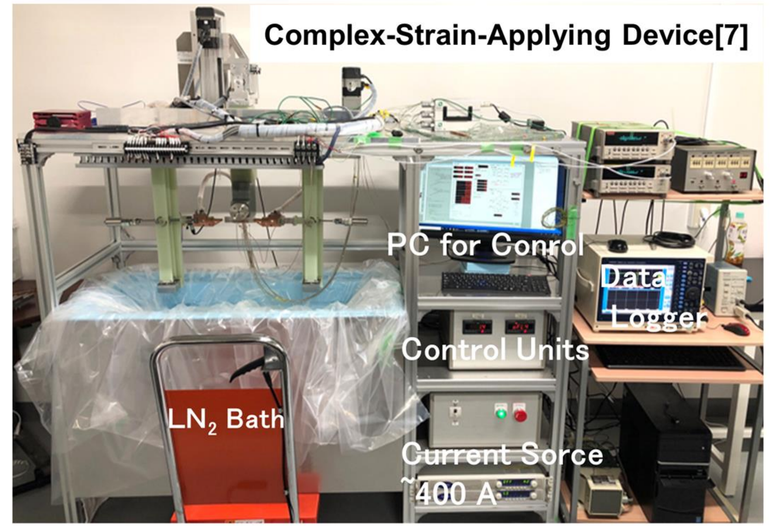


● Illustration of the Coil Windings



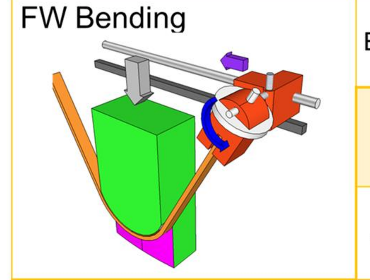
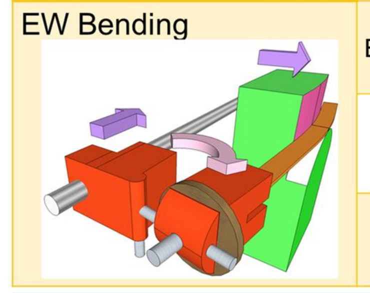
*Assumes that the stabilized copper layer is wound in the direction of the wind form

I_c Evaluation for Complex Bending Mode



■Experimental equation of I_c characteristic

$$I_{c(\varepsilon)}/I_{c,\max} = 1 - 0.77|\varepsilon - 0.07|^2$$

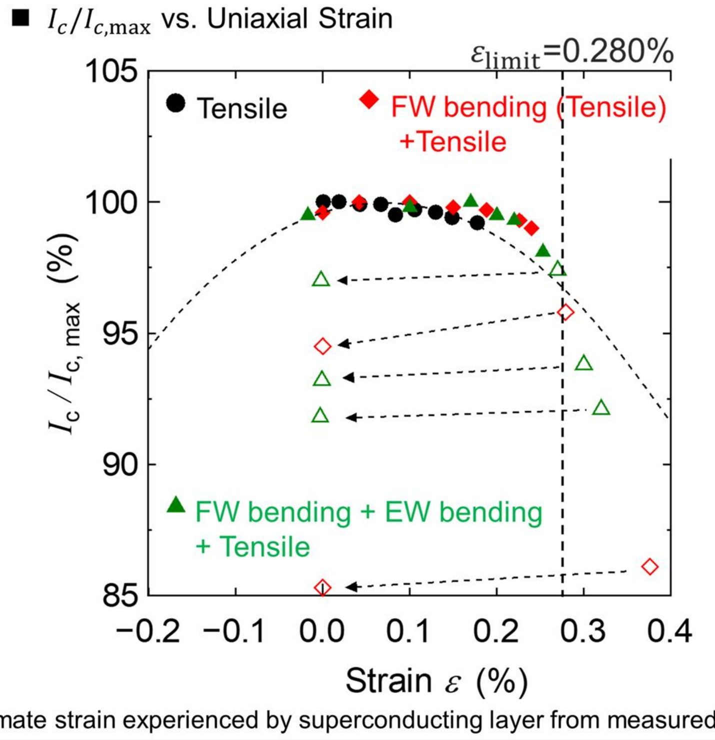



FW Bending	Bending Radius	30 mm
	Max. Strain ε	~0.33%
	Jig Movement	0 ~ 160 mm
EW Bending	Bending Radius	300 mm
	Max. Strain ε	~0.41%
	Jig Movement	0 ~ 30 mm

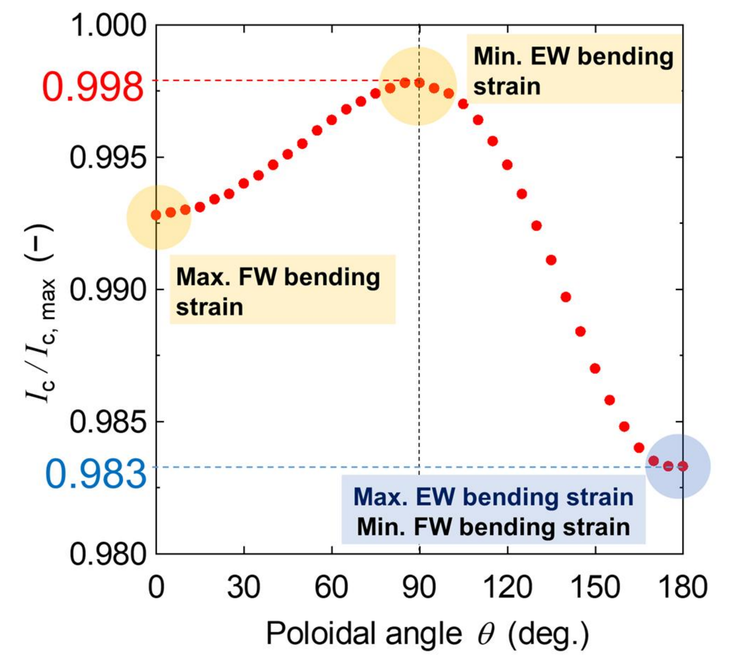
■ I_c Evaluation for uniaxial strain distribution[8]

$$I_{c(\varepsilon_{(\alpha)})} = \int_{\varepsilon_{-w(\alpha)}}^{\varepsilon_{w(\alpha)}} \frac{I_{c(\varepsilon)}}{\varepsilon_{w(\alpha)} - \varepsilon_{-w(\alpha)}} d\varepsilon$$

■ $I_c/I_{c,\max}$ vs. Uniaxial Strain



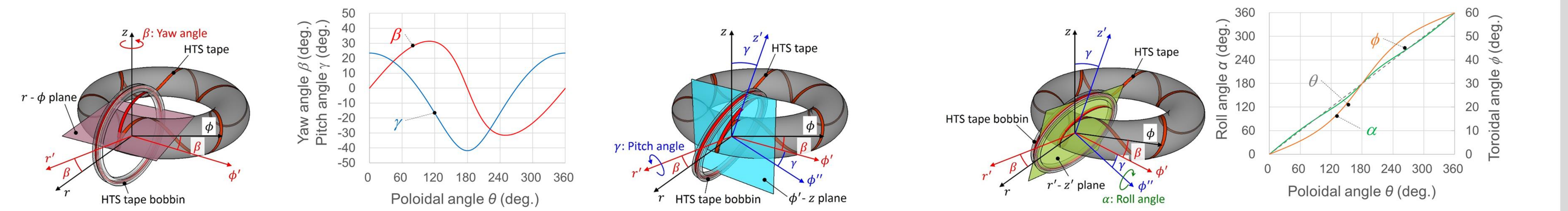
■ $I_c/I_{c,\max}$ vs. Poloidal angle θ



* Estimate strain experienced by superconducting layer from measured values

IV. Development of a Helical Winding Machine

Torsion Control Schemes of the HTS Tape Bobbin



1. The HTS tape bobbin is turned around z axis at the yaw angle β. The yaw angle β is a function of the poloidal angle θ and is given by

$$\beta = \cos^{-1}\left(\frac{\boldsymbol{b}_{r\phi} \cdot \boldsymbol{e}_\phi}{|\boldsymbol{b}_{r\phi}||\boldsymbol{e}_\phi|}\right)$$

where $\boldsymbol{b}_{r\phi}$ is the vector which the unit binormal vector $\boldsymbol{b}$ is projected on the $r-\phi$ plane, and $\boldsymbol{e}_\phi$ is the unit vector of the ϕ axis. In this process, the r and ϕ axes rotate at the yaw angle β.

2. The HTS tape bobbin is turned around r' axis at the pitch angle γ. The pitch angle γ is also a function of the poloidal angle θ and is calculated from

$$\gamma = \cos^{-1}\left(\frac{\boldsymbol{b}_{\phi' z} \cdot \boldsymbol{e}_{\phi'}}{|\boldsymbol{b}_{\phi' z}||\boldsymbol{e}_{\phi'}|}\right)$$

where $\boldsymbol{b}_{\phi' z}$ is the vector which the unit binormal vector $\boldsymbol{b}$ is projected on the $\phi' - z$ plane, and $\boldsymbol{e}_{\phi'}$ is the unit vector of the ϕ' axis. In this process, the ϕ' and z axes rotate at the pitch angle γ.

3. The HTS tape bobbin is inclines by the effect of the yaw and pitch angle controls, the poloidal angle at the winding point should be corrected. In this process, the HTS tape bobbin is turned around ϕ'' axis at the roll angle α. The roll angle α is also a function of the poloidal angle θ and is obtained by

$$\alpha = \cos^{-1}\left(\frac{\boldsymbol{t}_{r',z'} \cdot \boldsymbol{e}_{z'}}{|\boldsymbol{t}_{r',z'}||\boldsymbol{e}_{z'}|}\right)$$

where $\boldsymbol{t}_{r'z'}$ is the vector which the unit tangent vector $\boldsymbol{t}$ is projected on the $r'-z'$ plane, and $\boldsymbol{e}_{z'}$ is the unit vector of the z' axis. By means of these torsion control process, the direction of the HTS tape bobbin can coincide to the direction of the unit tangent vector of the helical winding.

Assembly of Helical Winding Machine for HTS Tapes

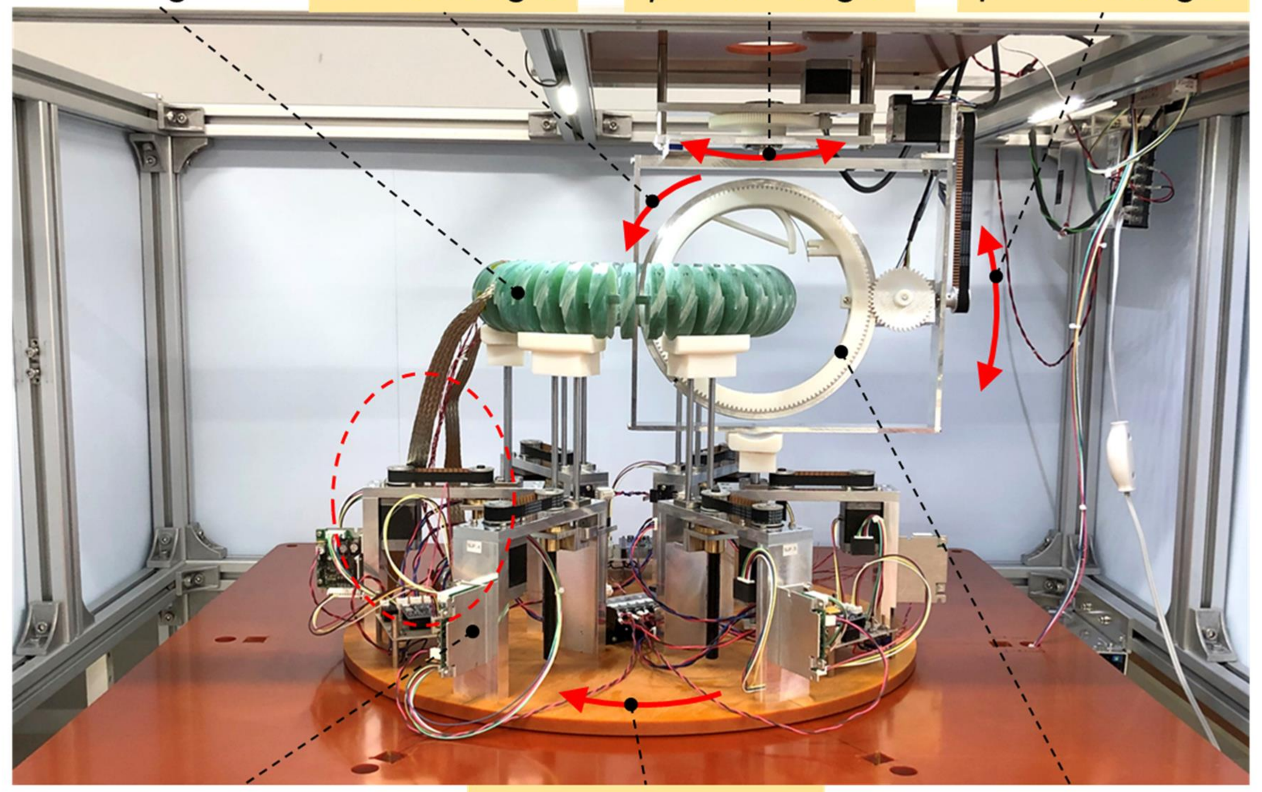
What is required for helical winding machine…

- Capable of helical winding without degradation in critical current of HTS tapes
- Capable of helical winding while applying a certain tension to HTS tapes
- Capable of continuous layer winding

✓ The assembly of the helical winding machine has been finished.
✓ From the results of the test operation, the authors visually confirmed that the support for the winding form works without interfering with the torsion control scheme

Further step of this work, the authors carry out the winding of the 1-T class HTS-FBC using REBCO tapes and the excitation test of the 1-T class HTS-FBC.

Winding form | α: Roll angle | β: Yaw angle | γ: Pitch angle



Winding form support | ϕ: Toroidal angle | HTS tape bobbin

V. Conclusions

The authors discussed the complex uniaxial strain of the 1-T class HTS-FBC applied to the HTS tapes caused by its helical configuration comparison with the reversible strain limit. In this work, the helical winding machine for continuous winding using REBCO tapes is developed.

From the results, the geodesic winding trajectory will be one of the feasible options as a winding configuration of the helical coils to minimize the edgewise bending strain, which effect leads to minimize the complex uniaxial strain in the HTS tapes within reversible strain limit.

The assembly of the helical winding machine has been finished.

From the results of the test operation, the authors visually confirmed that the support for the winding form works without interfering with the torsion control scheme based on the 4-spindle angle control system simultaneously with the HTS tape bobbin. This results seems that continuous helical winding using REBCO tapes is possible.

Further step of this work, the authors carry out the winding of the 1-T class HTS-FBC using REBCO tapes and the excitation test of the 1-T class HTS-FBC.

VI. References

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Acknowledgements: this work supported by the Grants-In-Aid for Scientific Research (B), number 16H04321, and also by the International Research Program of Meiji University.

Presented at the 26th International Conference on Magnet Technology , 2019 22 – 27 September 2019, Hyatt Regency Hotel Vancouver, Vancouver, Canada; Session: Power Applications I