

# 電気推進化航空機を目指した 超伝導回転機の開発と核融合への展開

超伝導・低温工学ユニット  
三浦 峻



# 自己紹介

名前：三浦 峻（みうら しゅん）

略歴：

H24年3月 岐阜大学工学部 卒業

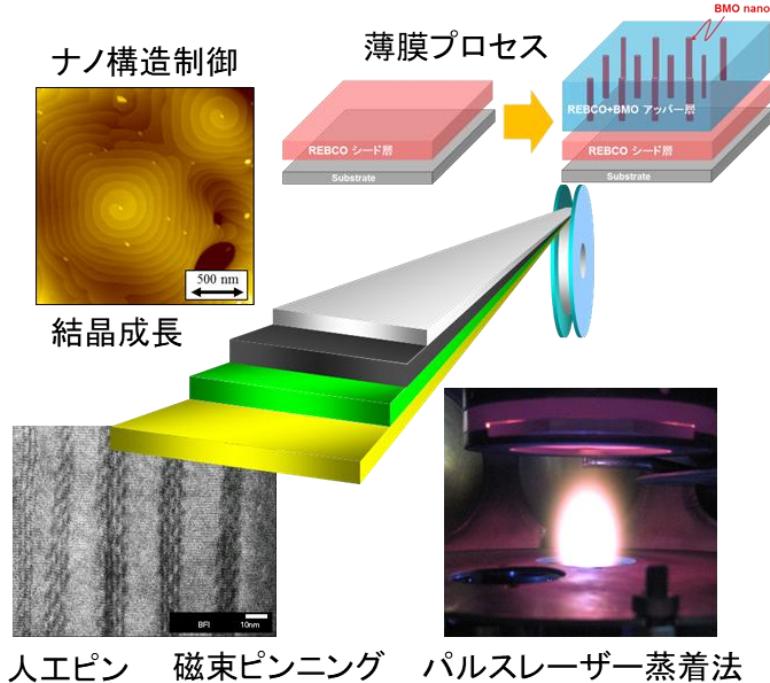
H29年3月 名古屋大学大学院工学研究科 博士（後期課程）修了（吉田研究室）

H29年4月- R7年6月 九州大学 大学院システム情報科学研究院 助教（岩熊研究室）

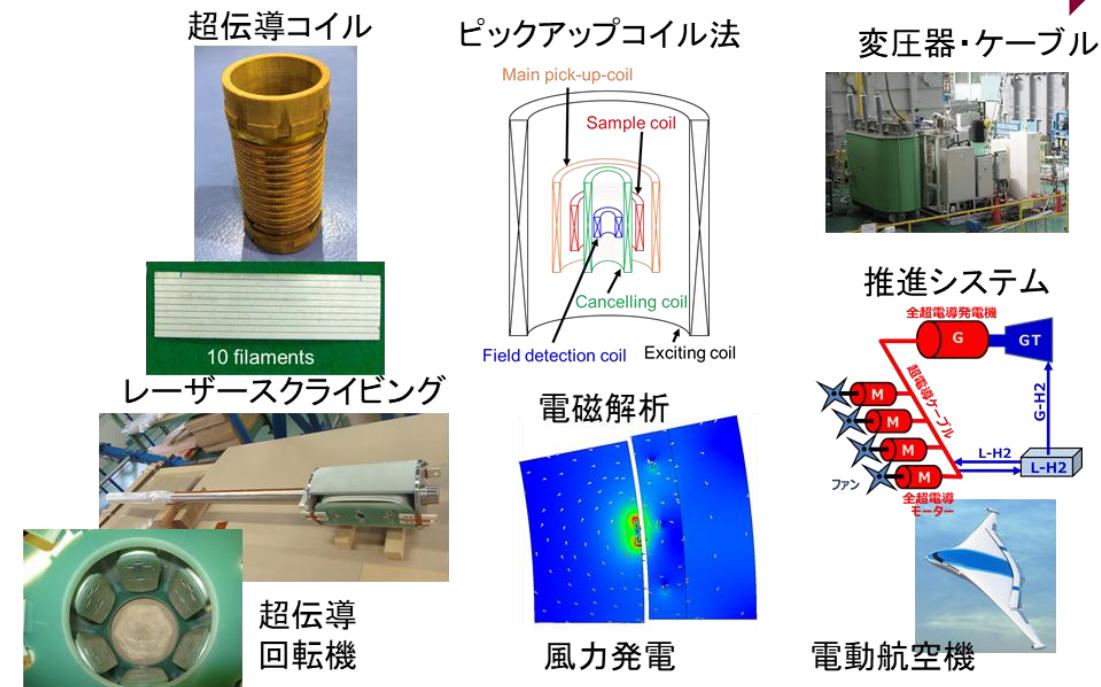
R7年7月~ 核融合科学研究所 研究部 超伝導・低温工学ユニット 准教授



**名古屋大学** (吉田研)



**九州大学** (岩熊研)



- 超伝導回転機向け低交流損失・大電流容量化技術
- NEDOプロジェクト(400 kW全超伝導モータ→2 MW全超伝導モータ)
- 核融合への展開



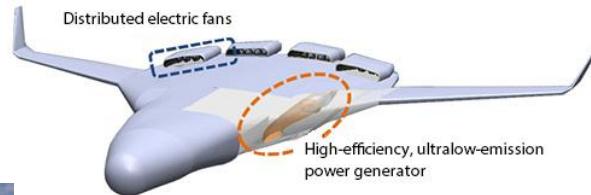
NASA, N3-X

<https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/n3x/>



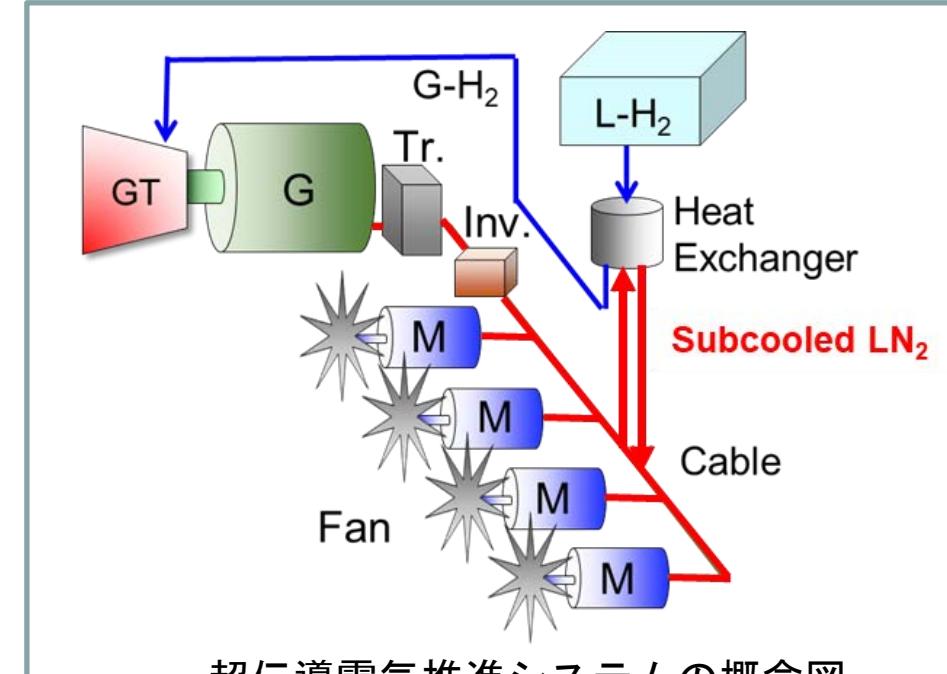
Airbus, ZEROe (BWB)

<https://www.airbus.com/en/innovation/energy-transition/hydrogen/zeroe>



JAXA, ハイブリッド電動推進システム

<https://www.aero.jaxa.jp/eng/research/frontier/feather/>



超伝導電気推進システムの概念図

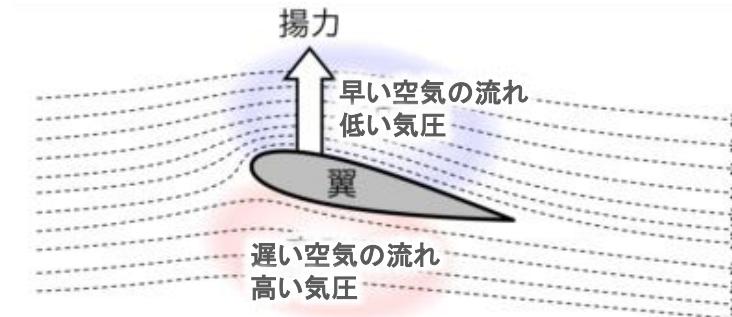
M: 超伝導モータ、G: 超伝導発電機、Tr.: 超伝導変圧器、Inv.: インバータ、Cable: 超伝導ケーブル、GT: 水素ガスタービン

- ✓ CO<sub>2</sub>低減の厳しい目標設定 (2050年Net-zero)
  - 水素を燃料・動力源 (電池は重いのでGTリアルタイム発電)
- ✓ 多発分散型ファン + 胴体翼による飛行効率の向上
- 電動推進化
- ✓ ~MW級推進用モータには~20 kW/kg以上の要求 (従来モータ ~5kw/kg)かつ低電圧高電流設計が要求
- 超伝導技術

- ✓ 航空機には型式証明に代表される厳しい認証フェーズ
- ✓ 推進機材の故障は重大な事故に繋がるため、10<sup>9</sup>時間に一回以下の故障しか許されない。

→ 軽量性+高い安全性・信頼性も要求される

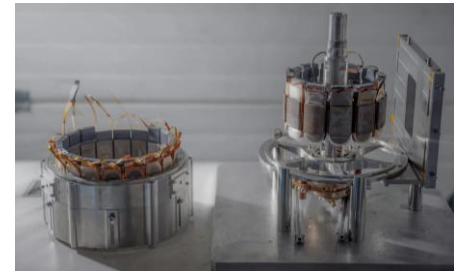
## 胴体翼 + 分散ファン上後部配置



翼(胴体)面積の増大 × 翼(胴体)上面気流速度の増大  
⇒ 揚力向上(エネルギー大幅削減)

This text explains the aerodynamic principle behind the design. It states that increasing the wing (body) surface area multiplied by the increase in air flow speed on the upper surface of the wing (body) results in increased lift. This leads to improved energy efficiency, as indicated by the red text "⇒ 揚力向上(エネルギー大幅削減)" (Lift increase (energy saving)).

# 最近の航空機向け超伝導モータの開発例



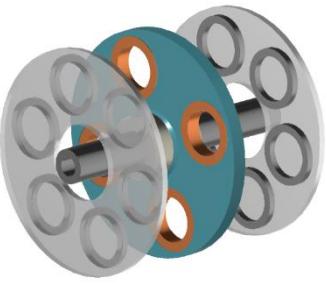
500 kW SC motor  
ASCEND, Airbus UpNext

<https://www.airbus.com/en/newsroom/stories/2023-12-ascending-to-new-heights-with-cryogenic-superconductivity>



SC motor with HTS stacks  
ASuMED, EU

F. Grilli et al. J. Phys: Conf. Series 1590 (2020) 012051



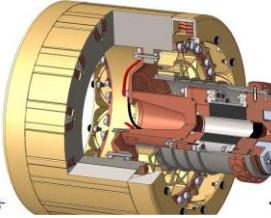
Fully SC motor  
ZEST1, U. Strathclyde

M. Zhang et al. presented in MT 28



Flux modulation motor  
RESUM, FROST, Safran

R. Dorget et al. presented EFATS 2023



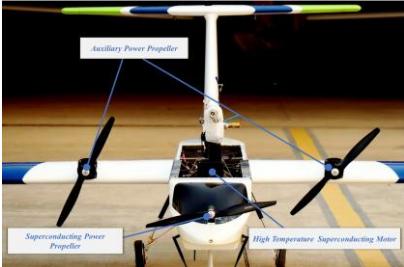
Partial SC motor  
NASA

J. Scheidler et al. Conf. Series 1302 (2024) 012020,



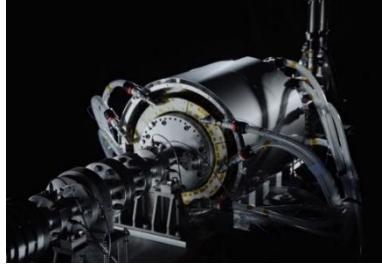
3 MW SC motor using flux pump  
AETP, Robinson Research Inst.

J. Storey et al. presented in MT 28



Partial SC motor. Flight verification  
Chinese Academy of Sci.

J. Zheng et al. SuST 37 (2024) 07LT02



2 MW partial SC motor  
Toshiba

<https://www.toshiba-clip.com/en/detail/p=3534>



400 kW Fully SC motor  
NEDO, Kyushu U.

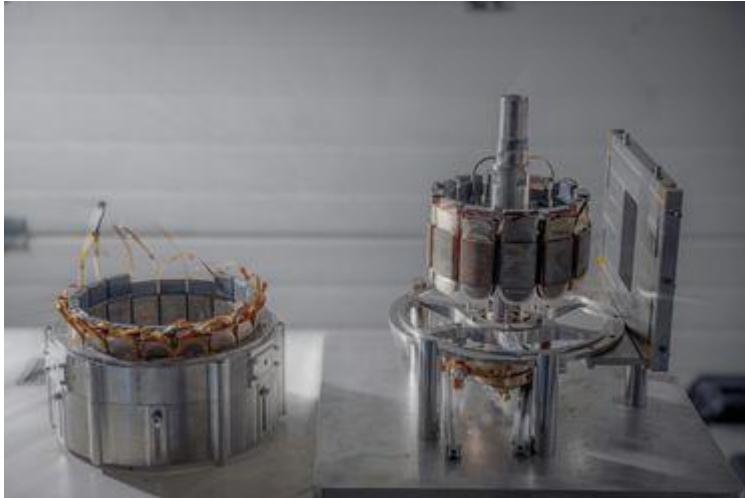
H. Miyazaki et al. IEEE TAS 34 (2024) 5200506

## Others (after 2018)

- J. Voccio et al: J. Phys. 1590 (2020) 012053
- G. Nam et al: IEEE TAS 31 (2021) 5202307
- Y. Terao et al : J. Phys. 1857 (2021) 012017
- C. Manolopoulos et al: IEEE TAS 28 (2018) 5207005
- S. Saeidabadi: AIAA-AFA (2024) 4091
- S. Kalsi et al : AIAA-AFA (2024) 4096
- M. Komiya et al: IEEE TAS 29 (2019) 5204306
- A. Colle et al: J. Phys. 1590 (2020) 012052
- R. Mellerud et al : IEEE TAS 33 (2023) 5204013
- R. Sugouchi et al : IEEE TAS 30 (2020) 3601905
- D. Dezhin et al: IEEE TAS 32 (2022) 3601105
- F. Weng et al: SuST 33 (2020) 104002
- S. Kalsi et al: IEEE TAS 31 (2021) 5206807
- N. Ivanov et al: IEEE TAS 33 (2023) 5200105
- M. Corduan et al: IEEE TAS 30 (2020) 5200810
- G. Lumsden et al: SuST 36 (2023) 105014
- P. Alvarez et al: IEEE Access 11 (2023) 144325
- R. Wang et al: SuST 36 (2023) 054003
- D. Liu et al: IEEE TAS 34 (2024) 5202606
- S. Saeidabadi : IEEE TAS 33 (2024) 5203107
- C. Manolopoulos et al: IEEE TAS 30 (2020) 5207407
- P. Alvarez et al: IEEE Access 12 (2024) 54182
- H. Sasa et al: IEEE TAS 31 (2021) 5200706
- J. Sheidler et al: IEEE TAS 33 (2023) 5202405
- Y. Terao et al : AIAA/IEEE (2020)
- Y. Wang et al : IEEE (CIEEC) (2024)
- R. Dorget et al: J. Phys. 1975 (2021) 012033
- T. Tymosch et al: IEEE TAS 31 (2021) 5200205
- Y. Terao et al : Physica C 617 (2024) 1354399
- H. Cho et al: IEEE TAS 32 (2022) 5202505
- X. Zhou et al Physica C 605 (2023) 1354207
- R. Mellerud et al: IEEE (ICEM) 31 (2021) 5

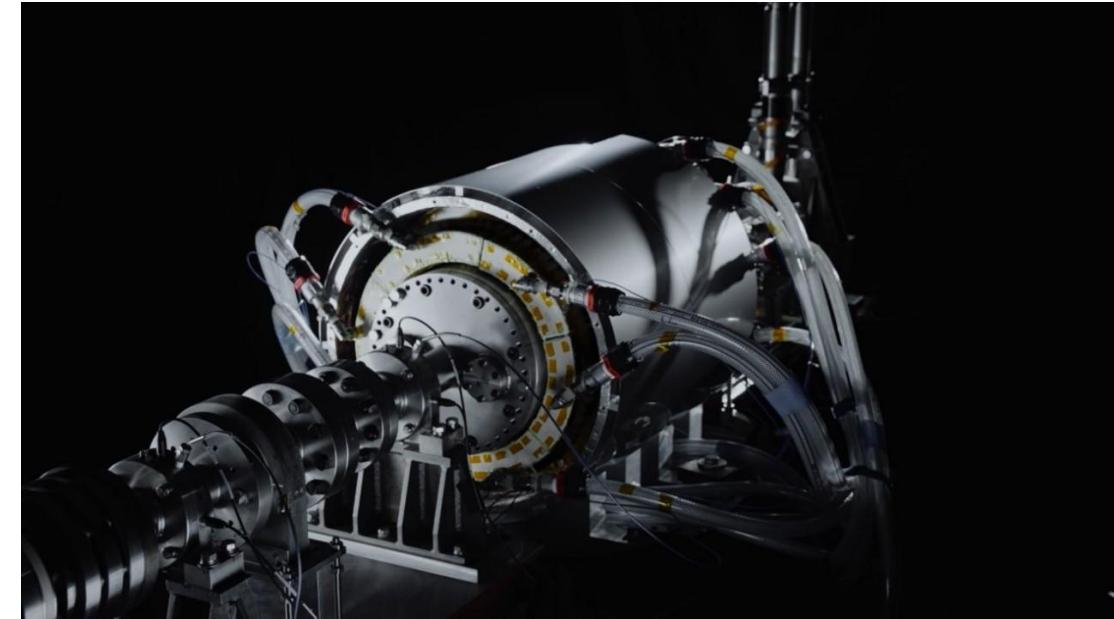
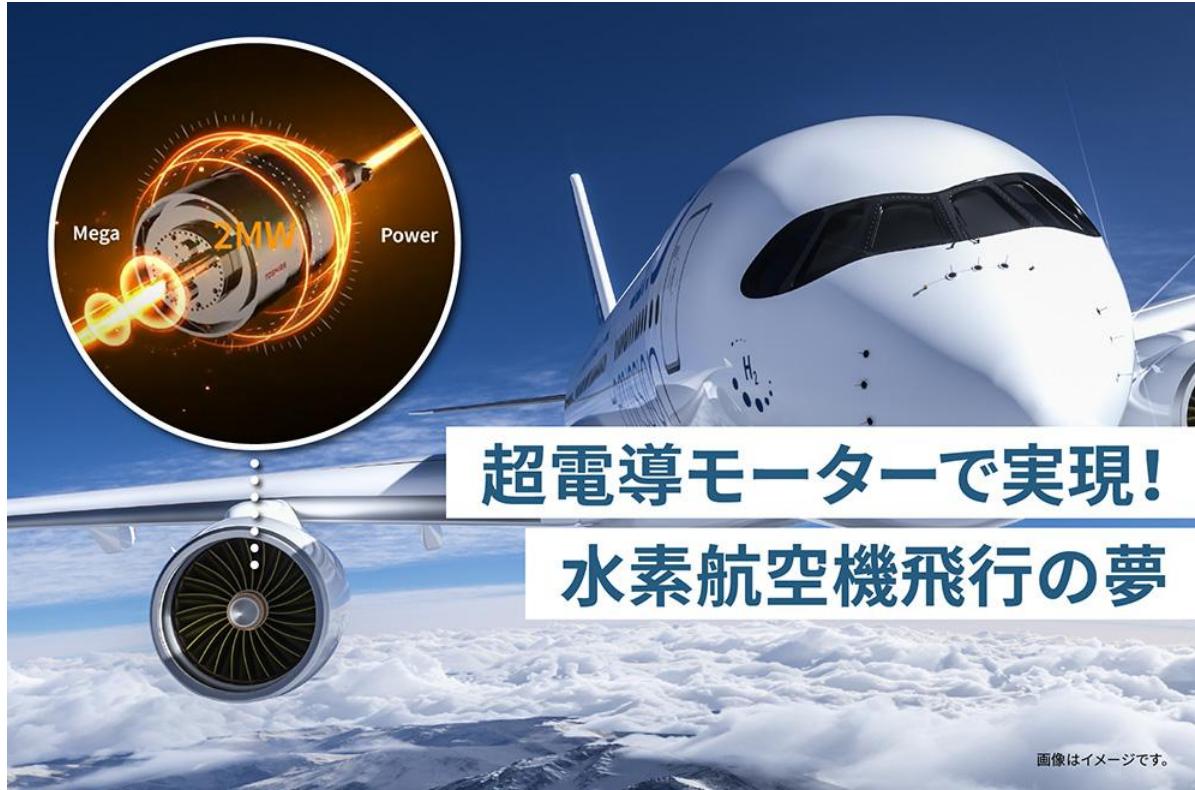
and more...

<https://mediaassets.airbus.com/medias/domain38/media102150/645093-0ooq65yh6l-480.mp4>



500 kW SC motor  
ASCEND, Airbus UpNext

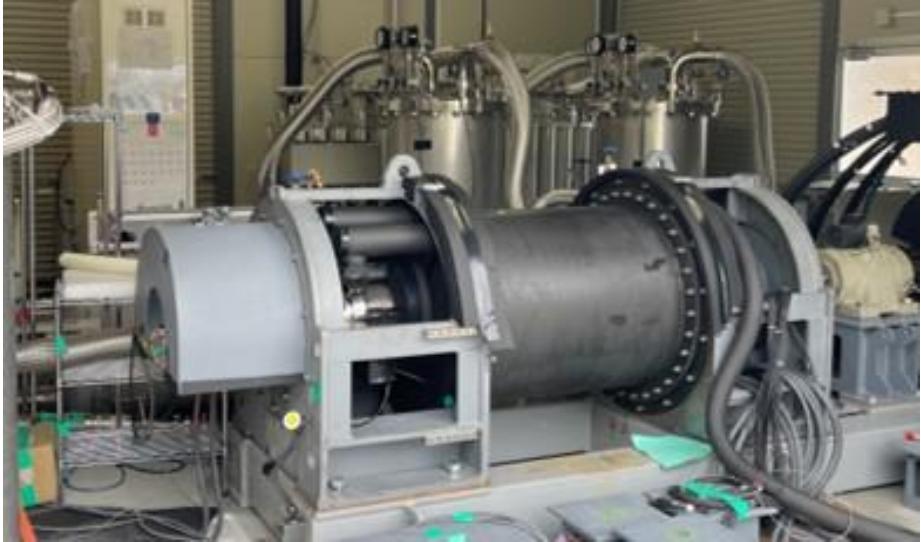
[https://www.global.toshiba/jp/news/energy/  
2022/06/news-20220623-01.html](https://www.global.toshiba/jp/news/energy/2022/06/news-20220623-01.html)



2 MW partial SC motor  
Toshiba



2024年の「2024国際航空宇宙展」で、共同研究の提携を表明

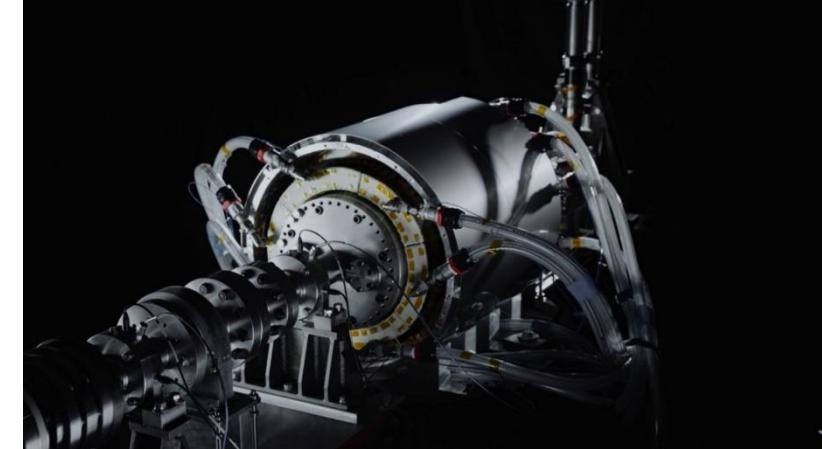
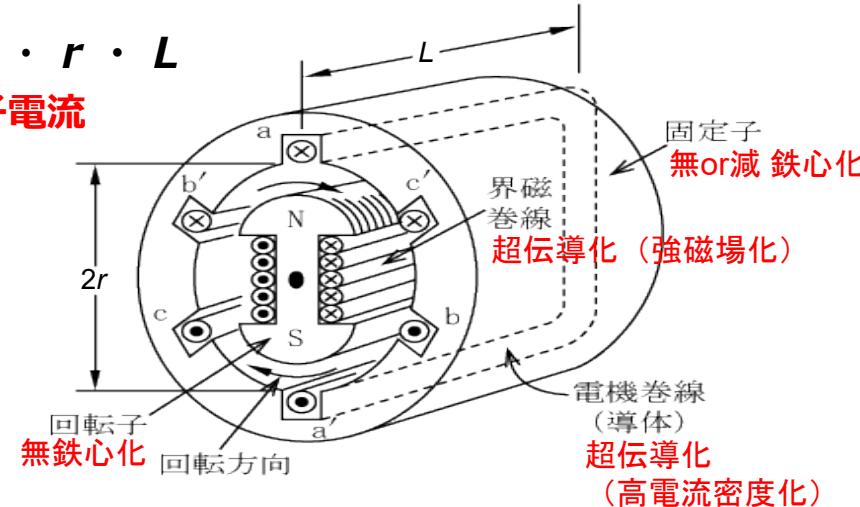


九州大学:全超伝導モータ

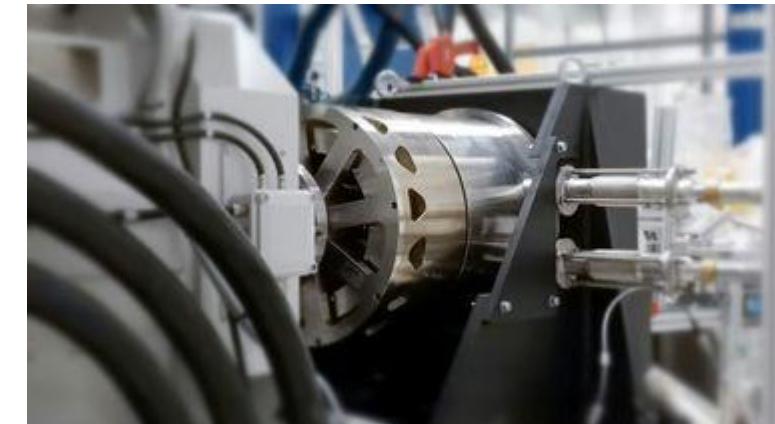
$$\begin{aligned} P (\text{出力}) &= \omega \cdot T \\ &= \omega \cdot \mathbf{B} \cdot I_a \cdot Z \cdot r \cdot L \end{aligned}$$

磁束密度 電機子電流

全超伝導モータのほうが、開発は難しいけど、ポテンシャルは高い



東芝:半超伝導モータ



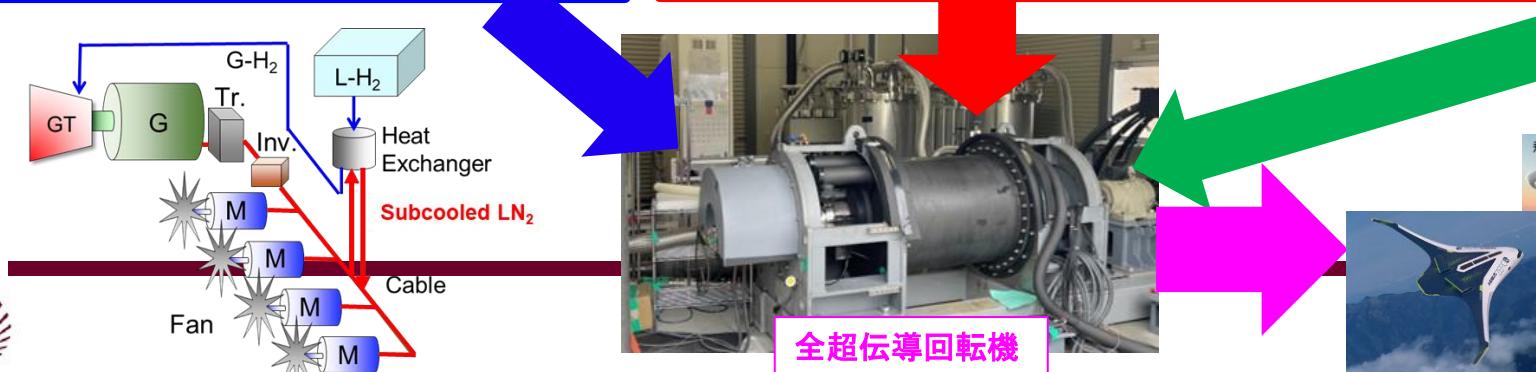
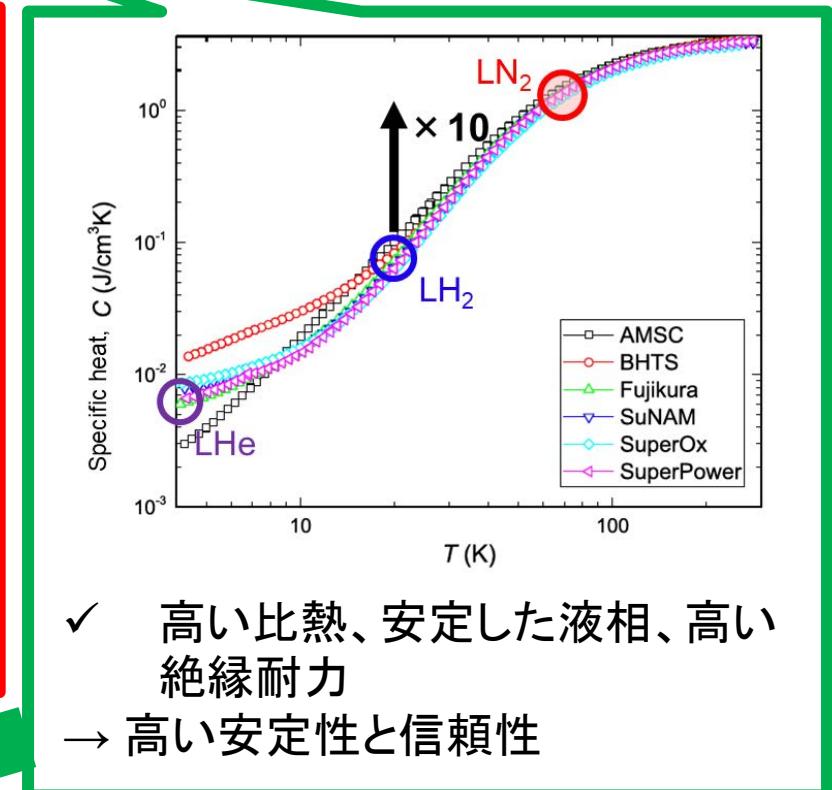
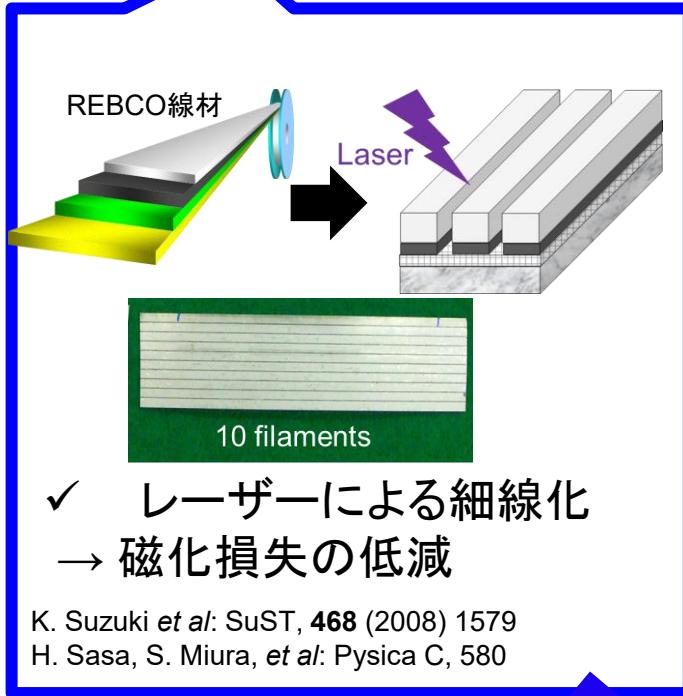
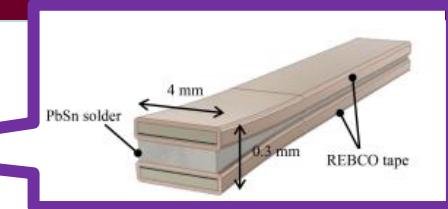
エアバス:半超伝導モータ

## ②大電流容量・低交流損失化を目指した導体・巻き線構成法の評価と開発

9

軽量性と同時に高い安全性・安定性を目指す九大グループの戦略・コア技術

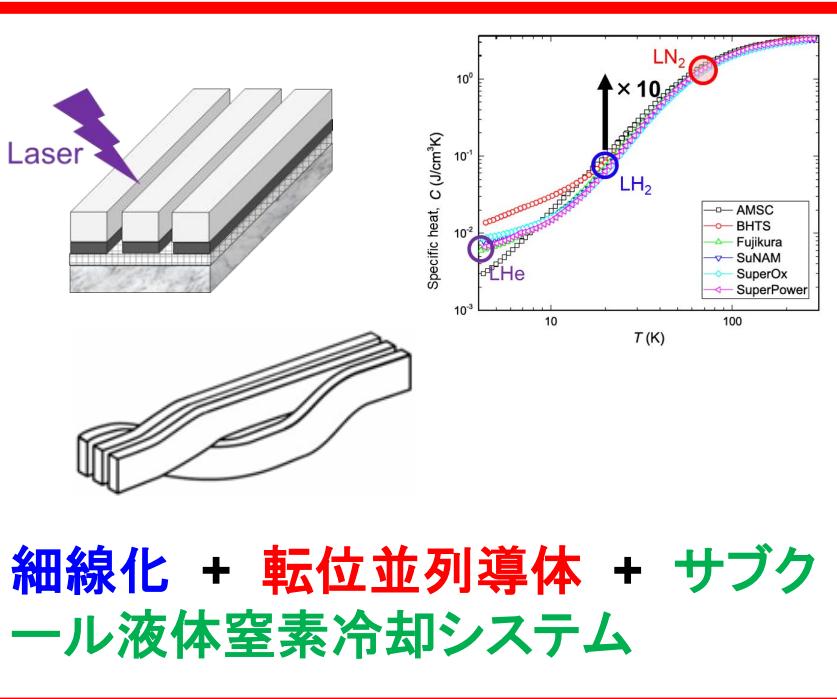
→ 細線化 + 転位並列導体 + サブクール液体窒素冷却システム + FFDS



全超伝導回転機

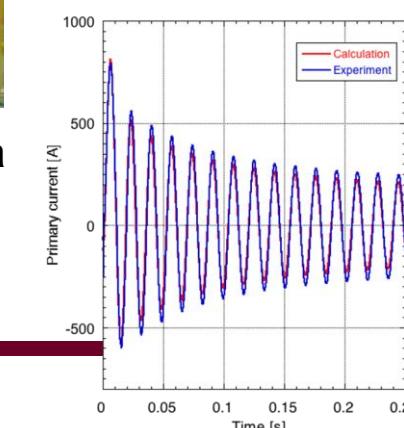
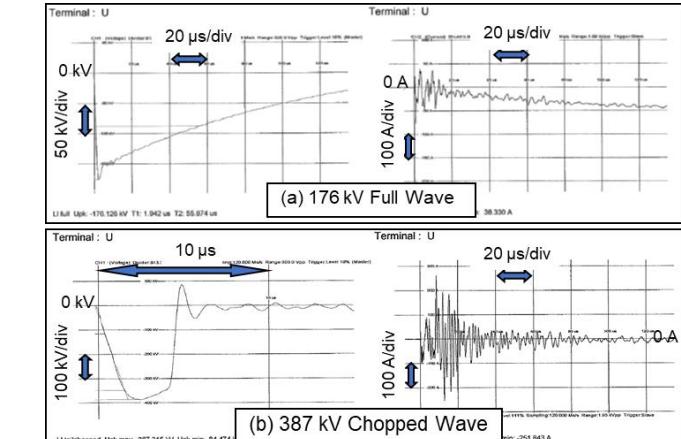


- ✓ 交流機器向けの低交流損失・大電流容量化かつ安定化技術を長年開発
- ✓ 超伝導変圧器に適用し、その信頼性を実証

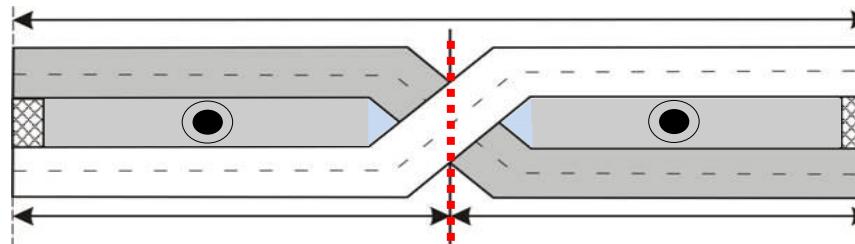
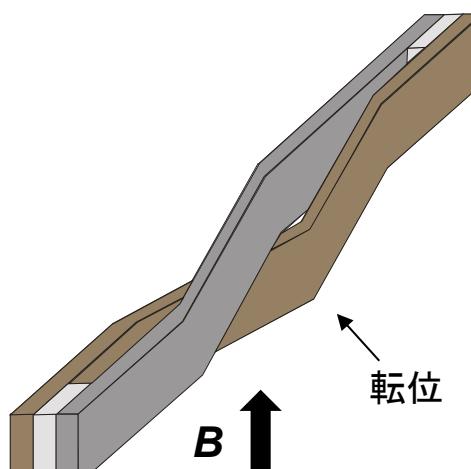
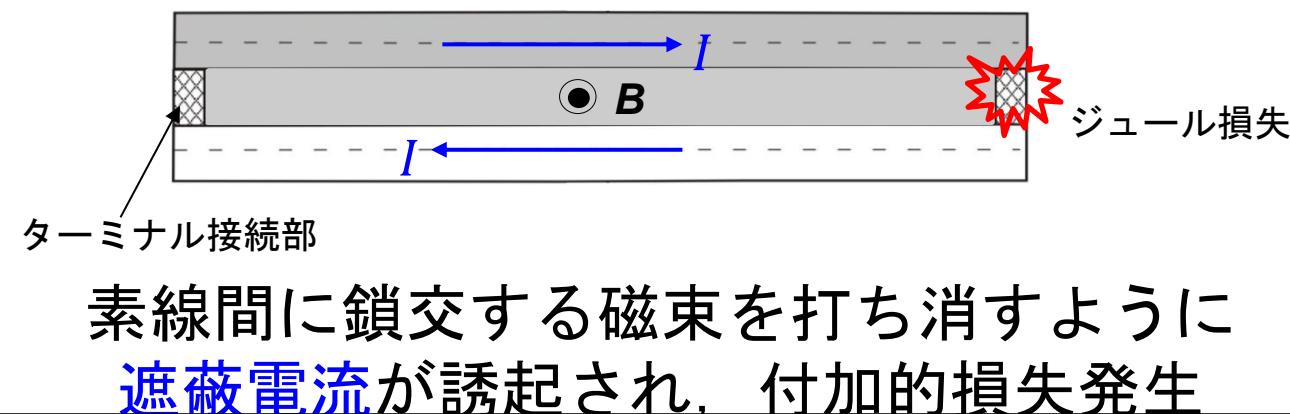
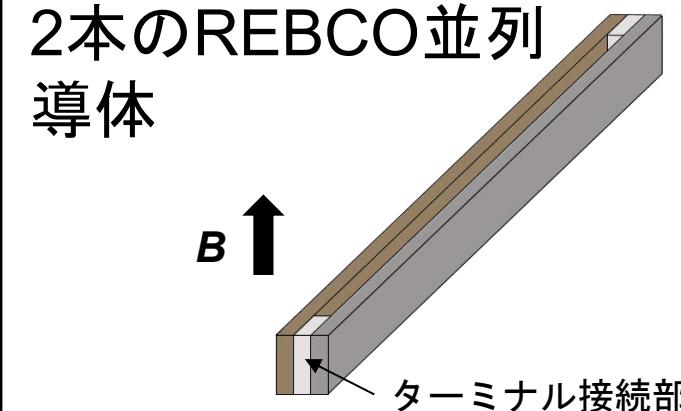


We have investigated the stabilities via superconducting transformers.

M. Iwakuma et al.: IEEE TAS 25, 5500206 (2015),  
Physica C 469 (2009) 1726, IEEE 21 (2011) 1405



# 転位(位置の入れ替え)の効果

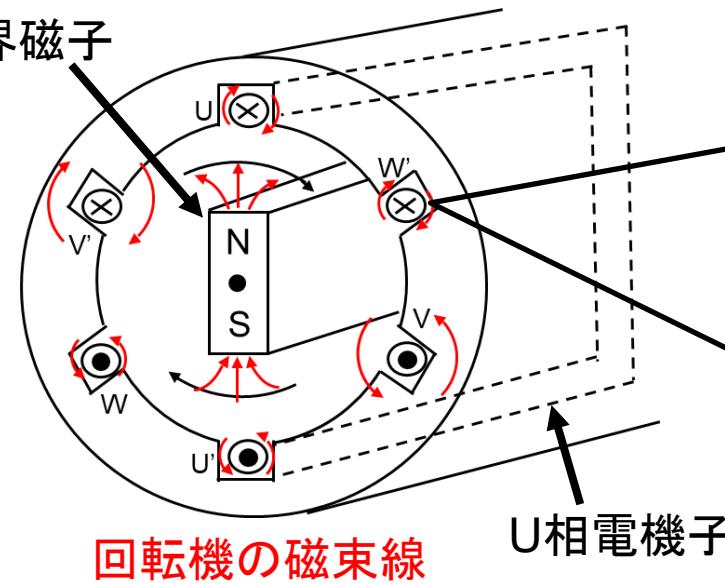


鎖交磁束が打ち消されて遮蔽電流流れない  
→付加的損失ゼロ





回転界磁子



- ✓ 三相電機子+回転界磁による複雑な電磁界環境
- ✓ あらゆるモータ設計条件に対応した転位構成

➡ 回転機向けの [ 簡易な解析手法  
電流均一化概念 (一般化) ]

転位並列導体



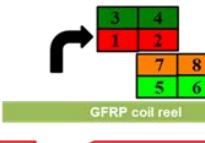
A6 arrow view



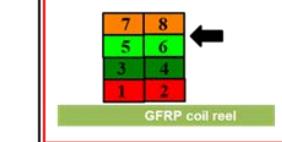
A1 arrow view



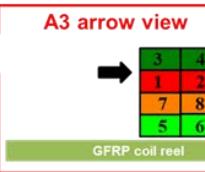
A2 arrow view



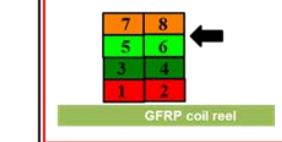
A5 arrow view



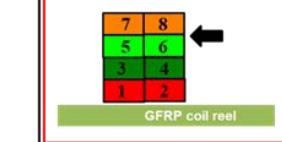
A3 arrow view



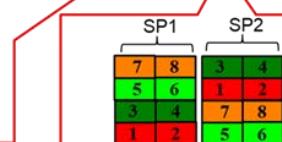
A4 arrow view



A6 arrow view



A1 arrow view



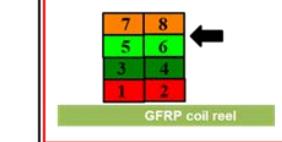
A2 arrow view



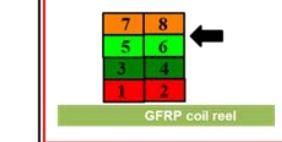
A3 arrow view



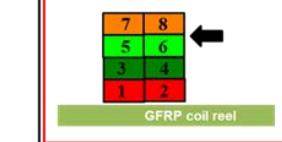
A4 arrow view



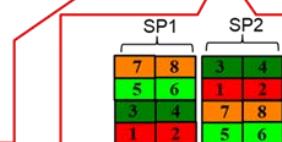
A5 arrow view



A6 arrow view



A1 arrow view



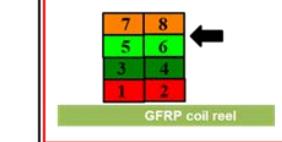
A2 arrow view



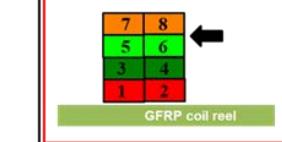
A3 arrow view



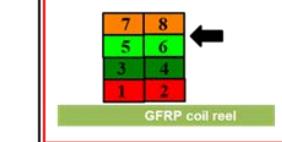
A4 arrow view



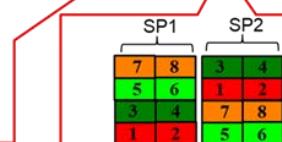
A5 arrow view



A6 arrow view



A1 arrow view



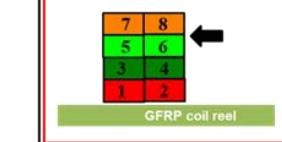
A2 arrow view



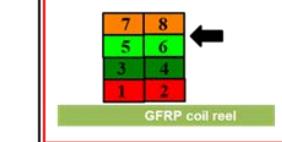
A3 arrow view



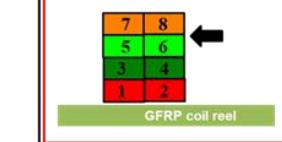
A4 arrow view



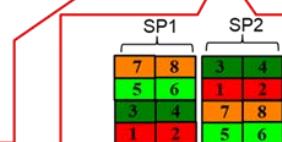
A5 arrow view



A6 arrow view



A1 arrow view



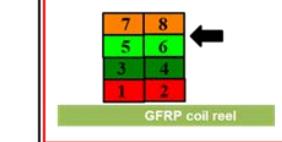
A2 arrow view



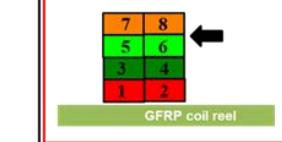
A3 arrow view



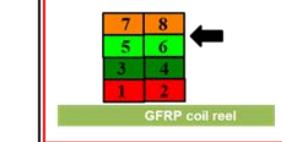
A4 arrow view



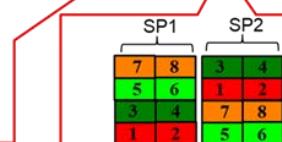
A5 arrow view



A6 arrow view



A1 arrow view



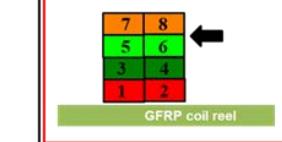
A2 arrow view



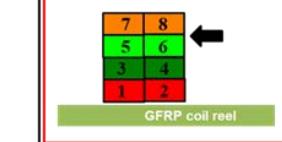
A3 arrow view



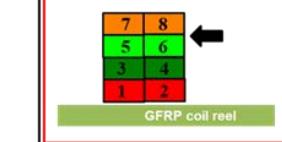
A4 arrow view



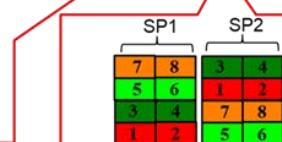
A5 arrow view



A6 arrow view



A1 arrow view



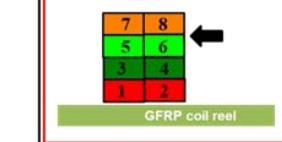
A2 arrow view



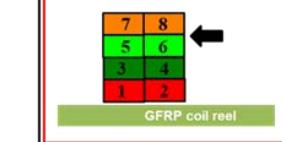
A3 arrow view



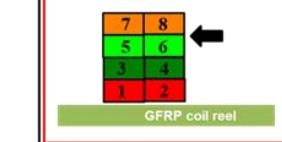
A4 arrow view



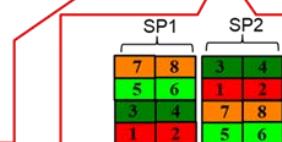
A5 arrow view



A6 arrow view



A1 arrow view



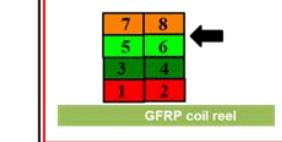
A2 arrow view



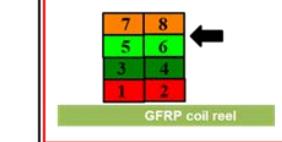
A3 arrow view



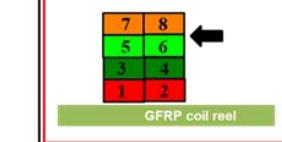
A4 arrow view



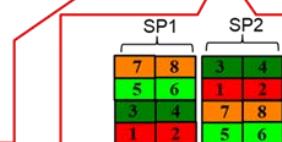
A5 arrow view



A6 arrow view



A1 arrow view



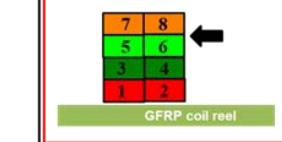
A2 arrow view



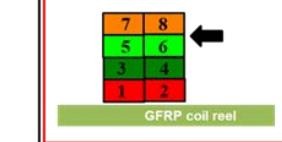
A3 arrow view



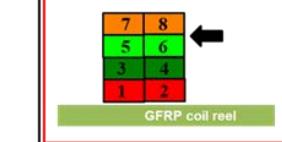
A4 arrow view



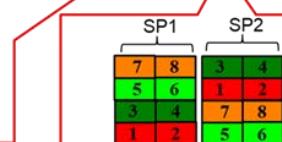
A5 arrow view



A6 arrow view



A1 arrow view



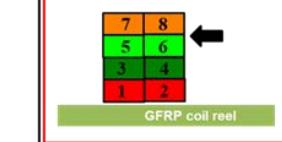
A2 arrow view



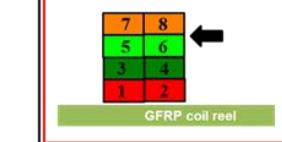
A3 arrow view



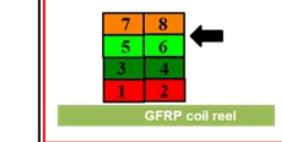
A4 arrow view



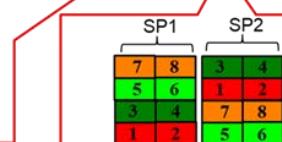
A5 arrow view



A6 arrow view



A1 arrow view



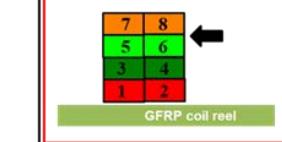
A2 arrow view



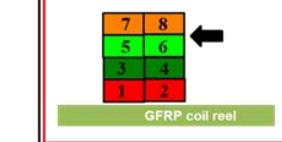
A3 arrow view



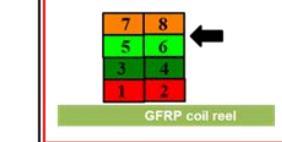
A4 arrow view



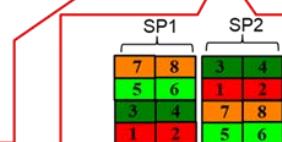
A5 arrow view



A6 arrow view

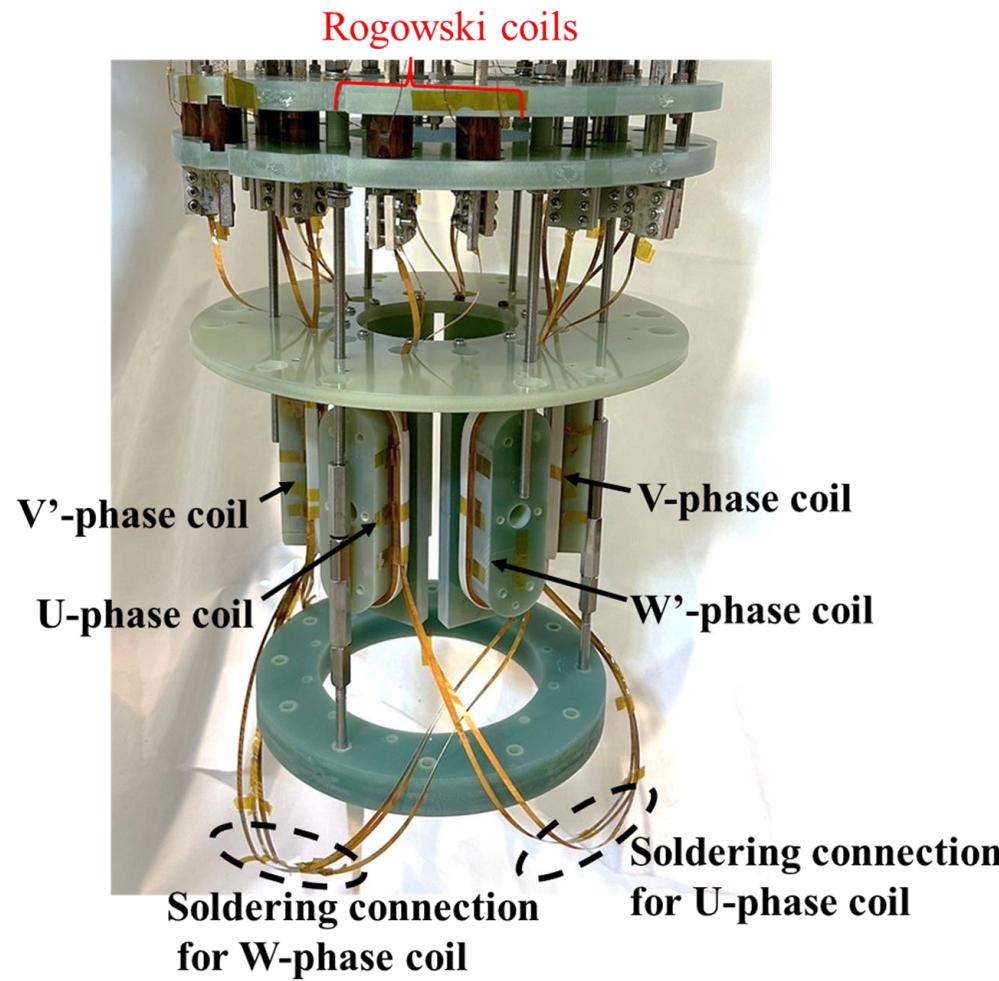


A1 arrow view

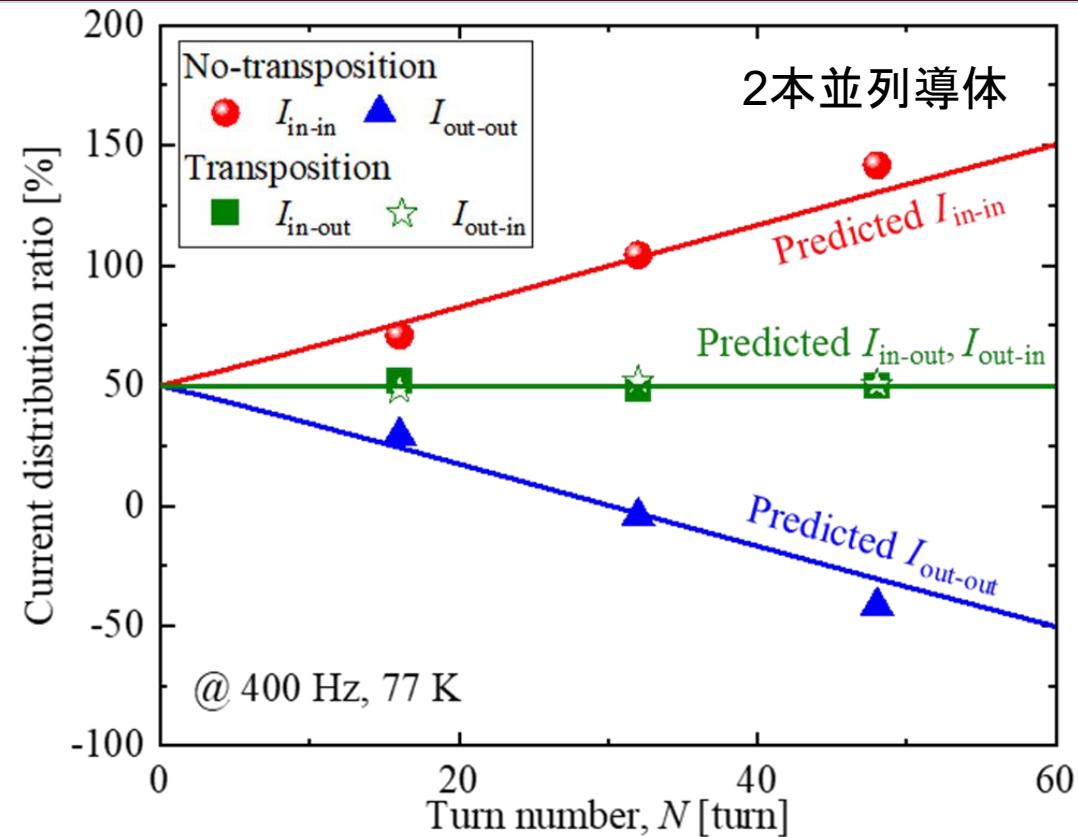


A2 arrow view





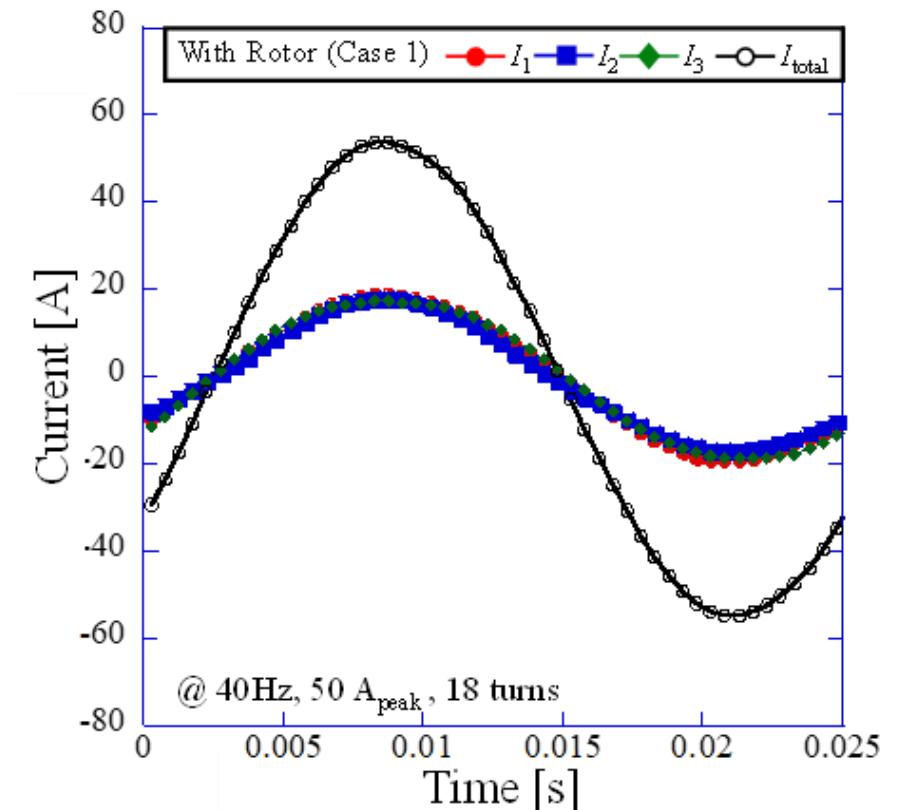
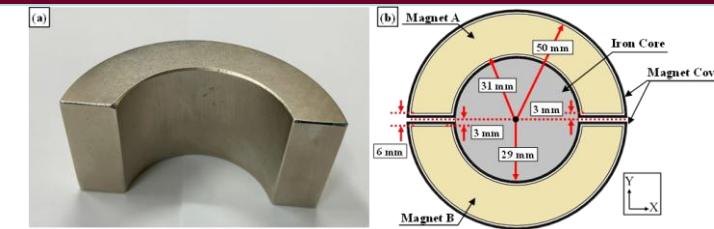
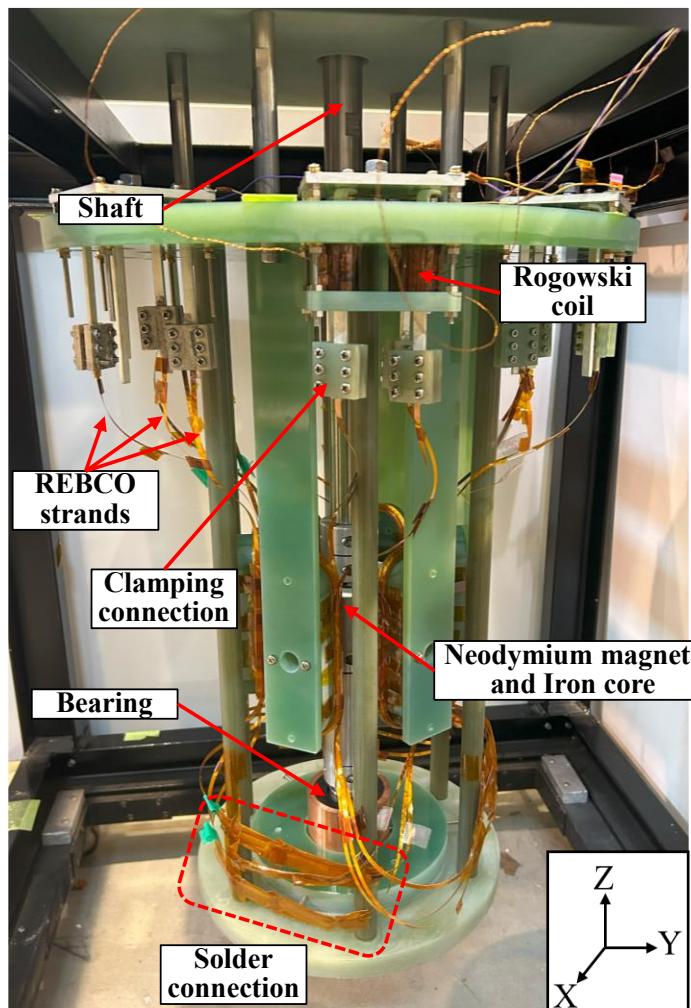
✓ 電流分流の実測による実証試験



- ✓ 解析手法が精度良く電流分流を予測できることを実証
- ✓ 回転機の磁界対称性を利用
- ✓ 2-16本並列の転位並列導体構成法（一般化概念）を確立
- ✓ 特殊な加工なしに大電流容量化

# 三相電機子+回転界磁の環境下における電流分流測定

14



✓ 回転界磁がある実際の回転機環境でも均一な電流分流を達成



- 超伝導回転機向け低交流損失・大電流容量化技術
- NEDOプロジェクト(400 kW全超伝導モータ→2 MW全超伝導モータ)
- 核融合への展開

Rotor, Field windings

Need Low windage loss → Gas He

Slip ring and brush

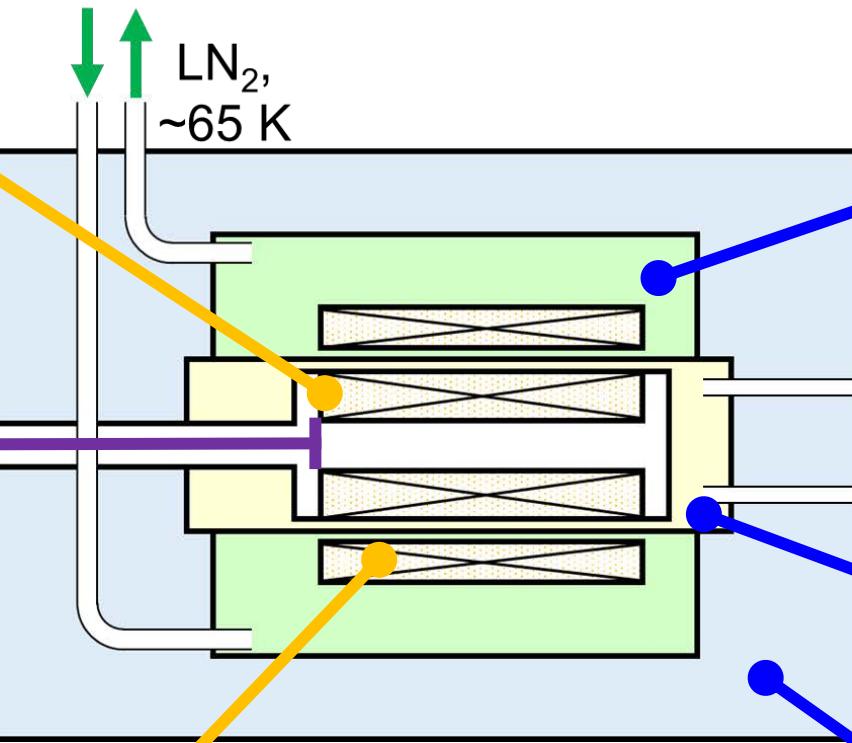
Rotor shaft

Ferrofluidic seal

Stator, Armature windings

Armature windings generate large AC loss → Subcooled  $\text{LN}_2$  and multifilament

Need Low voltage (= High current) → Transposed multi-strand parallel conductor



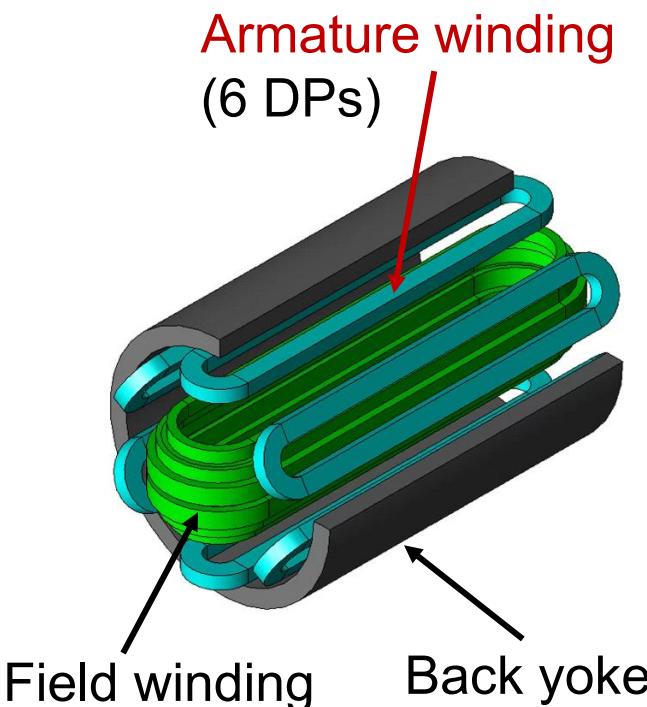
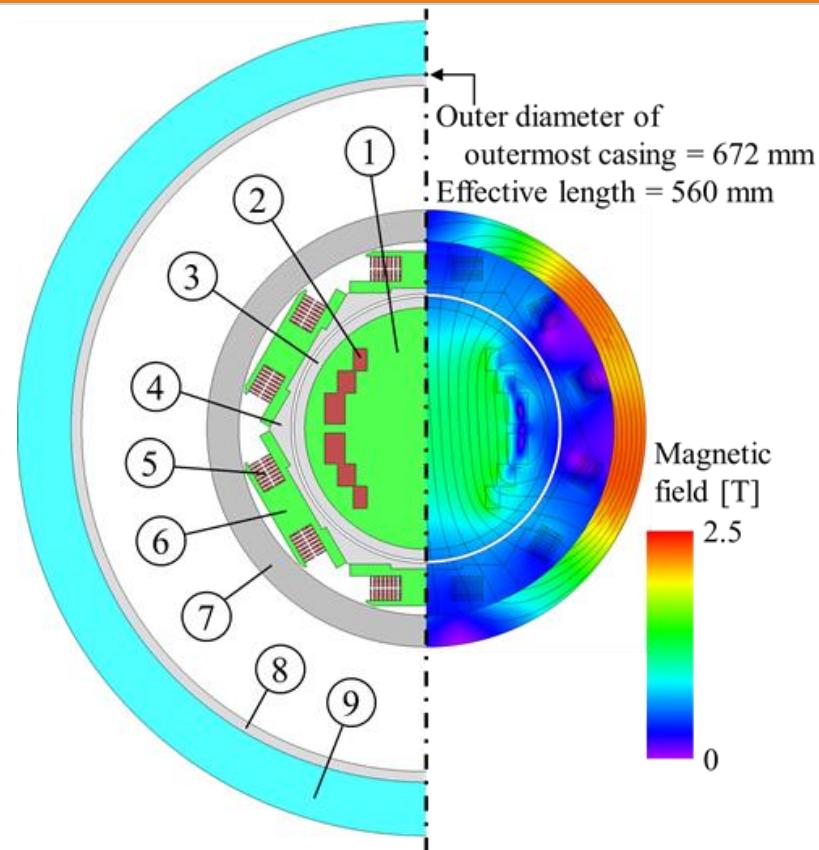
Stator room,  
subcooled  $\text{LN}_2 \sim 65 \text{ K}$

Rotor room,  
Gas He 60-65 K

Thermal insulation layer

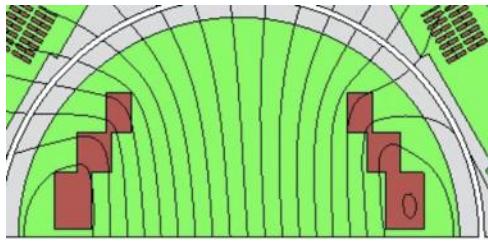
One of the project goals: To manufacture this casing structure operating in hundreds kW-class and thousands rpm.

Type	FULLY SUPERCONDUCTING SYNCHRONOUS MOTOR
Superconducting wire	4 mm-width REBCO tape
Output power	433 kW
Iron loss	2.1 kW
Eddy current loss in inner casing of armature (CFRP)	1.49 kW
Eddy current loss in tube covering field (CFRP)	$4.29 \times 10^{-2}$ kW
Number of poles	2
Rotational speed	2500 rpm
Armature frequency	41.7 Hz
Rated voltage	450 V <sub>rms</sub>
Rated current	576 A <sub>rms</sub>
Field current	110 A
Magnetic field at gap	0.69 T
Efficiency	98.7%
Armature windings	
Number of turns	30 turns/coil
Number of parallel conductors	6
Load factor at 64 K	69.7%
AC loss at 64 K	2.75 kW
Field windings	
Number of turns	2247 turns
Number of parallel conductors	1
Load factor at 64 K	87.7%
AC loss at 64 K	0.13 kW

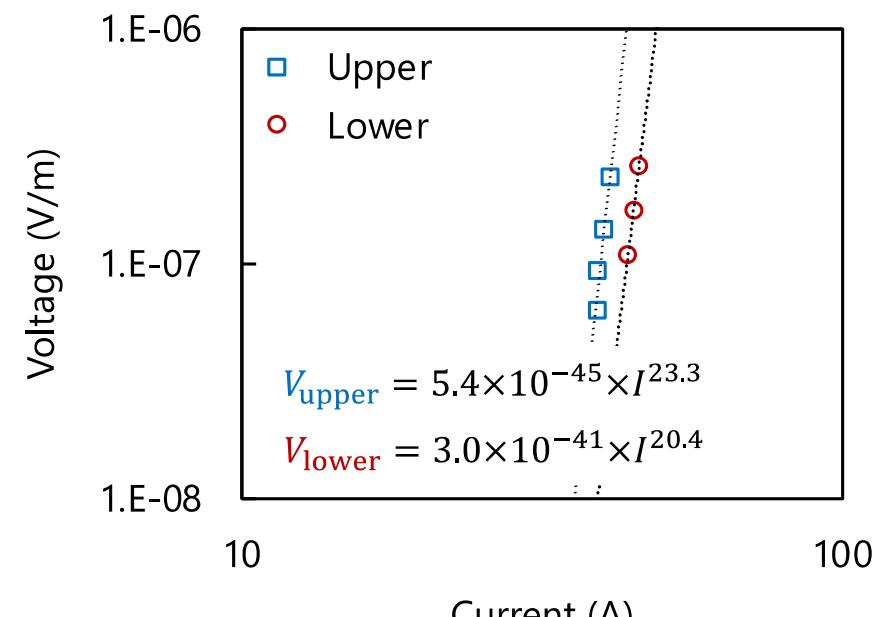


#	PARTS	Material	Radial thickness [mm]
1	Frame for field	GFRP	-
2	Field winding	REBCO tape	-
3	Tube covering field	CFRP	10
4	Inner casing for armature	CFRP	5.3-21.0
5	Armature winding	REBCO tape	-
6	Frame for armature	GFRP	-
7	Back yoke	Permendur	30
8	Outermost casing	CFRP	10
9	Thermal insulator	Foamed resin	-

- The field coil was wound using a cos-theta-like racetrack distribution
- Separate lower and upper part
- Both parts were tested in LN<sub>2</sub>



Upper winding



Measured V-I curves at 77K

Both windings were integrated and assembled Rotor

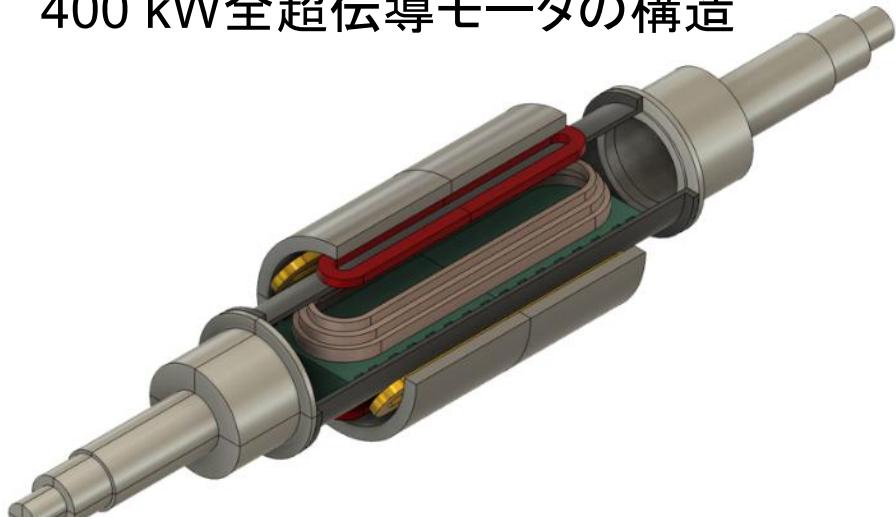
# Preparation for trial test

- The 400kW-class motor was tested as a synchronous generator.
- A conventional normal-conducting motor was connected.
- The 400kW-class motor was tested with no load and 3-phase short-circuits.

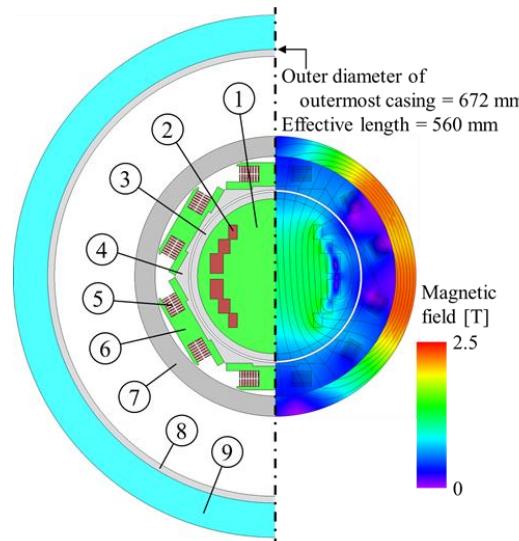


400kW-class superconducting motor

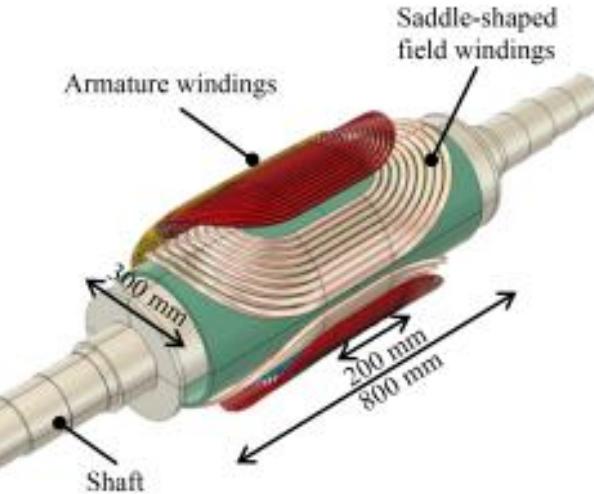
400 kW全超伝導モータの構造



- ✓ 界磁・電機子巻き線とともにレーストラックコイル



2 MW全超伝導モータの構造



- ✓ 界磁・電機子巻き線ともに鞍型巻き線を採用
- ✓ 電機子は分布巻き

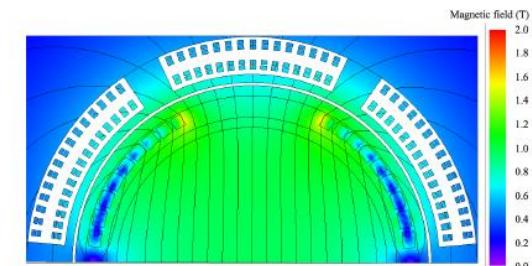
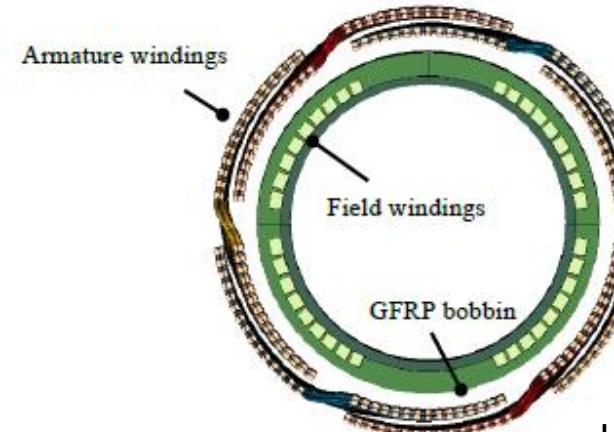
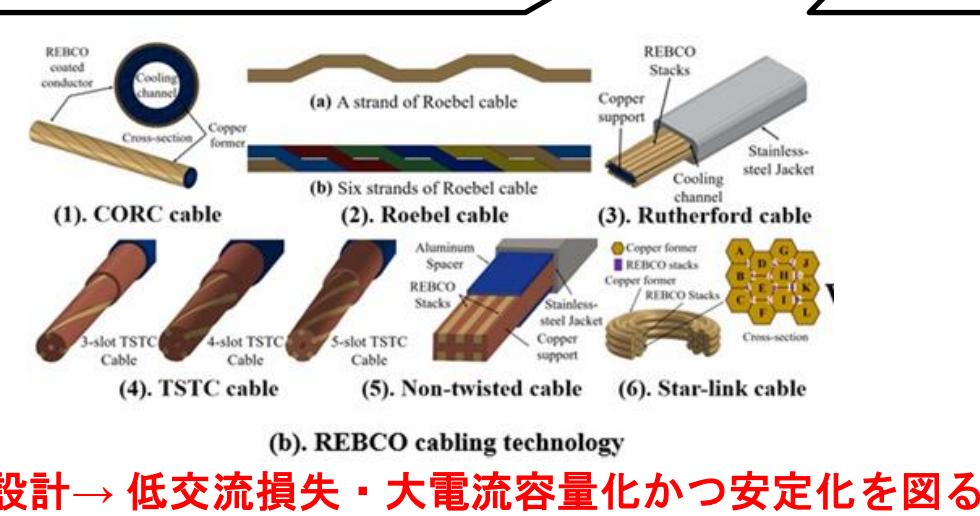
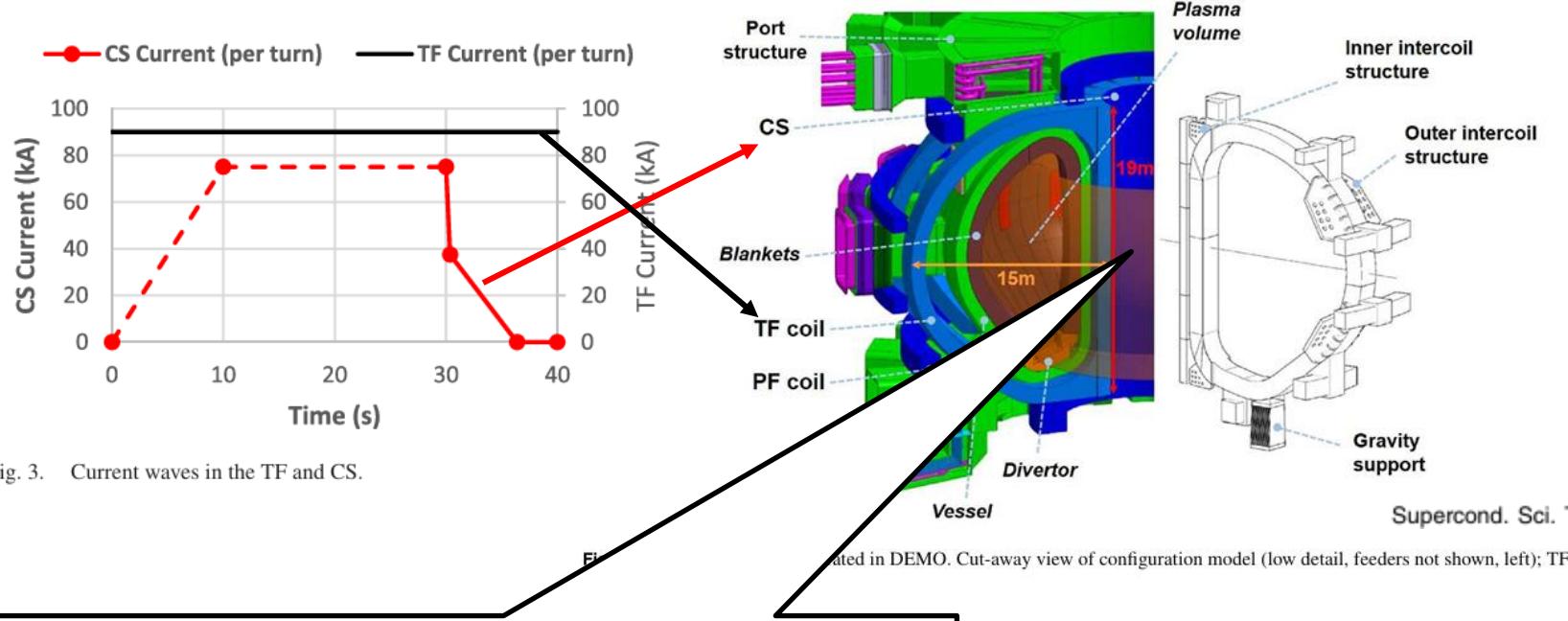


Fig. 5. Calculated magnetic fields in the field and armature windings.

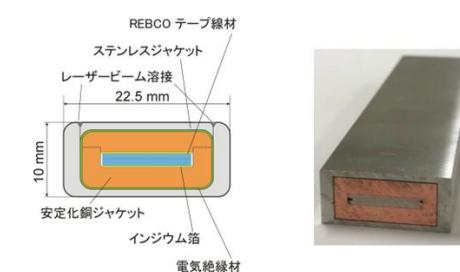
- 超伝導回転機向け低交流損失・大電流容量化技術
- NEDOプロジェクト(400 kW全超伝導モータ→2 MW全超伝導モータ)
- 核融合への展開

# 核融合への展開

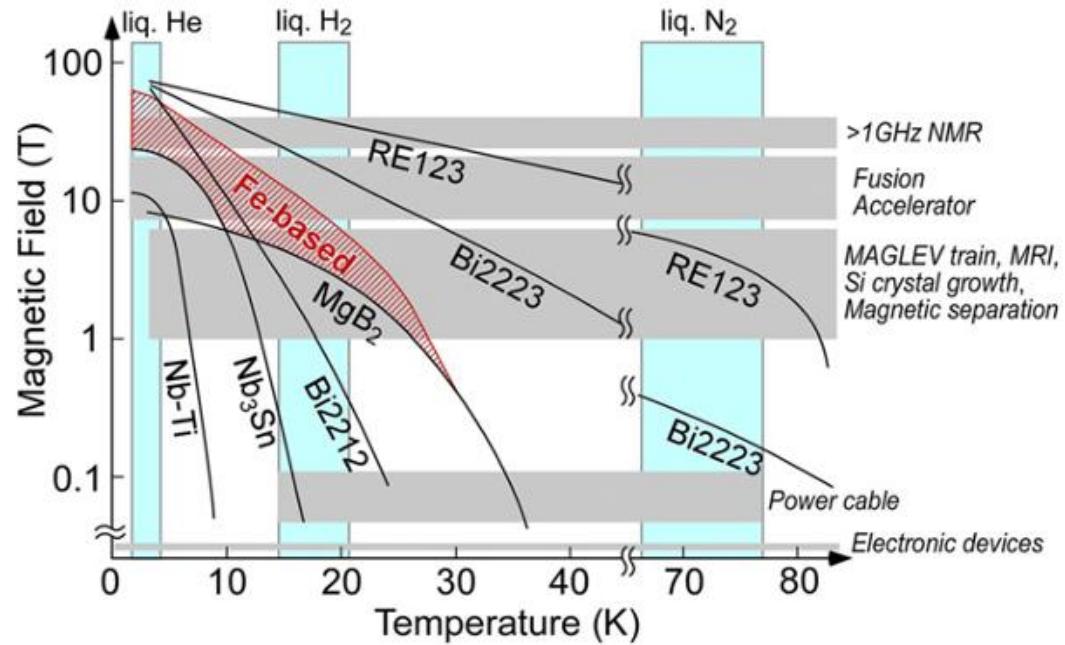
トカマク型では**交流損失**が課題の一つ(特にコンパクトトカマク)



✓ モータとの大きな違いは電磁力  
九大Gの2 MWモータ: 0.7-24 kN/m  
CFSのTFコイル: 750-822 kN/m



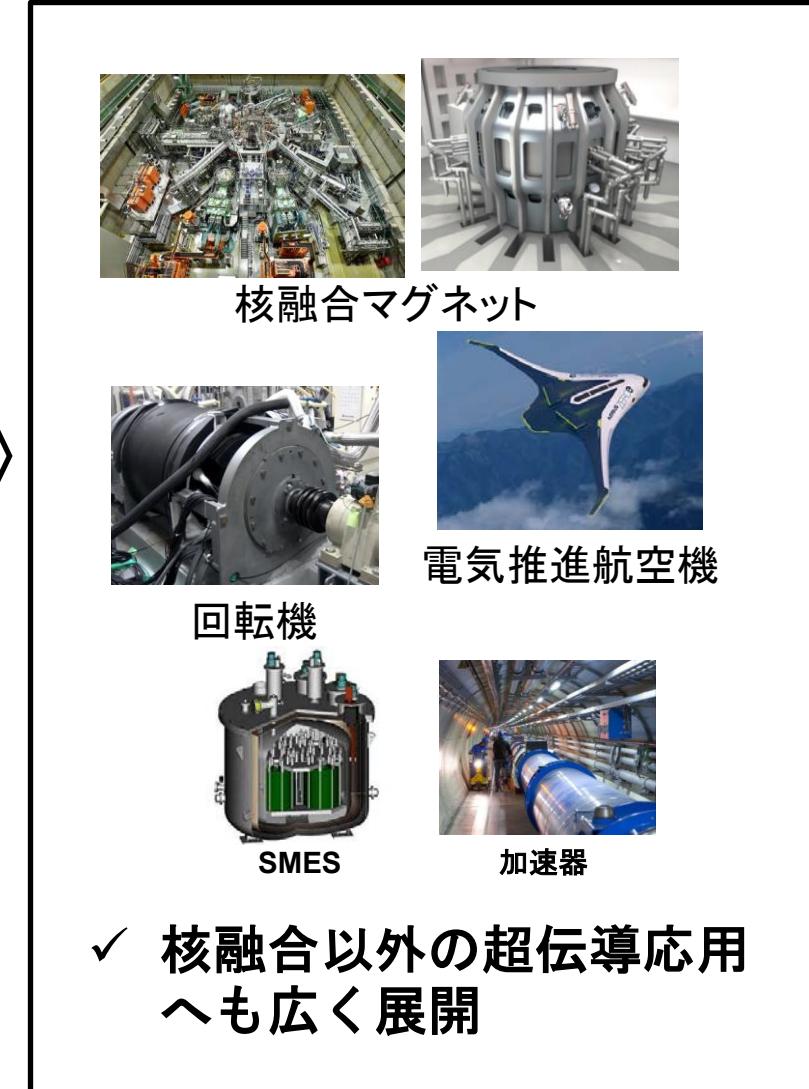
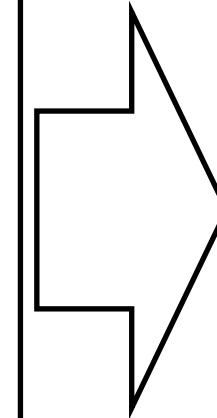
✓ STARS導体の電磁特性  
柳先生、Yessimzhanさん(総研大PhD学生)と共同研究



**Figure 10.** Applicable conditions for  $J_e > 10^4 \text{ A cm}^{-2}$  for various superconducting tapes and wires.

J. Shimoyama 27 044002 (2014)

- ✓ 最新の超伝導線材の交流損失を含む特性を評価
- ✓  $\text{MgB}_2$ 線材を含む丸線の超伝導線材・導体
- ✓ 経済安全保障重要技術育成プログラム(研究代表者: 平野先生): 3次元立体形状超伝導マグネットを経済的に実現できる基盤技術の構築 (仮称)



- ✓ 核融合以外の超伝導応用へも広く展開