Ripple field effects on the No-insulation HTS rotor windings of machines

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Results incorporated in this standard have received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 799902".

Outlines

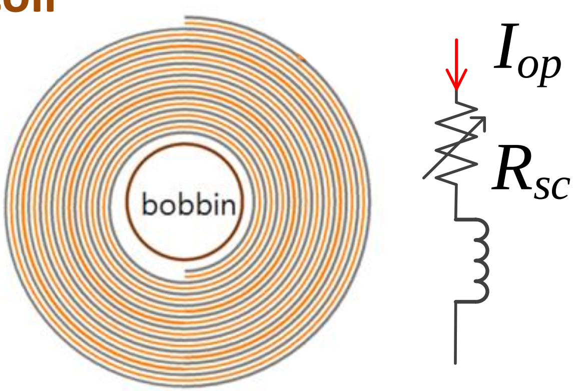
- Introduction to NI HTS coils for machines
- Equivalent circuit network model for NI coils
- Influences of ripple fields on NI HTS coils
- Conclusions

No-insulation REBCO coil

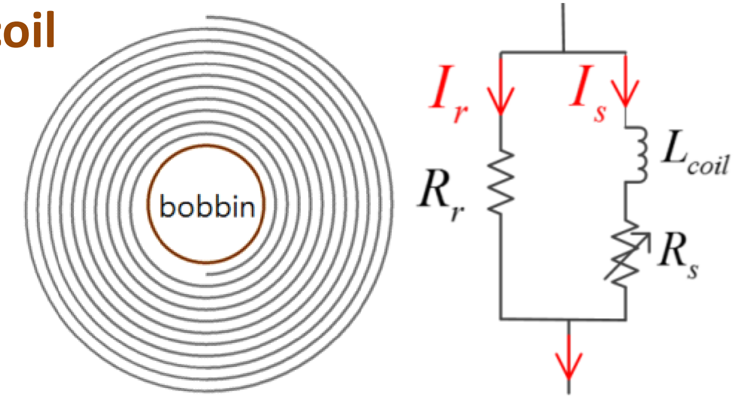
no-electric-insulation (NI) HTS coils

TYPE OF WINDING	Insulated Coil		Non-insulated	Metal as insulation
Strategy	Current margin	Quench heater	Free current path	Co-winding with a metallic layer
Advantage	Magnetic stability and linearity	High operating current	Self protection	Self-protection
Drawback	Moderate B !	Quench detection	Charging time	Possible assymetric forces at quench Complex to simulate

INS coil

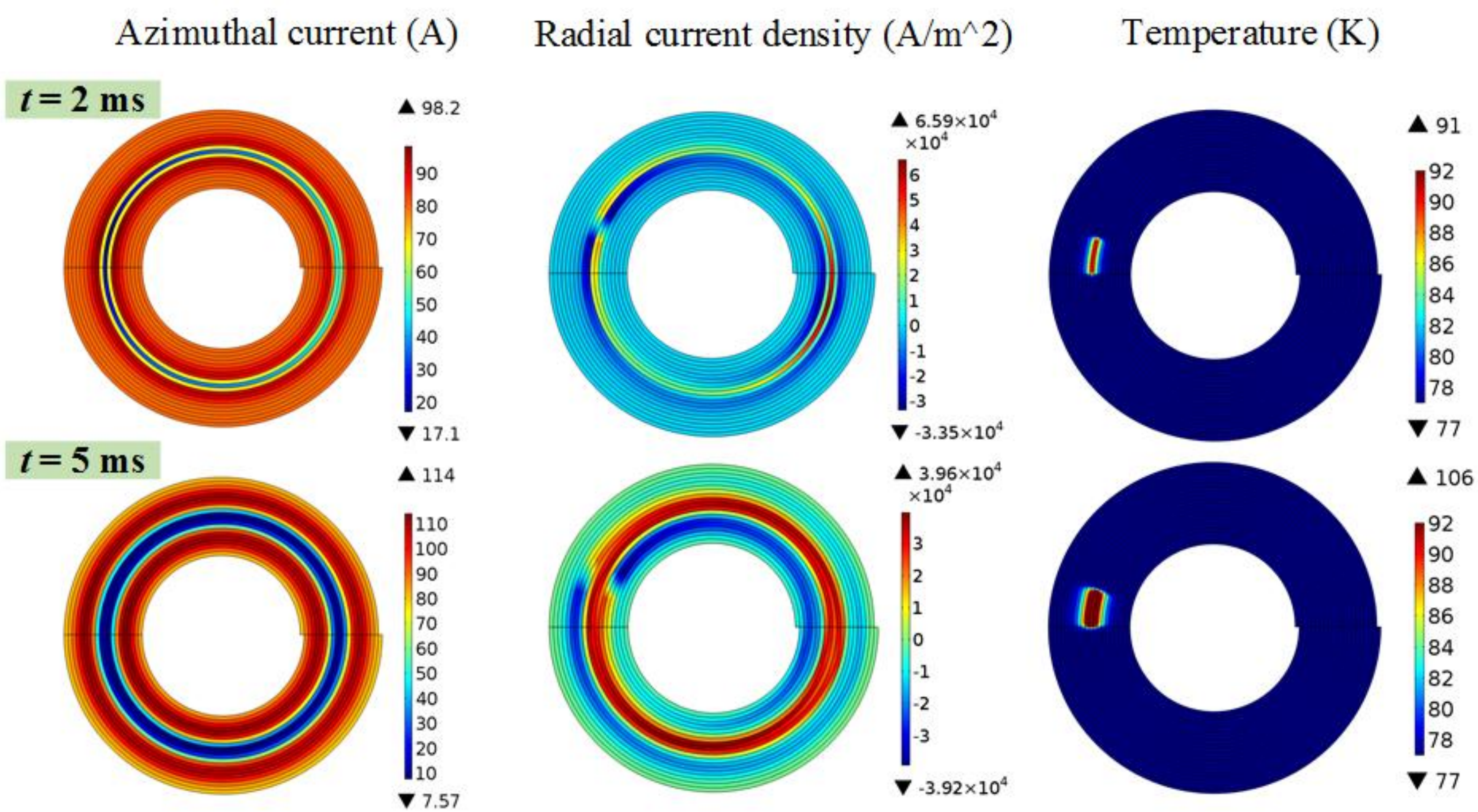


NI coil



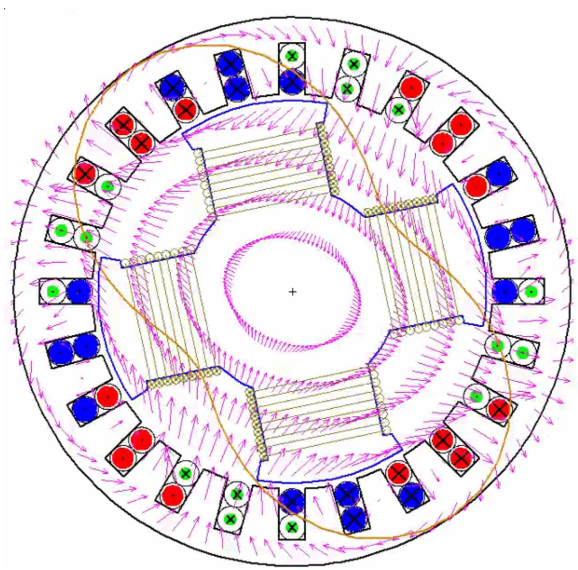
No-insulation REBCO coil

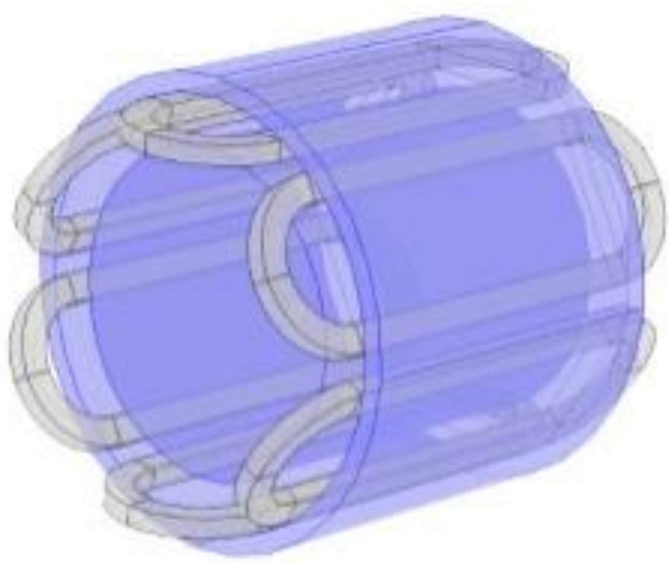
Advantages: Enhanced thermal stability during local quench, due to current redistribution among turns.



NI HTS rotor windings

- **Idea:** applying the NI technique on the rotor of machine.
- **Advantages:** enhanced thermal stability and reliability.
- **Challenges:** ripple fields from stators can induce an extra eddy loss on the NI HTS rotor coils, which may significantly affect the efficiency. Modelling tool is required for this study.





Network model for NI coil

- **An equivalent circuit network model** is developed for NI coil. Each turn is subdivided into fine arc elements, each element is equivalent to circuit parameter (R, L), and the whole coil is equivalent to a circuit network.

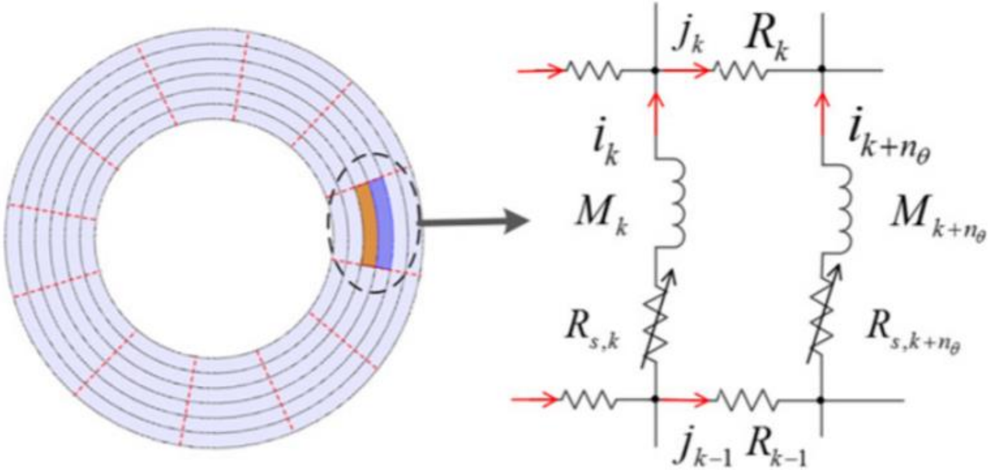
i_k Azimuthal current

j_k Radial current

$$R_k = \rho_e \frac{\Delta}{S_k} = \rho_e \frac{\Delta}{w_d l_k}$$ Turn-to-turn-contact resistance

$R_{s,k}$ Resistance of HTS, which is zero in this study

$M_{k,m}$ Mutual inductances



Network model for NI coil

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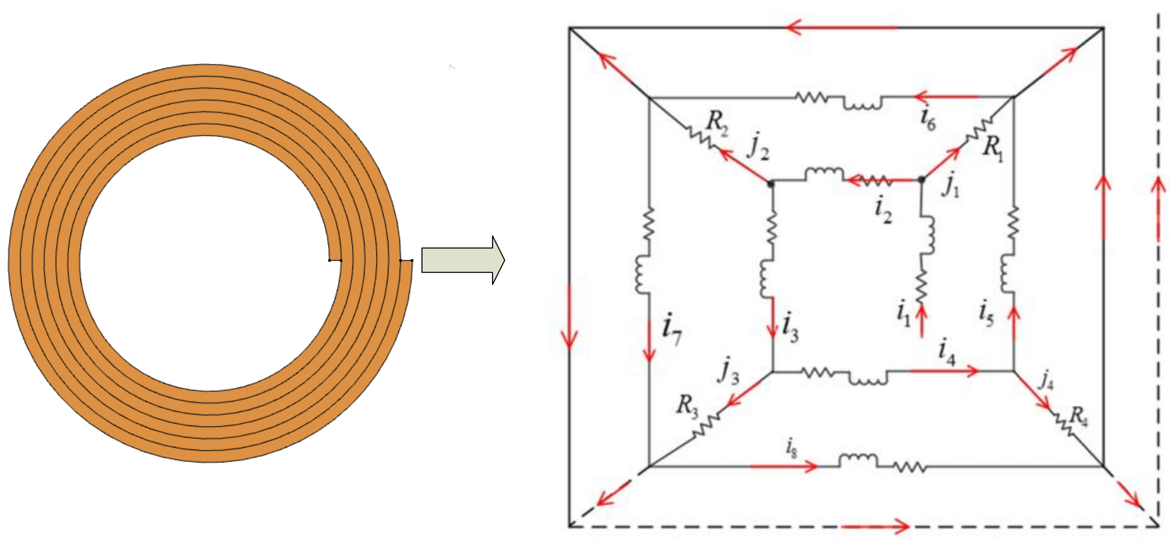
- **Governing equation** is derived from Kirchhoff current and voltage law

$$\begin{cases} i_k - i_{k+1} + j_{k-n_e} - j_k = 0; \qquad \text{(KCL)} & \text{Independent circuit node} \\ u_k - u_{k+n_e} - j_{k-1}R_{r,k-1} + j_k R_{r,k} = 0 \quad \text{(KVL)} & \text{Independent circuit mesh} \end{cases}$$

- Eddy loss is generated by radial current **j** on turn-to-turn contacts.

$$\begin{cases} W_{t2t} = \sum_k j_k{}^2 R_k \\ Q_{t2t} = \int W_{t2t} dt, \end{cases}$$



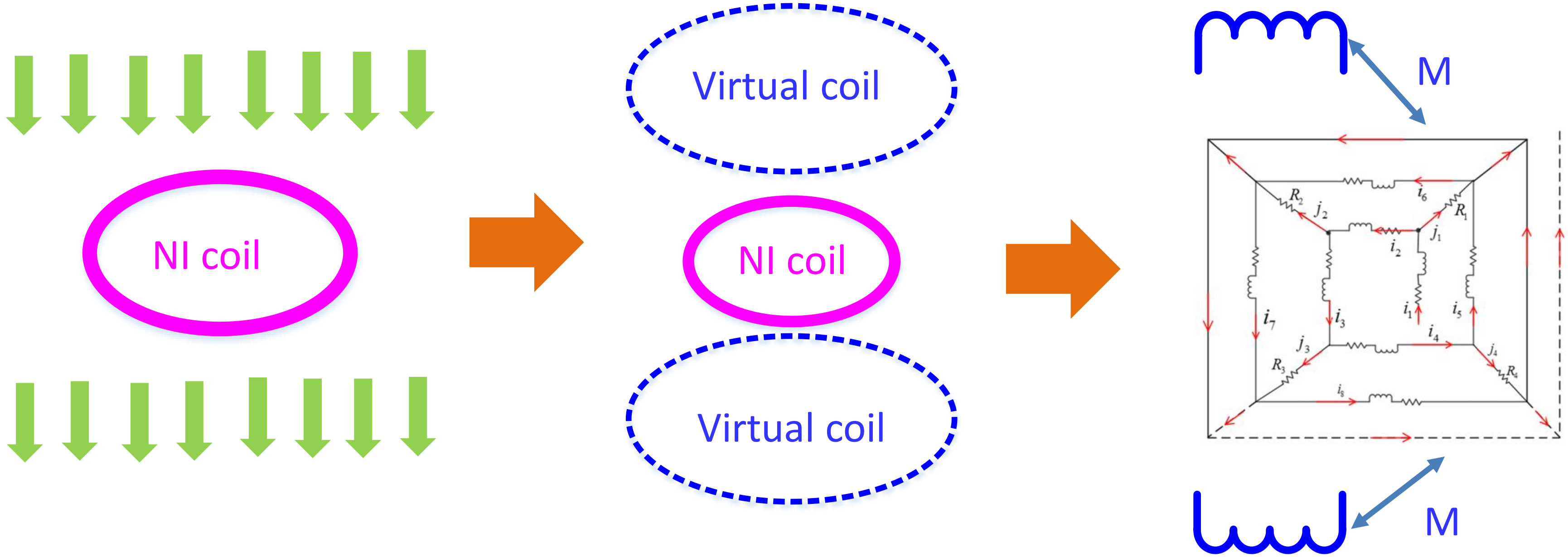
Network model for NI coil

➢ **How to impose the background ripple fields**

Virtual coils with AC current are designed to generate the background ripple fields. The ripple field effect is transferred to electromagnetic coupling between coils.

Frequency of current ⟷ Frequency of ripple field

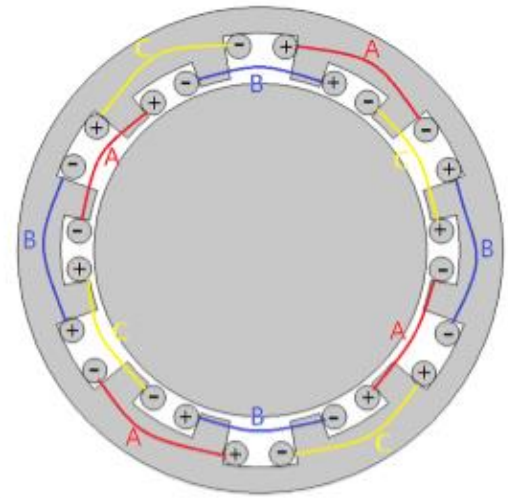
Amplitude of current ⟷ Amplitude of ripple field

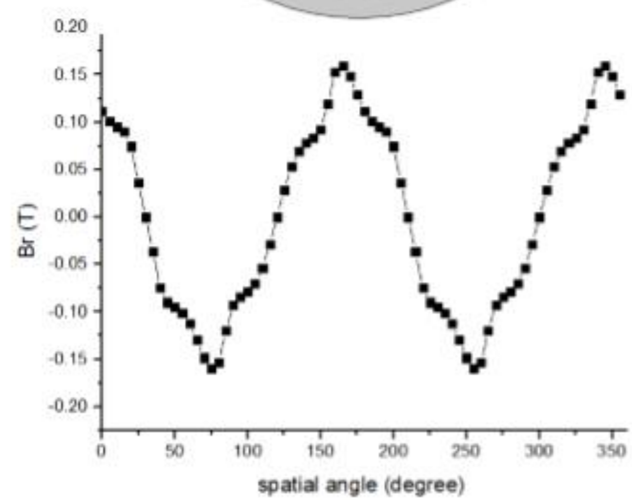


Results- sample

Ripple fields of 3-phases machines：
Origin: 5^{th}, 7^{th}, 11^{th}, harmonics.
Amplitude: 1~20 mT
Frequency: 25~500 Hz

Parameters	Test NI HTS Coil
Coil type	SP
Number of turns	42
Tape, Ic/width/thickness	127A/4mm/0.1m
Inner/outer diameter	89/97 mm
Height	4mm
Total length of wire	38 m
Coil inductance, cal.	1.886 mH
B_z per amp	4 mT/A
I_c coil	70 A @ 77 K
Turn-to-turn resistivity	10~100 μΩ·cm^2



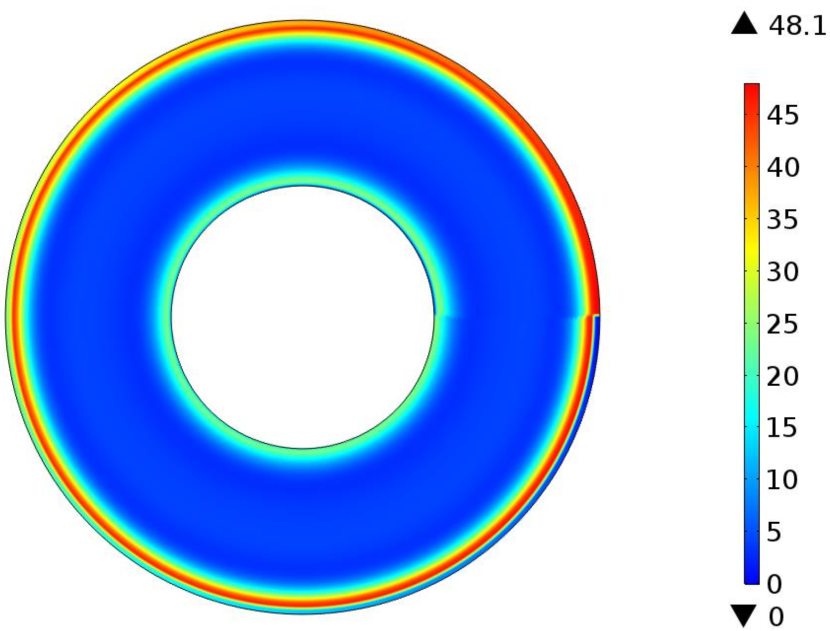


Results

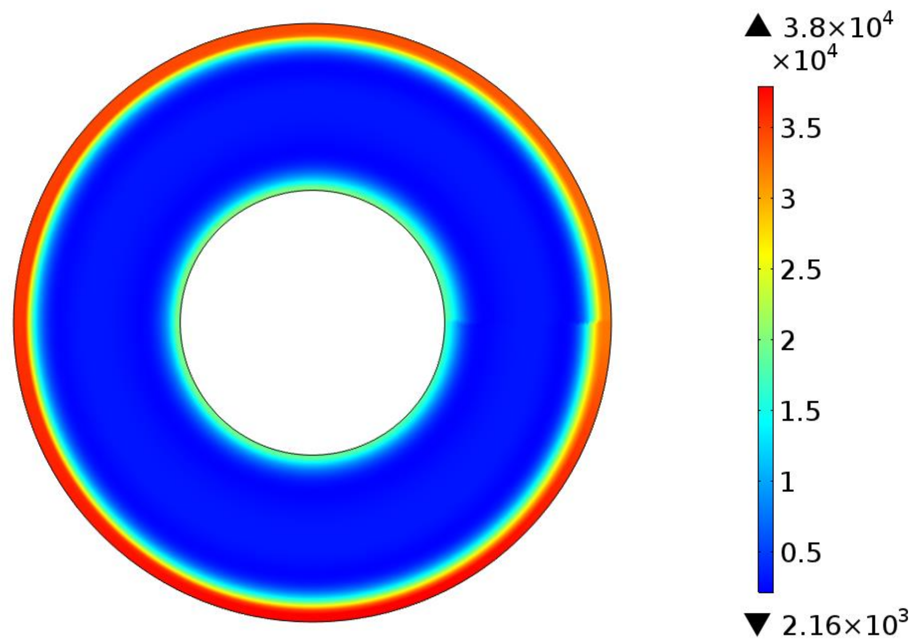
➢ **Eddy current distribution**: azimuthal and radial currents are induced on the turns near inner and outer side.

Ripple field: 10mT/25Hz

- Azimuthal current

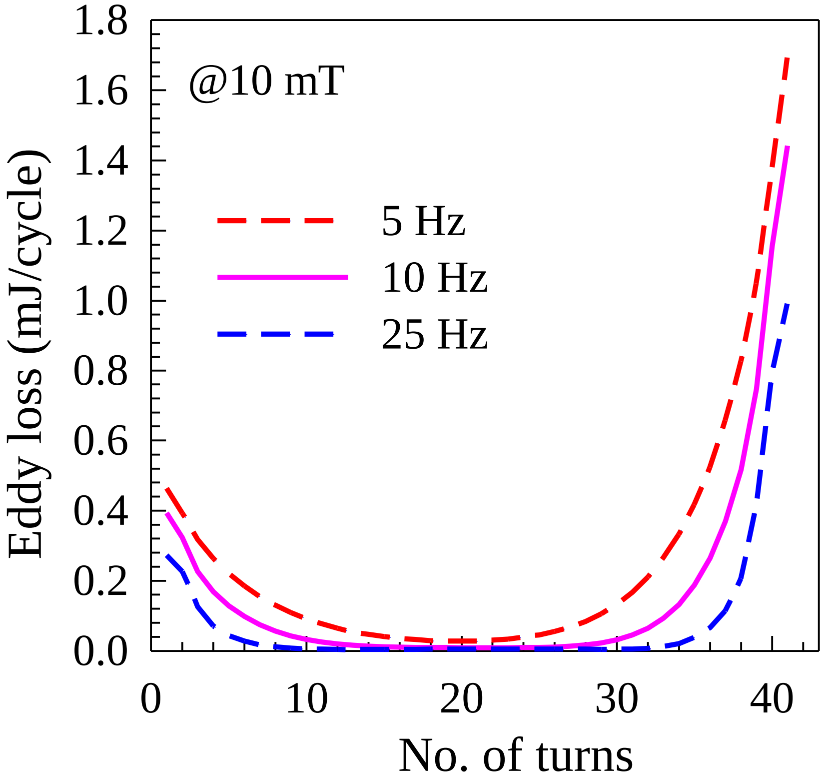


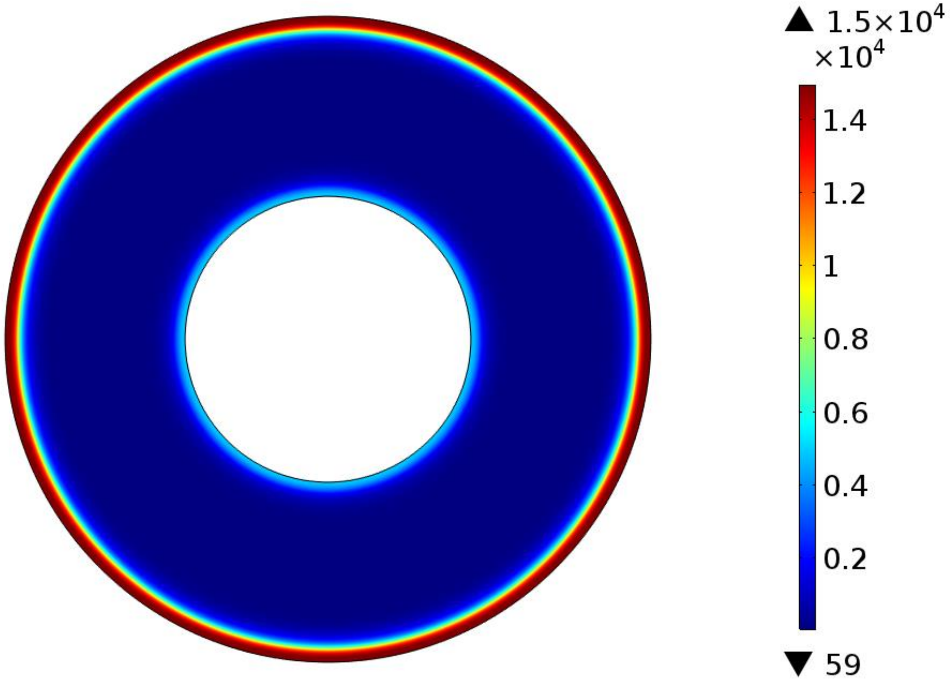
- Radial current density



Results

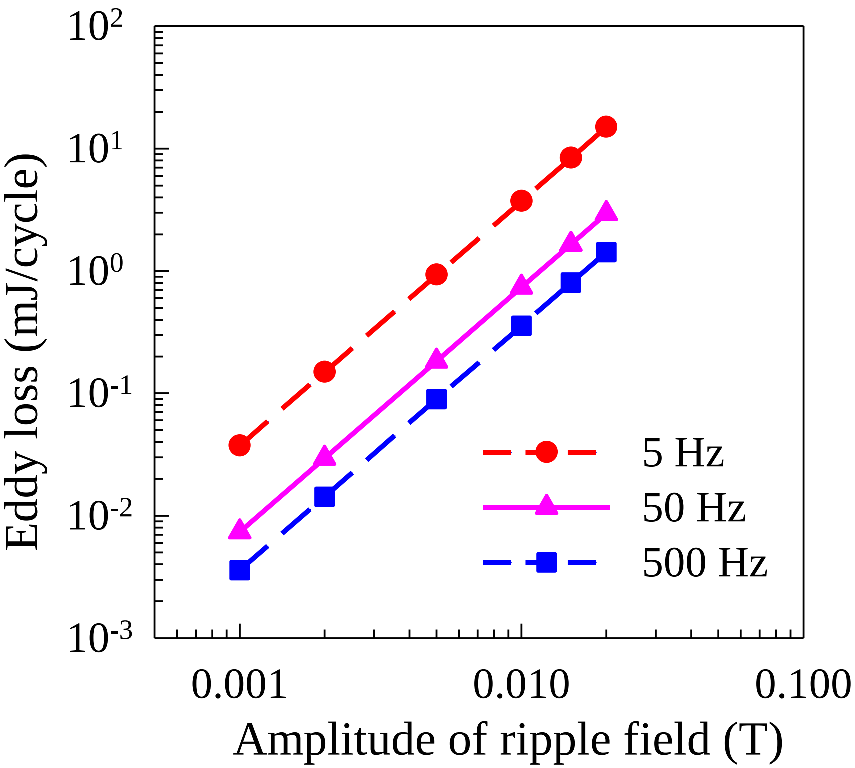
- **Eddy loss distribution among turns**:
  most of eddy loos happens on the turns near outer sides.

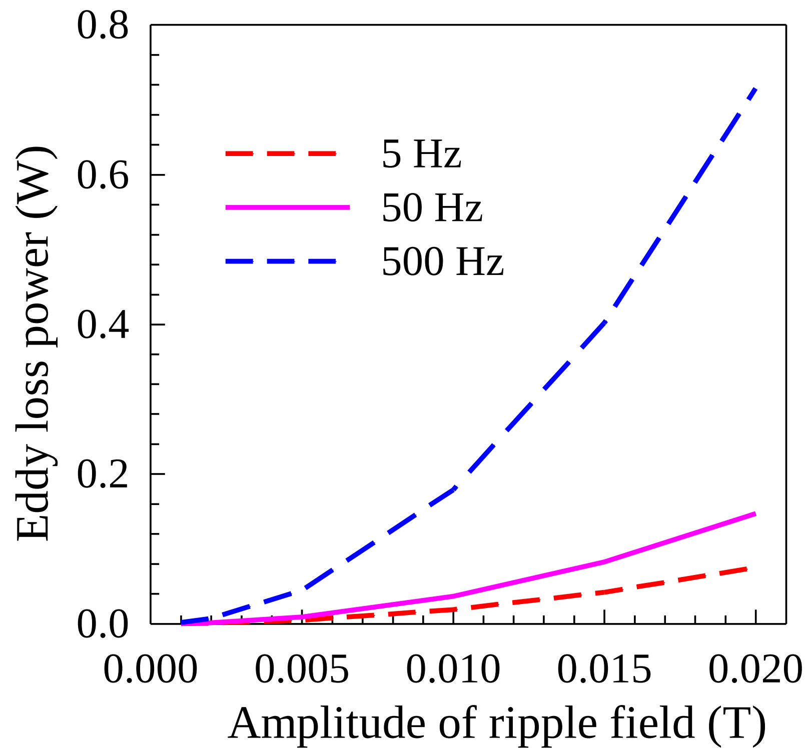




Results

➢ **Eddy loss VS amplitude of ripple fields.**



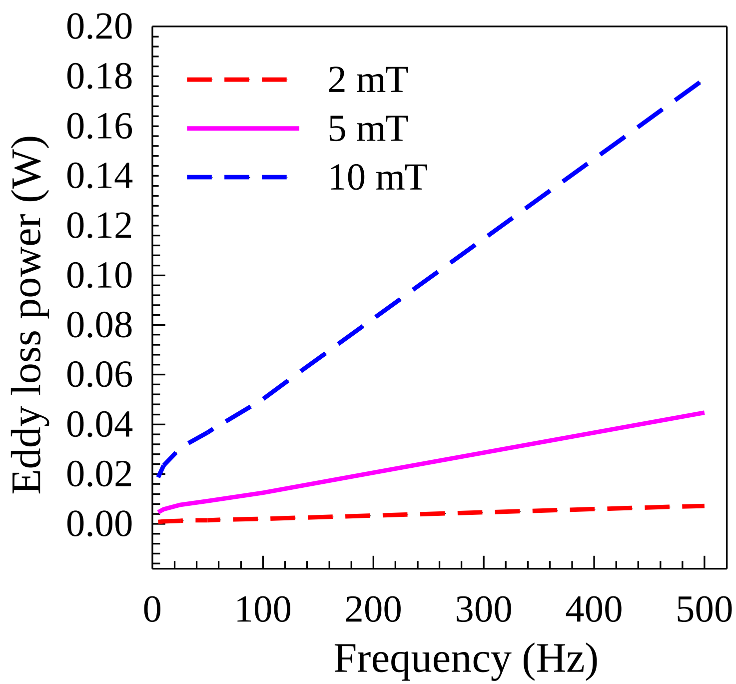


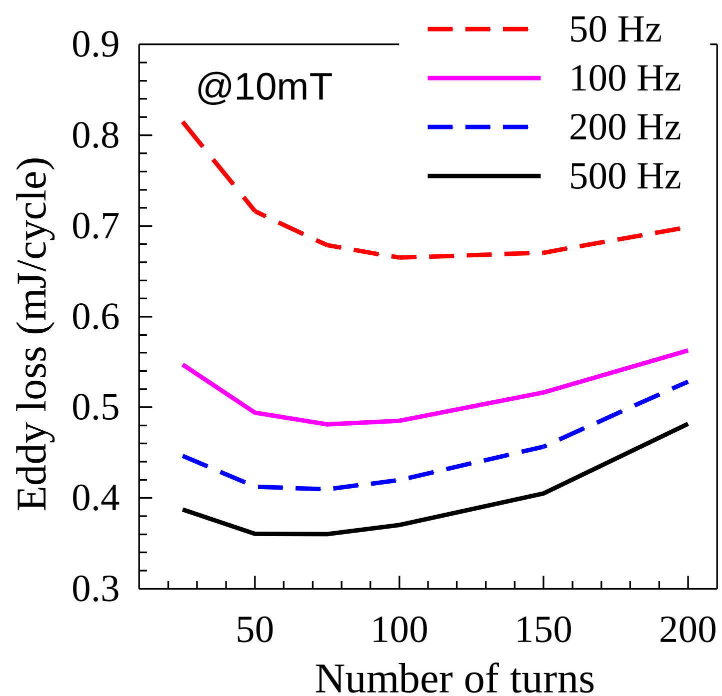
Results

➢ Eddy loss VS frequency and No. of turns

Eddy loss power increases linearly with frequency.

the number of turns has a slight influence on eddy loss.





Results

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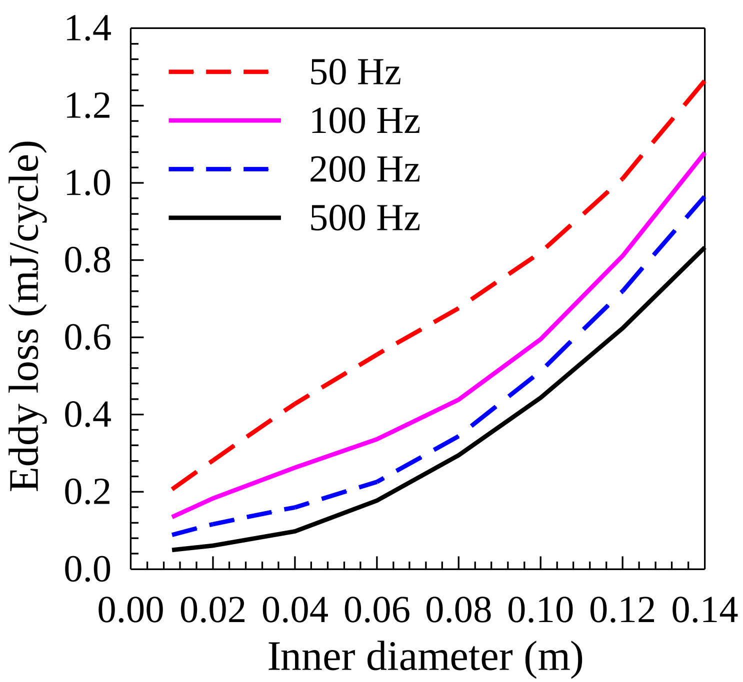
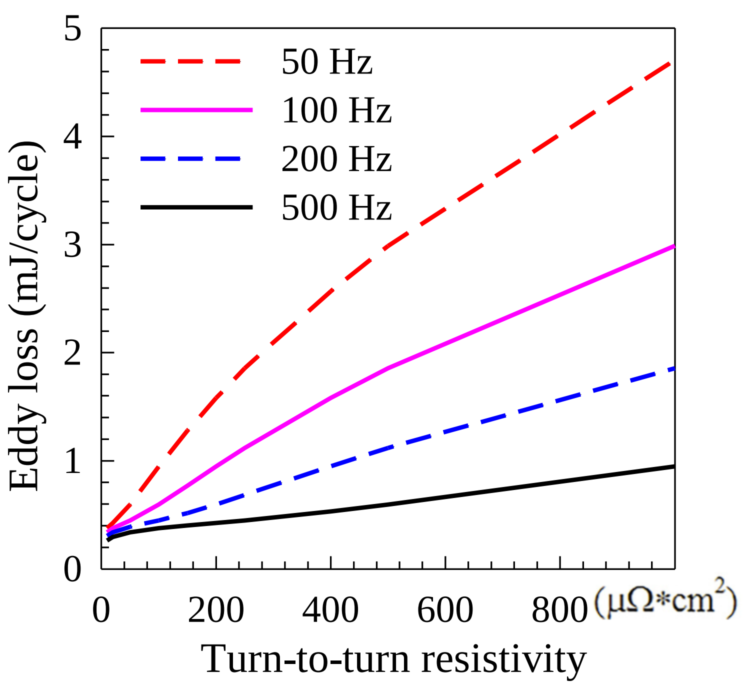
➢ Eddy loss VS inner diameter and turn-to-turn resistivity

Eddy loss increases approximatly linearly with inner diameter.

Eddy loss increase with turn-to-turn resistivity.

Eddy loss depends mainly on the amplitude and frequency of ripple fields, coli diameter, turn-to-turn resistivity.

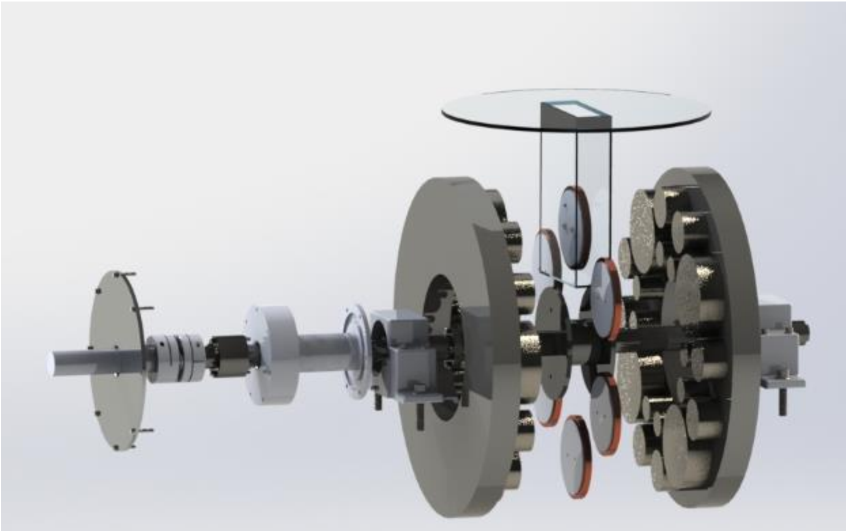


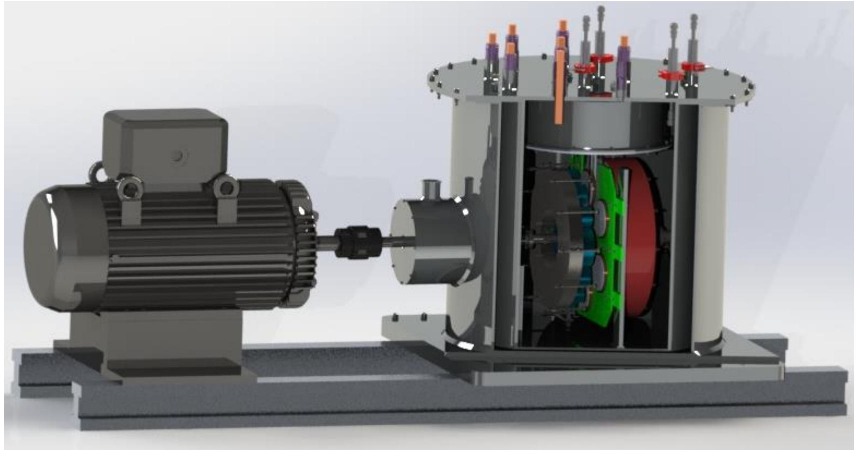


Measurements

Calorimetric Method：

- **AC magnetic fields are generated by rotating permanent magnets.**
- **The frequency depends on the rotation speed.**
- **The amplitude is adjusted by changing gap between NI coils and permanent magnets.**
- **Measurements and model validation will be performed in next month.**





Circuit network model applications:

- Extremely efficient in calculation for electromagnetic characteristics of no-insulation HTS coils and its industrial applications.
  - ✓ Current distribution and eddy loss inside NI HTS coils.
  - ✓ Electromagnetic interaction between stator and NI rotor winding of HTS machines.
  - ✓ Ramping and dynamic response of NI HTS magnets.
- Coupled with a thermal model to study thermal behaviour of NI HTS coils:
  - ✓ Temperature distribution of NI HTS rotor windings during operation.
  - ✓ Quench study of NI HTS coils in machine environments and other applications.
  - ✓ The two topics are being studied. And models development will be finished within two months.

Best approach for a detailed analysis on the dynamic electromagnetic and thermal behaviours of all the NI HTS applications.

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