Comparison of screening current simulation modellings of REBCO pancake coils

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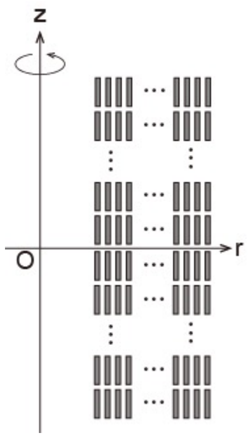
Background

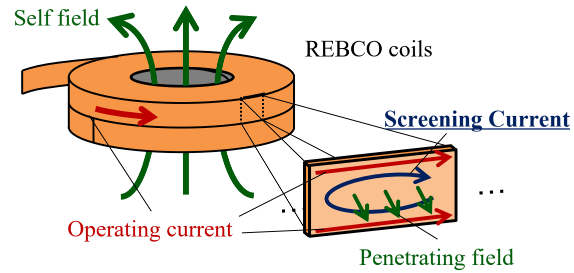
- The screening current is troublesome:
  - ✓ Undesired field is generated.
  - ✓ Overstress is generated.

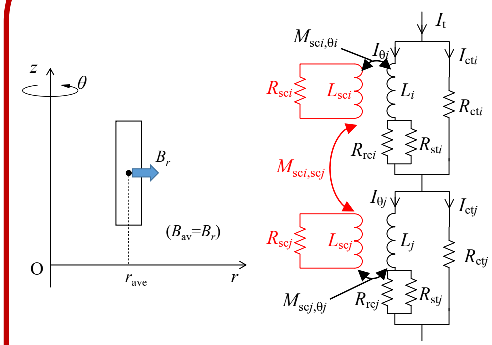
- A few screening current model have been proposed:
  - ✓ Axisymmetric FEM
  - ✓ FEM + thin film approximation
  - ✓ Simple equivalent circuit
  - ✓ Complicated network equivalent circuit (newly developed)

Overview

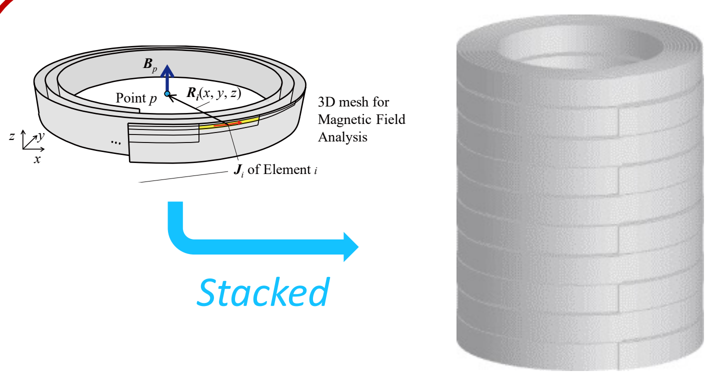


Axisymmetric FEM

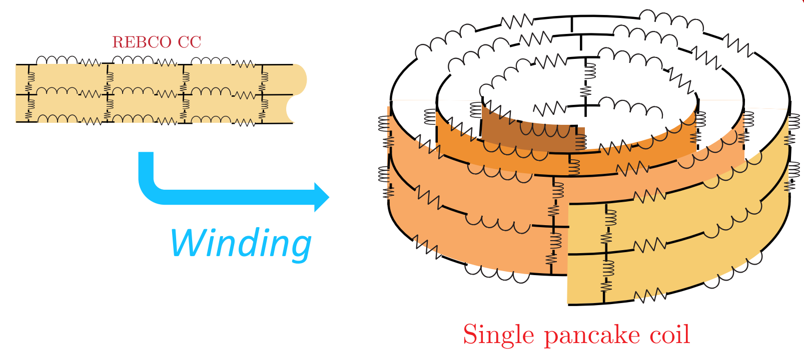




Simple equiv. circuit



FEM + Thin Film Approximation



Complicated network equiv. circuit

Overview

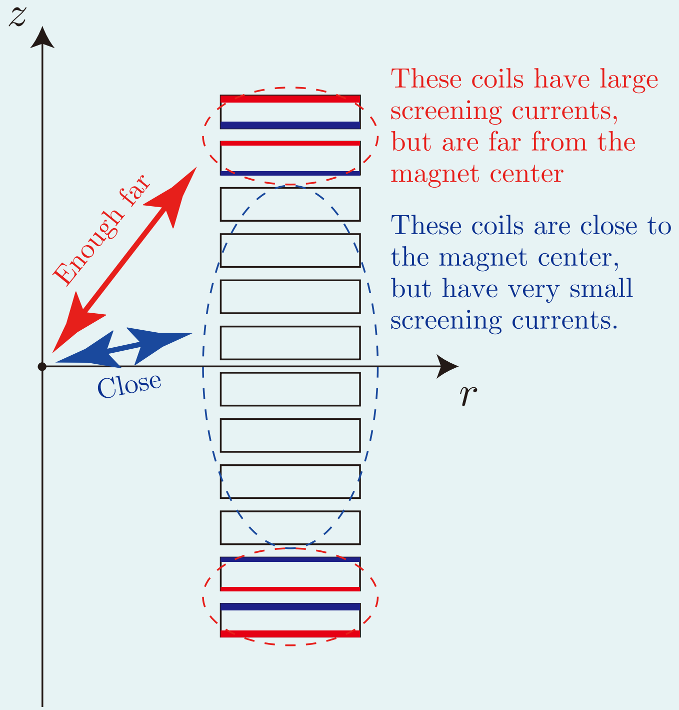
Screening current REBCO coil

#	Model	Advantages	Disadvantages
I	**Axisymmetric FEM** - FEM-based -	• Simple • Short computation time • Small memory usage	• Not considering winding structure • No axial current
II	**FEM + thin film approximation technique** - FEM-based -	• High accuracy • Considering winding structure and axial current	• Hard to implement • Long computation time • Large memory needed • Special technique (e.g. Fast multipole method) needed • Ignore time-varying axial field
III	**Simple equivalent circuit** - Circuit-based -	• Simplest • Easy to implement • Possible to couple with NI simple simulation	• Poor accuracy • Not considering winding structure • No axial current
IV	**Complicated network equiv. circuit** - Circuit-based -	• High accuracy • Considering time-varying axial field • Considering winding structure and axial current	• Hard to calculate inductances

Overview

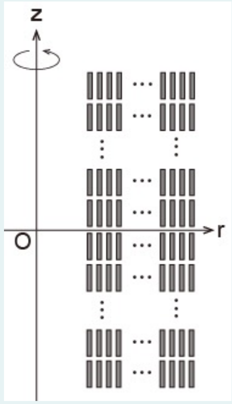
Important!

- **Why is the detailed screening current distribution needed?**
  - ✓ **Mostly, the magnet center is sufficiently far from coils having screening current. Hence, if the net amount of screening current was right, we can obtain the accurate screening-current-induced field at magnet center.**
    All the simulation methods can compute the magnetic field at magnet center with enough accuracy.



  - ✓ **In recent years, we have an attention to the coil stress. A large stress deteriorates the critical current or destroys the REBCO tape mechanically, sometimes plastic deformation occurs. Therefore, to know the detailed stress, the accurate current distribution is desired.**

I. Axisymmetric FEM

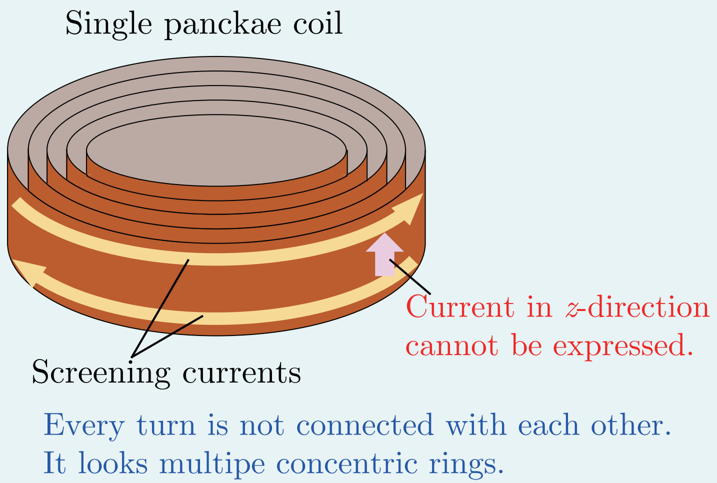
Modelling	Equations
	$$\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial A}{\partial z}\right)+\frac{\partial}{\partial r}\left\{\frac{1}{r\mu}\frac{\partial}{\partial r}(rA)\right\}-\left(\sigma\frac{\partial A}{\partial t}+J_{\mathrm{op}}\right)=0$$

Features

- **Easy to solve, but hard to generate a mesh**
- **Need a special technique to flow the operating current.**
- **Not exist the axial current**
- **Impossible to model the pancake-winding structure**

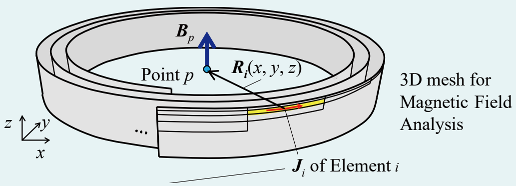
I. Axisymmetric FEM

- **Disadvantages**
  - ✓ **Screening current flows along the edges of REBCO tapes. Hence, it would be overestimated.**
  - ✓ **Current in the z-direction cannot exist. The current at the end of tape cannot be simulated correctly.**

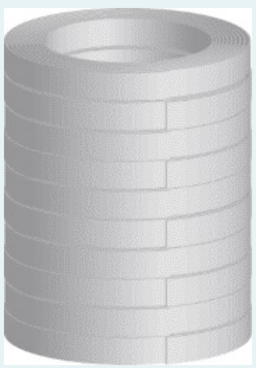


II. FEM + Thin film approximation

Modelling



Stacked



Equations

$$\nabla \times \rho(\nabla \times \boldsymbol{T}) + \frac{\mu_0}{4\pi} \int_v \frac{(\nabla \times \boldsymbol{T}') \times \boldsymbol{R}}{R^3} \mathrm{d}v = -\frac{\partial \boldsymbol{B}_0}{\partial t}$$

Thin film approximation

$$\{\nabla \times \rho(\nabla T \times \boldsymbol{n})\} \cdot \boldsymbol{n} + \frac{\mu_0 d}{4\pi} \frac{\partial}{\partial t} \int_s \frac{(\nabla T' \times \boldsymbol{n}') \times \boldsymbol{R}}{R^3} \mathrm{d}s' = -\frac{\partial \boldsymbol{B}_0}{\partial t} \cdot \boldsymbol{n}$$

Features

- **Hard to implement a code**
- **Long computation time and large memory usage**
  - ✓ **To improve them, a special technique (e.g., fast multipole method) is used.**
- **Considering the pancake-winding structure and the axial current**
- **Ignoring the electrical field induced by the time-varying axial magnetic field**

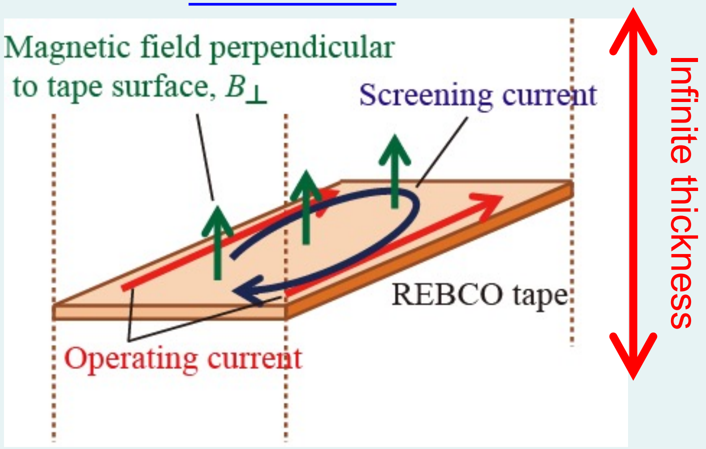
II. FEM + Thin film approximation

Issue

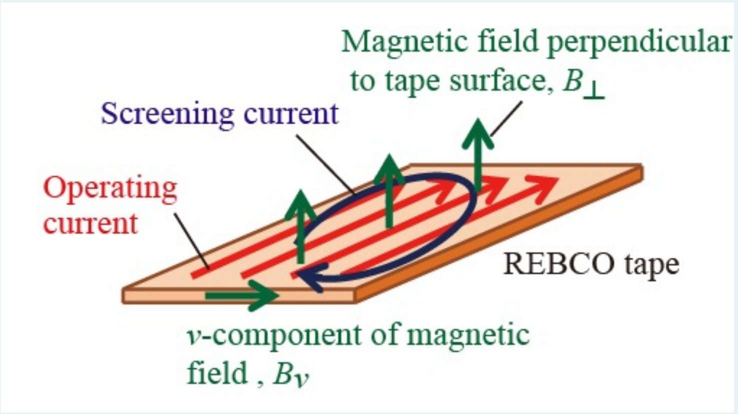
- **What happens, when the *z* component of inductance term is neglected?**

  Thin film approximation (TFA) assumes (1) very thin film, (2) uniform phenomenon in the thickness direction, and (3) no enforced current. Due to (3), the enforced current flows along the film edges, like the Bean model. According to the Norris's paper [2], that is wrong.

TFA model



Actual model



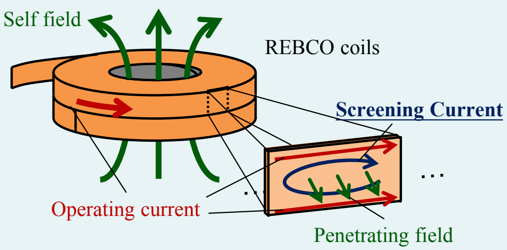
- ✓ Homogeneous into thin direction due to infinite length
- ✓ Operating current flows along the edge of REBCO tape

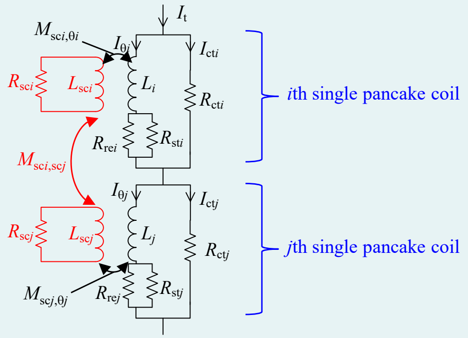
- ✓ Finite thickness
- ✓ Operating current flows uniformly in REBCO tape (*v* component of field must be considered)

[2] W. T. Norris, "Calculation oh hysteresis losses in hard superconductors carrying ac: isolated conductors and edges of thin sheets, *Journal of Physics D: Applied Physics*, 3, 489-507, 1969.

III. Simple equivalent circuit

Modelling





Equations

$$L\frac{\mathrm{d}I_\theta}{\mathrm{d}t} + M\frac{\mathrm{d}I_{sc}}{\mathrm{d}t} + \frac{R_{\mathrm{re}}R_{\mathrm{st}}}{R_{\mathrm{re}}+R_{\mathrm{st}}}I_\theta = R_{\mathrm{ct}}(I_{\mathrm{t}} - I_\theta)$$

$$I_\theta = I_{\mathrm{re}} + I_{\mathrm{st}}$$

$$R_{\mathrm{re}}I_{\mathrm{re}} = R_{\mathrm{st}}I_{\mathrm{st}}$$

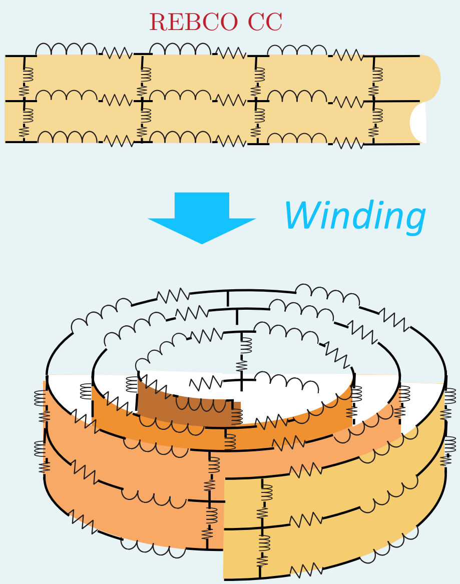
$$L\frac{\mathrm{d}I_{\mathrm{sc}}}{\mathrm{d}t} + M\frac{\mathrm{d}I_\theta}{\mathrm{d}t} = R_{\mathrm{sc}}I_{\mathrm{sc}}$$

Features

- **Easiest**
- **Simple RL parallel circuit method**
- **Short computation time and small memory usage**
- **Not considering the pancake-winding structure and the axial current**

IV. Complicated network equivalent circuit

Modelling



Single pancake coil

Equations

$$\sum_m L_{i,m}\frac{\mathrm{d}I_m}{\mathrm{d}t} + R_i I_i + \sum_n L_{j,n}\frac{\mathrm{d}I_n}{\mathrm{d}t} + R_j I_j + \sum_p L_{j,p}\frac{\mathrm{d}I_p}{\mathrm{d}t}$$

$$= \sum_n L_{k,n}\frac{\mathrm{d}I_n}{\mathrm{d}t} + R_k I_k + \sum_m L_{j+1,m}\frac{\mathrm{d}I_m}{\mathrm{d}t} + R_{j+1} I_{j+1} + \sum_p L_{j+1,p}\frac{\mathrm{d}I_p}{\mathrm{d}t}$$

$$\cdots,\ h,\ \cdots,\ j-1,\ j,\ j+1,\ \cdots \in m$$

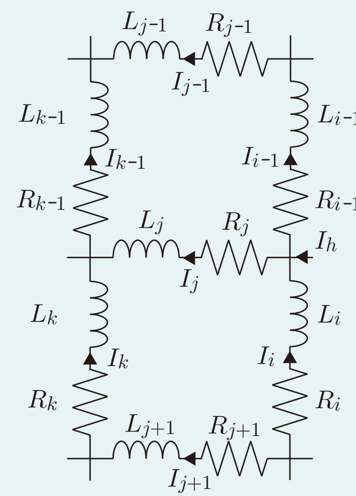
$$\cdots,\ i-1,\ i,\ \cdots,\ k-1,\ k,\ \cdots \in n$$

$$\text{other pancake coils} \in p$$

$$I_h - I_{i-1} + I_i - I_j = 0$$

$$R_j = \frac{l_j}{S_j}\frac{E_c}{J_c}\left(\frac{J_t}{J_c}\right)^{n-1}$$

$$J_t = \left\{\left(\frac{I_j}{S_j}\right)^2 + \frac{1}{16}\left(\frac{I_{i-1}}{S_{i-1}} + \frac{I_i}{S_i} + \frac{I_{k-1}}{S_{k-1}} + \frac{I_k}{S_k}\right)^2\right\}^{1/2}$$

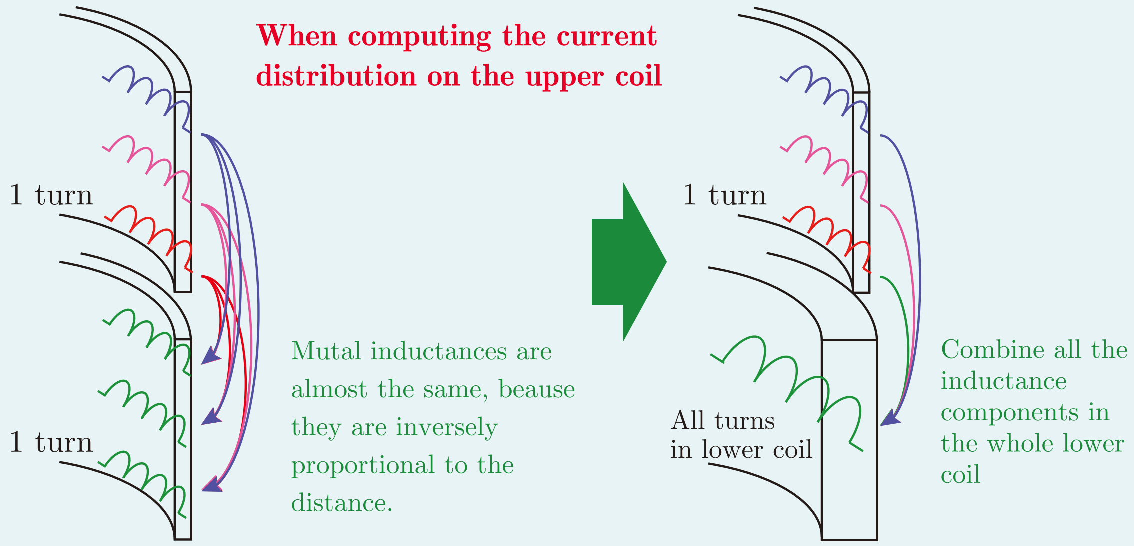


Features

- ➢ **Long computation time, and large memory usage**
  - ✓ **They are better than the FEM + thin film approximation.**
- ➢ **Considering the pancake-winding structure and the axial current**
- ➢ **Considering the electrical field induced by the time-varying axial magnetic field**
- ➢ **Extendable to NI simulation**

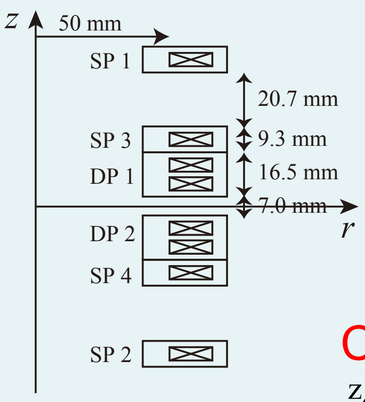
IV. Complicated network equivalent circuit

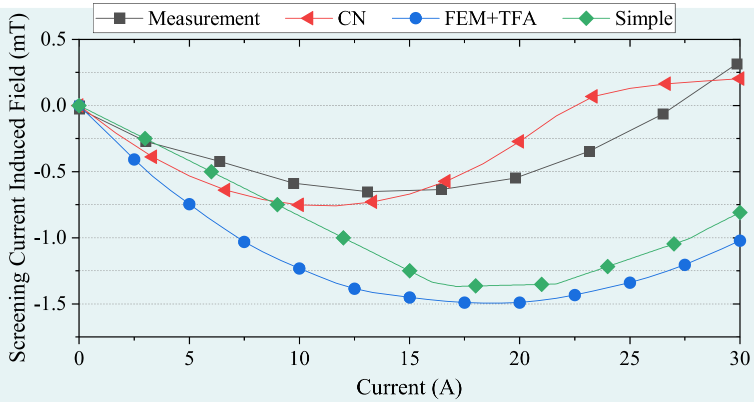
- **Acceleration and downsizing**
  - ✓ **The inductance is a function of 1/R. The mutual inductance slightly changes with distance. The mutual inductance at arbitrary points of a pancake coil from arbitrary points of the other pancake coils does not largely change. Eventually, it is possible to use the mutual inductance at arbitrary points of a pancake coil from a whole pancake coil in the complicated network circuit model. i.e., the screening current can be computed for each individual pancake coil.**



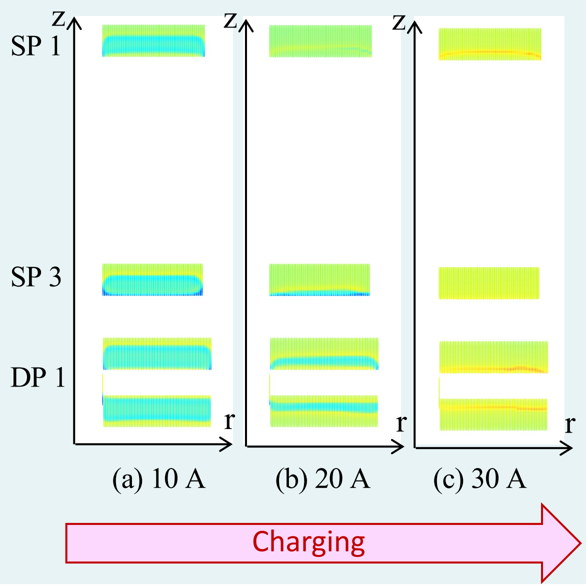
V. Simulation Result

➢ Simulation example #1

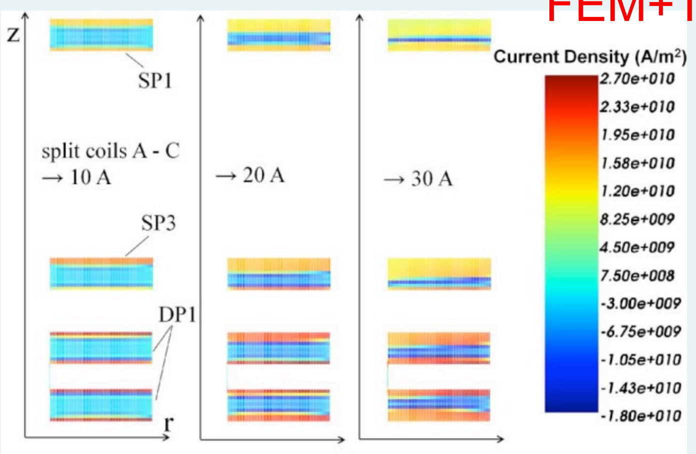




Complicated Network (CN)



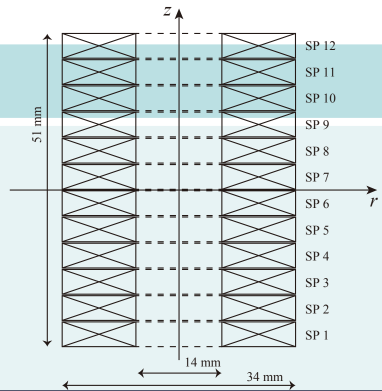
FEM+TFA

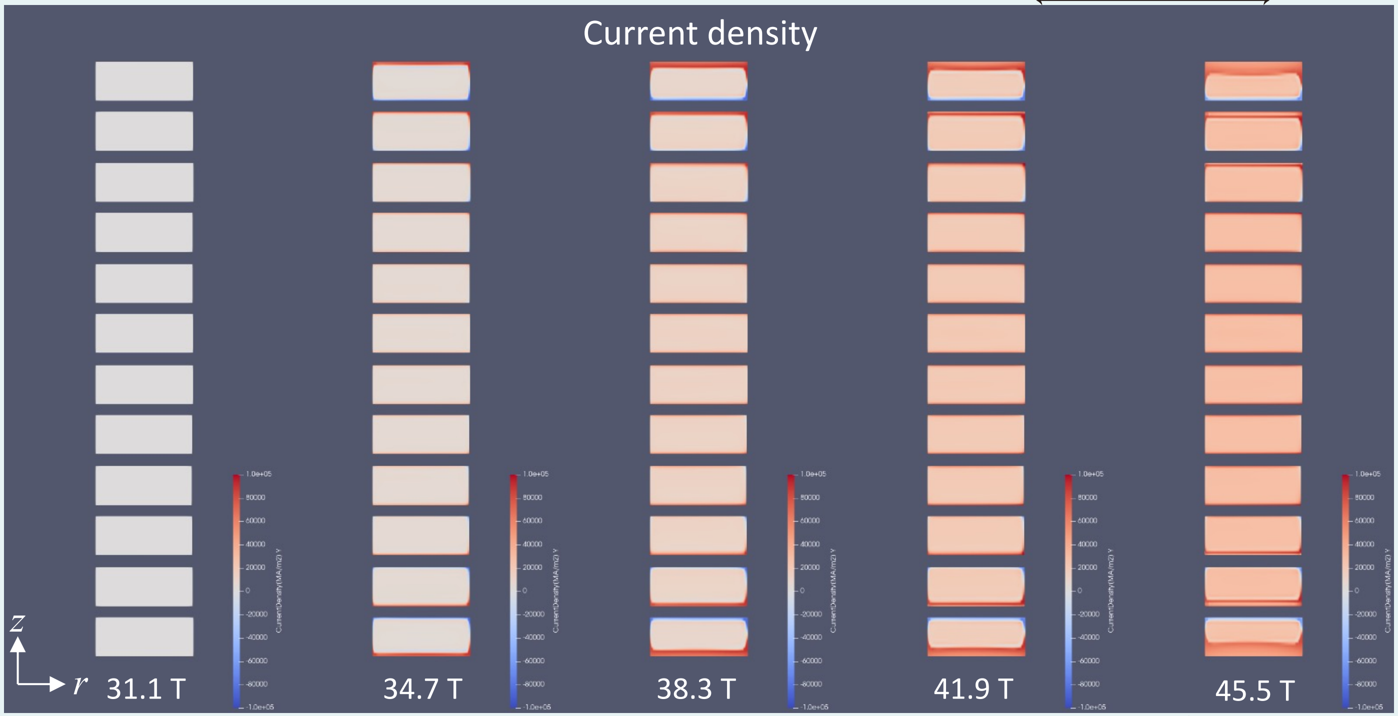


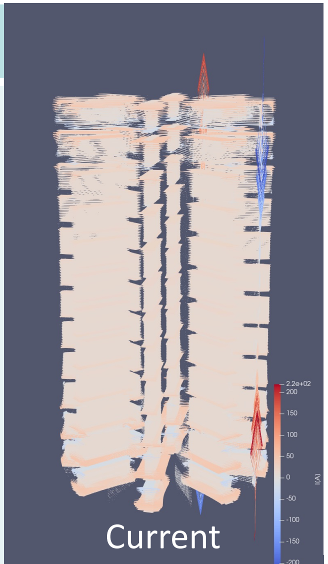
Evaluation of magnetic-field distribution by screening current in multiple REBCO coils, by H. Ueda, et al, in IEEE Trans. Appl. Supercond., 25(3) 2015, 4700705

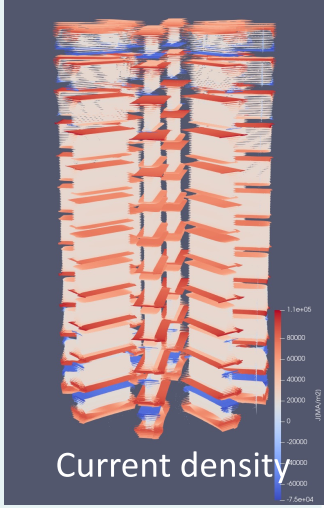
V. Simulation Results

- **Simulation example #2**
  - ✓ LBC3 (45.5-T magnet)
    - 2,717 turns in total
    - 14.4 T generation inside 31.1 T









Charging

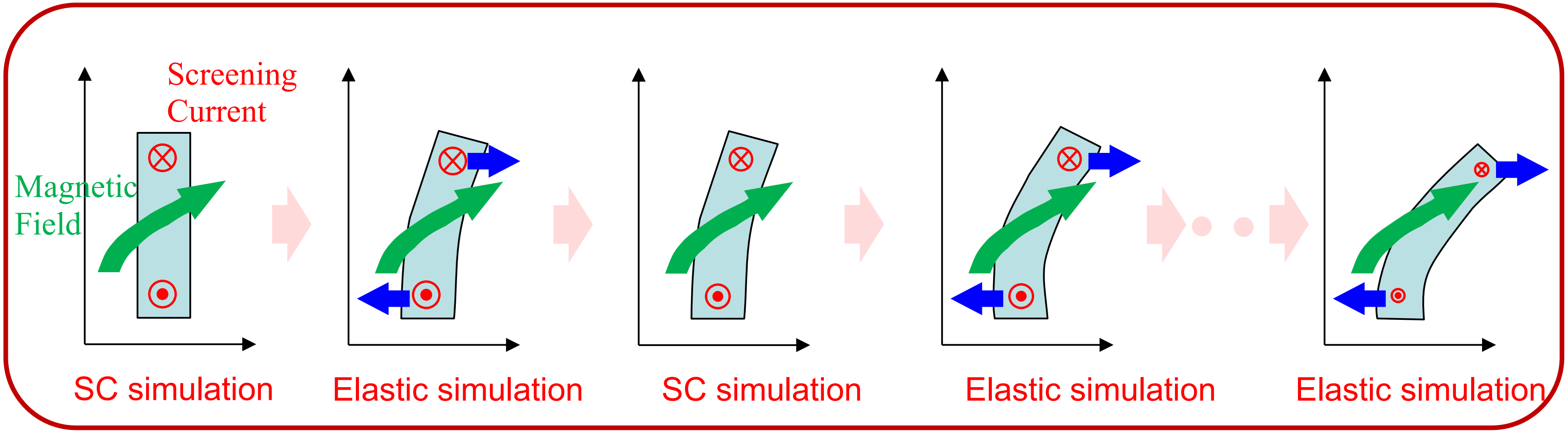
Summary

Screening current REBCO coil

	FEM based		Circuit based	
	Axisymmetric FEM	FEM + Thin film approx.	Simple equiv. circ.	CN equiv. circuit
Accuracy	△	○	△	◎
Implementation	△	×	◎	×
Computation time	○	×	◎	○
Memory usage	△	×	◎	○
Preparation	△	×	◎	△
Special technique	Needed	Needed	Not needed	Not needed
Axial current	×	○	×	○
Winding structure	×	○	×	○
Time-varying axial field	○	×	×	○
Special coil shape	×	○	△	△
Possible to simulate NI coil	×	×	◎	◎

Stress Simulation Considering Screening Current

Alternatively simulated



Comparing with a simulation without consideration of coil deformation:

✓ By changing the angle of magnetic field to REBCO tape, an accurate screening current can be simulated.

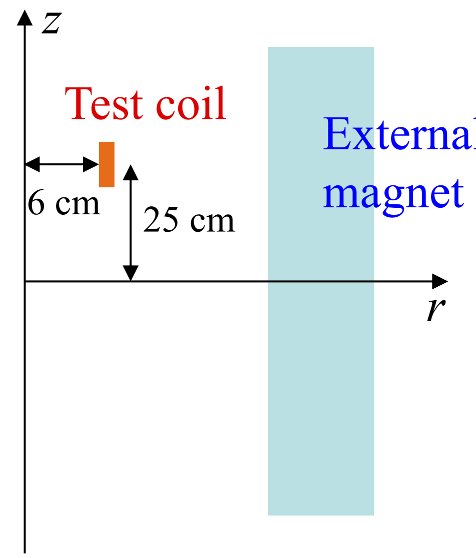
✓ By changing the angle of magnetic field to c-axis, Jc also changes,

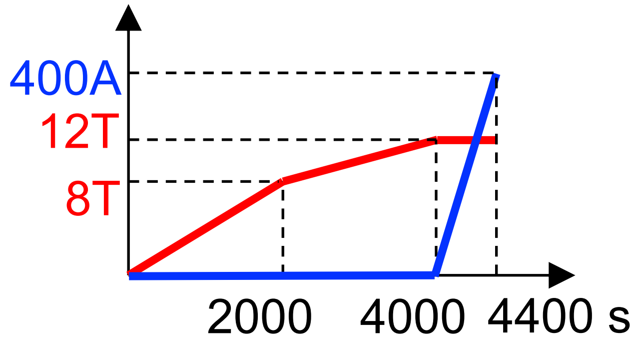
Stress Simulation Considering Screening Current

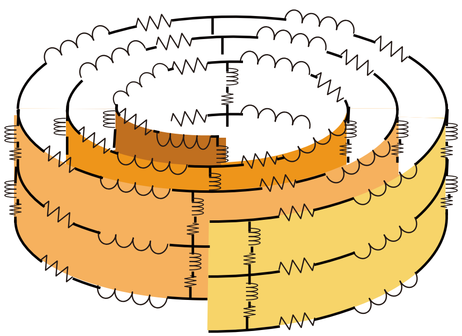
5-turn test coil

A small test coil was charged inside an external magnet.

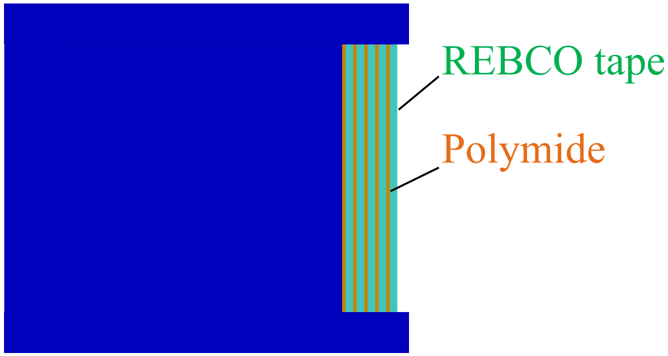
- Test coil was placed 25 cm away from the midplane.
- Operation profile is shown bellow.
- Screening current and elastic simulation were done.







Screening current simulation

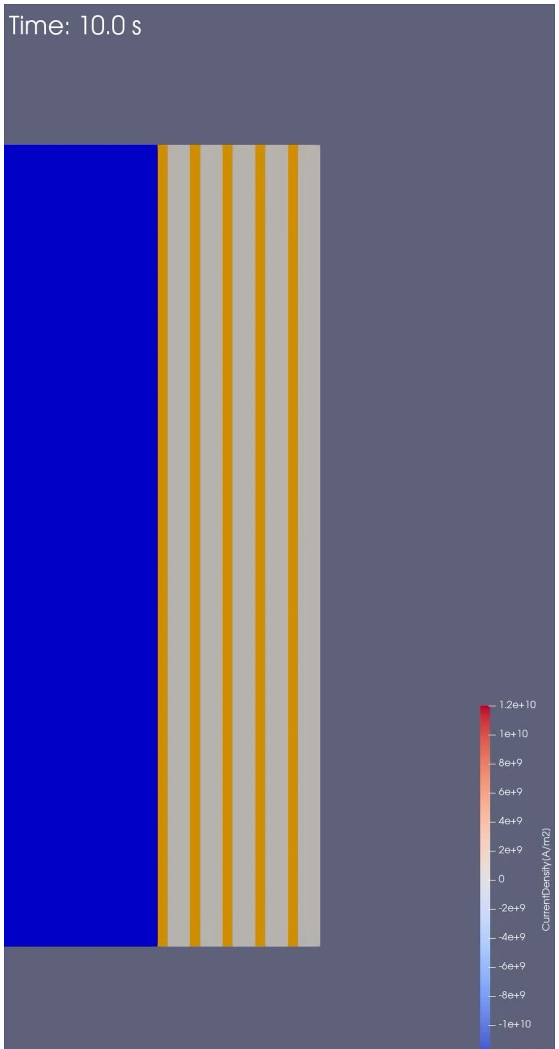


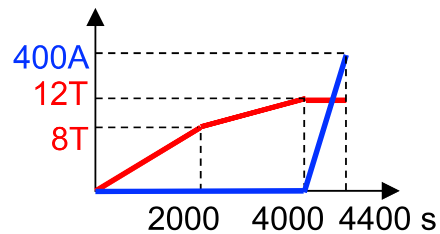
Stress simulation

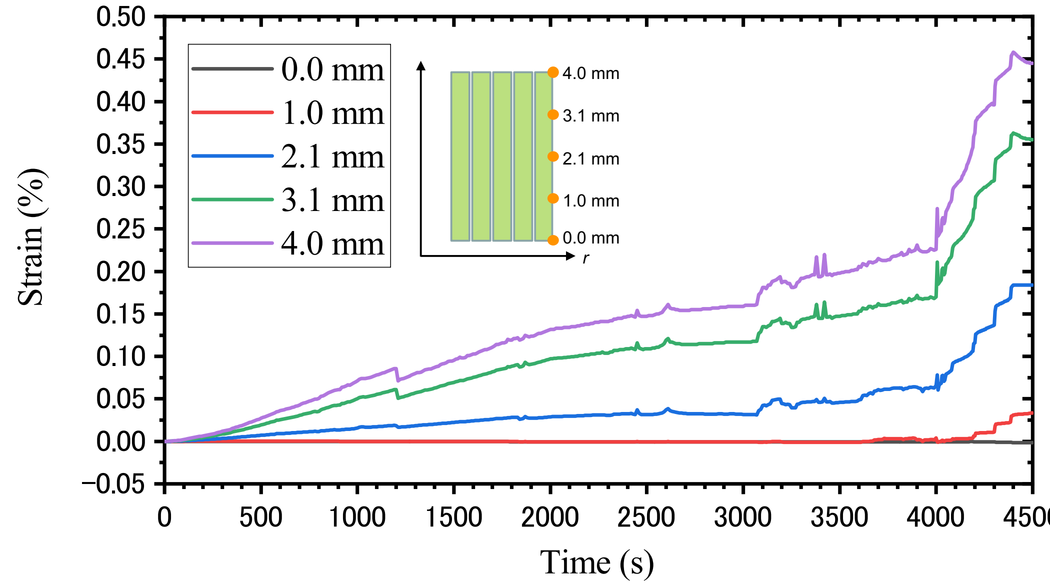
Stress Simulation Considering Screening Current

Current distribution with Field Vectors

With considering deformation







Conclusion

- A few screening current models have been proposed, each model have different features.
  - ✓ Axisymmetric FEM
  - ✓ FEM + thin film approximation
  - ✓ Simple equivalent circuit
  - ✓ Complicated network equivalent circuit (newly developed)
- Coil deformation must be considered to accurately simulate screening current.
- Benchmarks are needed as soon as possible.

Thank you for listening!