Modelling AC losses in a high-temperature bulk superconducting axial-flux synchronous machine

22nd June 2021

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- Results.
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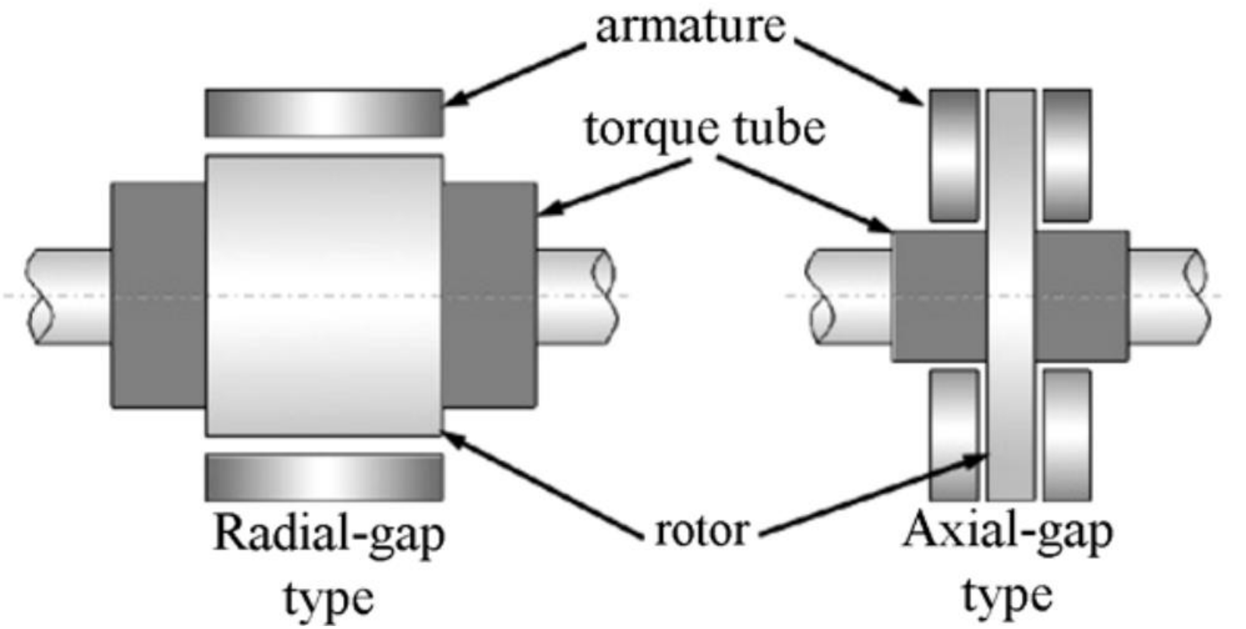
Brief introduction – What's an axial-flux machine?

Radial machine

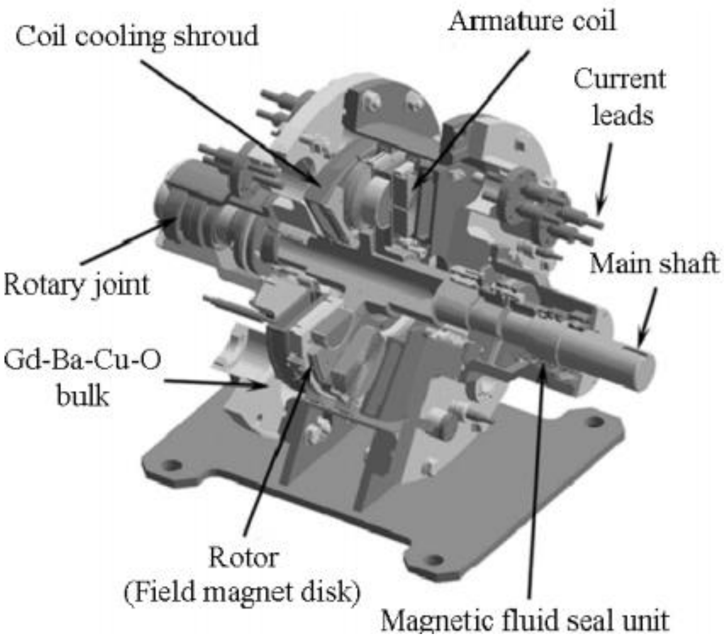
Axial machine



Brief introduction – What's an axial-flux machine?

Advantages

- Potentially higher power density.
- Higher torque
- Suitable for PFM in bulk superconducting trapped field magnets
- HTS have trapped fields as high as 17 T, incorporation is attractive



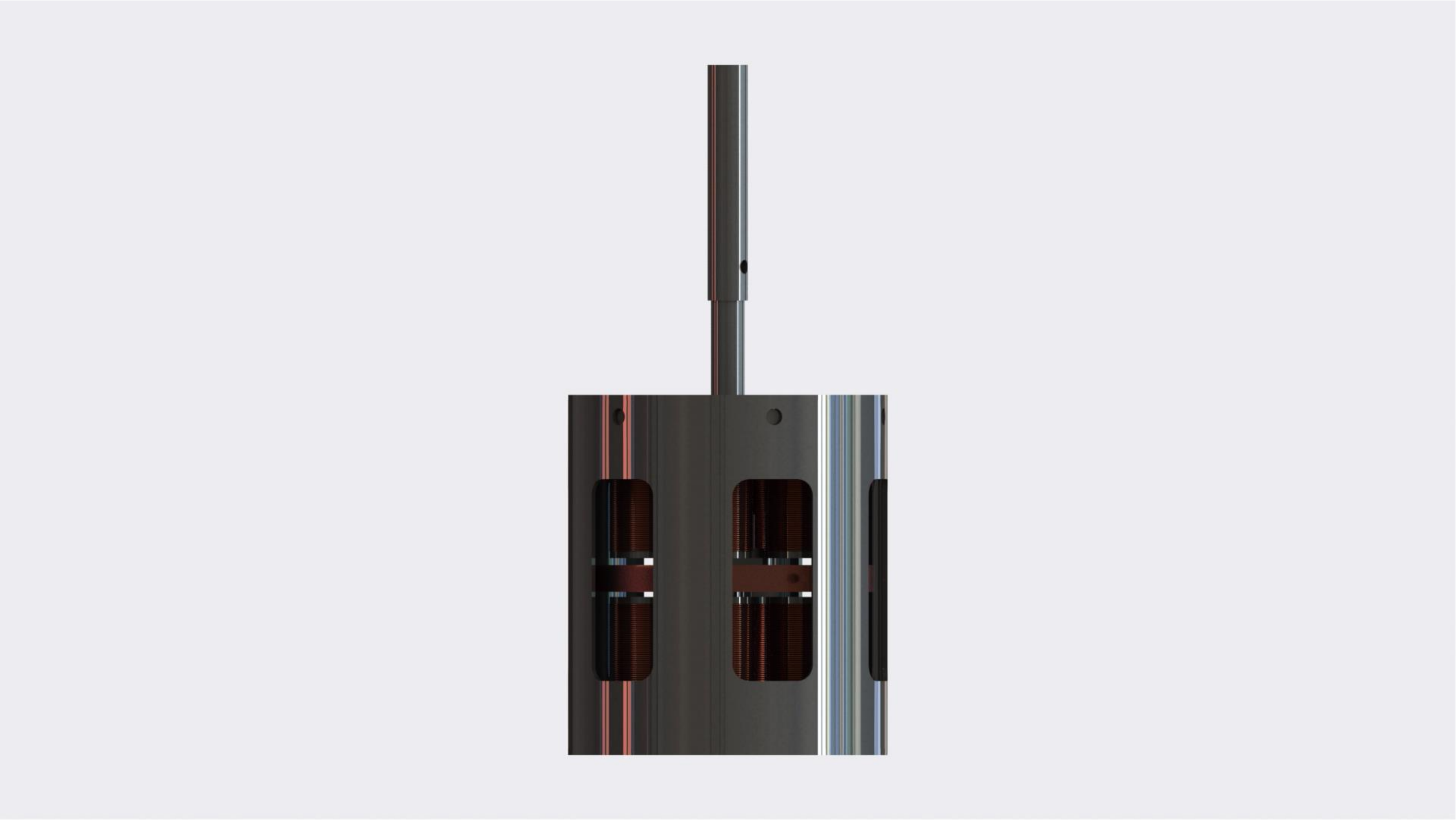
Axial machine

J. H. Durrell, M. D. Ainslie, D. Zhou, P. Vanderbemden, T. Bradshaw, S. Speller, M. Filipenko, D. A. Cardwell, "Bulk superconductors: a roadmap to applications," Supercond. Sci. Technol., Vol. 31, No. 10, Art. no. 103501, 2018.

Motivation

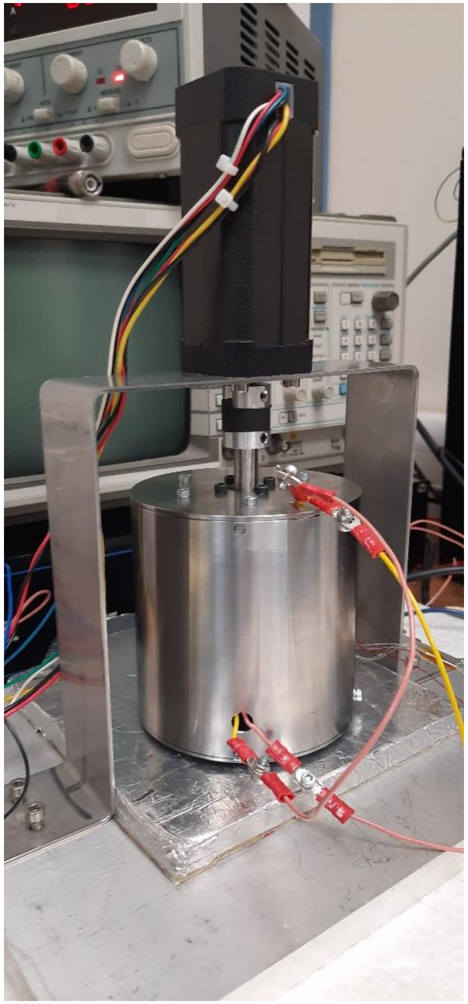
- AC losses are a source of concern for incorporation of trapped field superconductor magnets in machines.
- Most losses come from displaced currents, at low frequencies when proper cooling is applied.
- Simple experiments may overrepresent the problem.
- The modelling can give a quick idea of parameters to optimize.

Operation animation



Experimental setup – Parameters – 2nd version

HTS bulks	Side length, a	20 mm
	Thickness, t_b	8 mm
	Corner fillet radius, r_f	2 mm
	Critical current density, J_c [Self-field, 77 K]	2.29×10^8 A/m^2
Rotor	Rotor radius, d_r	42.85 mm
	Rotor thickness, t_r	8 mm
Stator	Coil internal radius, d_i	4 mm
	Coil external radius, d_e	14 mm
	Coil height, h	33 mm
	Copper coil wire diameter, d_c	1 mm
	Number of turns,n_i	290
Motor enclosure	Can diameter	95 mm
	Can wall thickness	2 mm
Shaft	Shaft diameter	10 mm
	Shaft height	130 mm



Experimental setup - Bulk superconductors

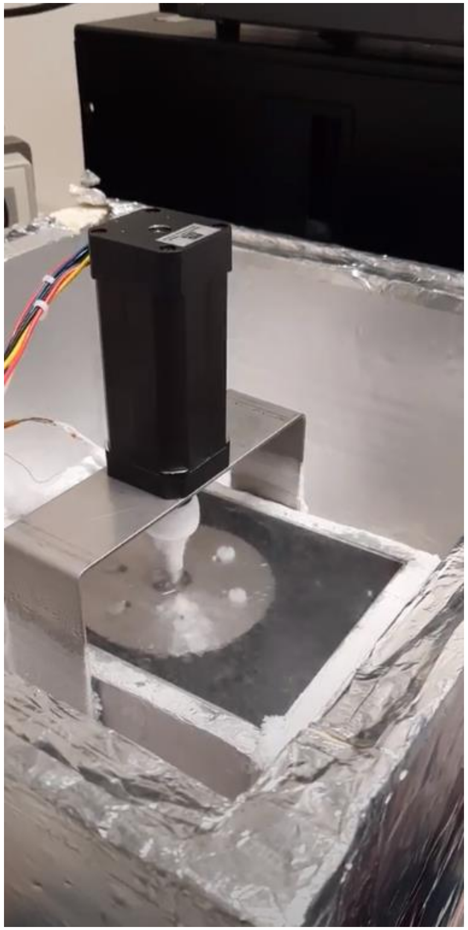
- Superconductors were made using top seeded melt growth method by Dr. Yunhua Shi
- The high-temperature superconducting material is bulk GdBCO

D. Zhou, S. Hara, B. Li, K. Xu, J. Noudem, M. Izumi, “Significant improvement of trapped flux in bulk Gd–Ba–Cu–O grains fabricated by a modified top-seeded melt growth process,” Supercond. Sci. Technol., Vol. 26, No. 1, Art. no. 015003, 2013.

Y. Shi, D. K. Namburi, W. Zhao, J. H. Durrell, A. R. Dennis, D. A. Cardwell, “The use of buffer pellets to pseudo hot seed (RE)–Ba–Cu–O–(Ag) single grain bulk superconductors,” Supercond. Sci. Technol., Vol. 29, No. 1, Art. no. 015010, 2016.

Experimental setup – Cryogenics and magnetisation

- The operating temperature is at 77 K using a liquid nitrogen bath.
- Magnetization is accomplish using field cooling in a 1.5 T electromagnet



J. Srpčič, F. Perez, K. Y. Huang, Y. Shi, M. D. Ainslie, A. R. Dennis, M. Filipenko, M. Boll, D. A. Cardwell, J. H. Durrell, "Penetration depth of shielding currents due to crossed magnetic fields in bulk (RE)-Ba-Cu-O superconductors," Supercond. Sci. Technol., Vol. 32, No. 3, Art. no. 035010, 2019.

Model setup – Geometry

Main geometrical parameters

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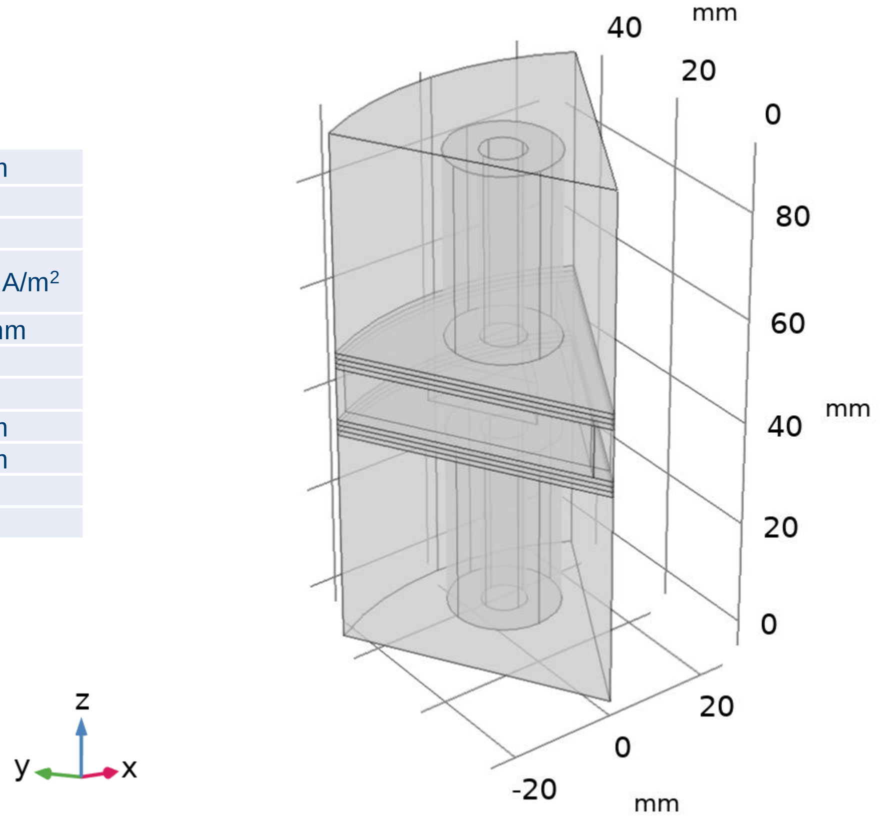
	Coil height, h	33 mm
	Copper coil wire diameter, d_c	1 mm
	Number of turns,n_i	390



Model setup – Geometry - Materials

Main geometrical parameters

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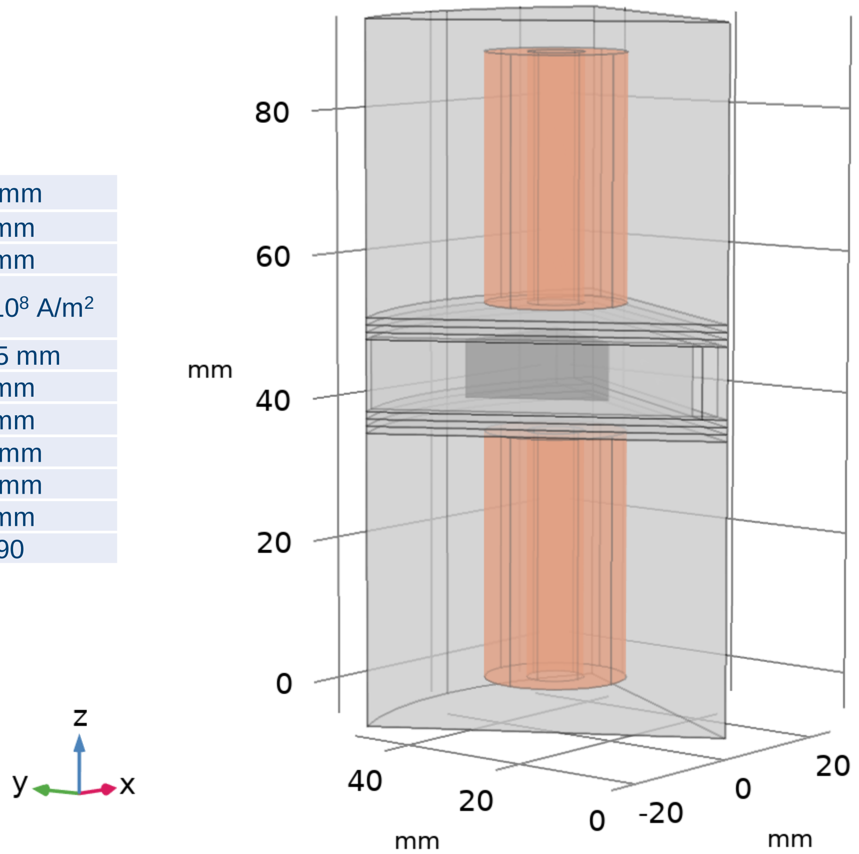
Coil	Copper
Superconductor	GdBCO



Model setup – Geometry

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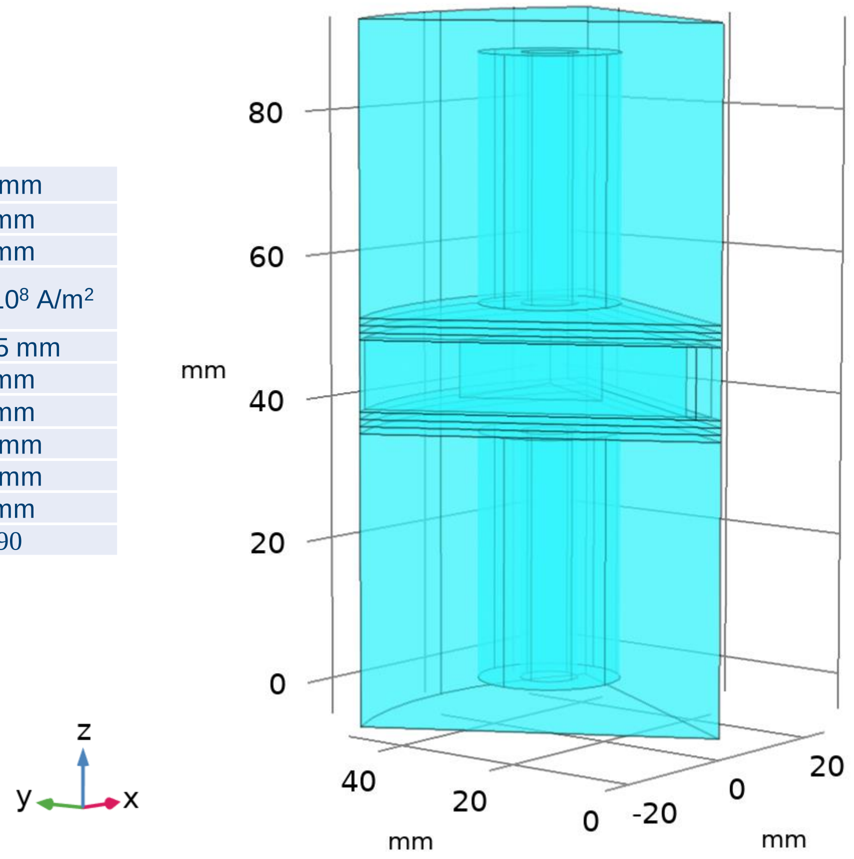
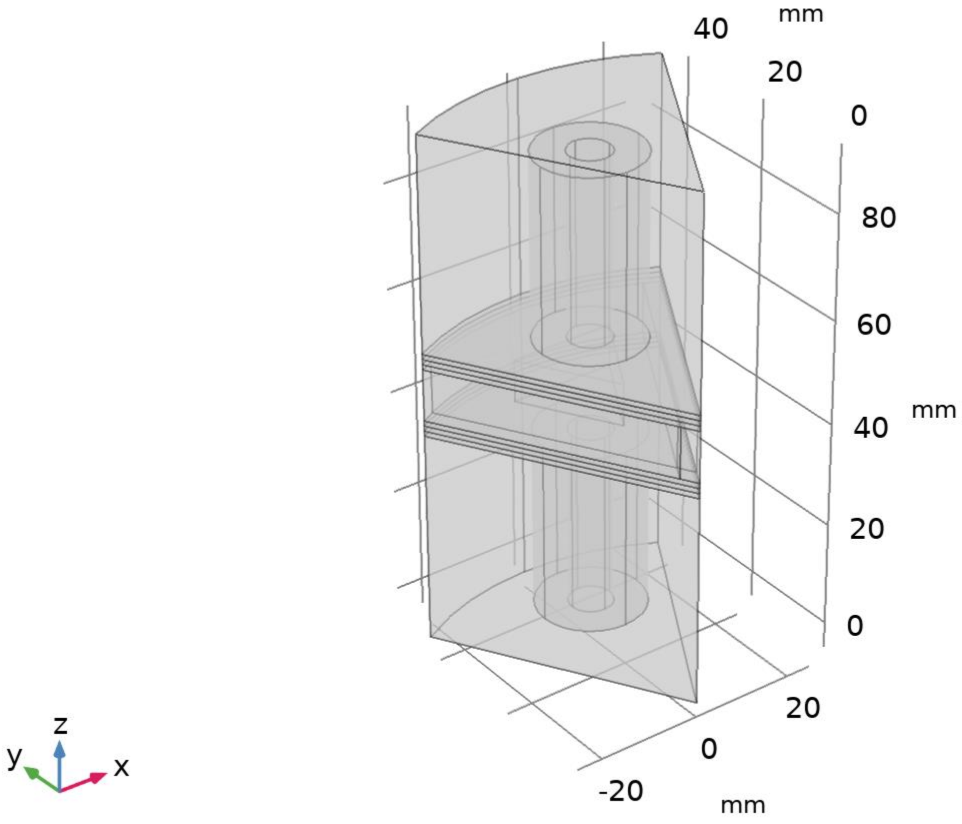
Coil	Copper
Superconductor	GdBCO
Air	



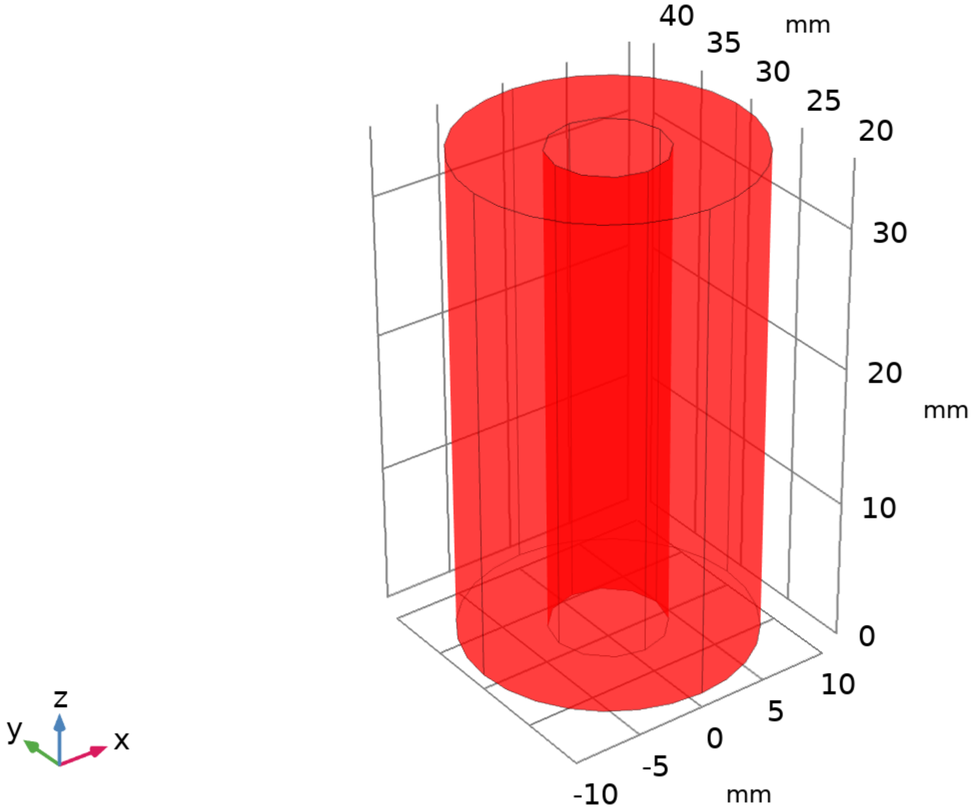
Model setup – Physics

- Maxwell's Equations
- Using three formulations with COMSOL default physics



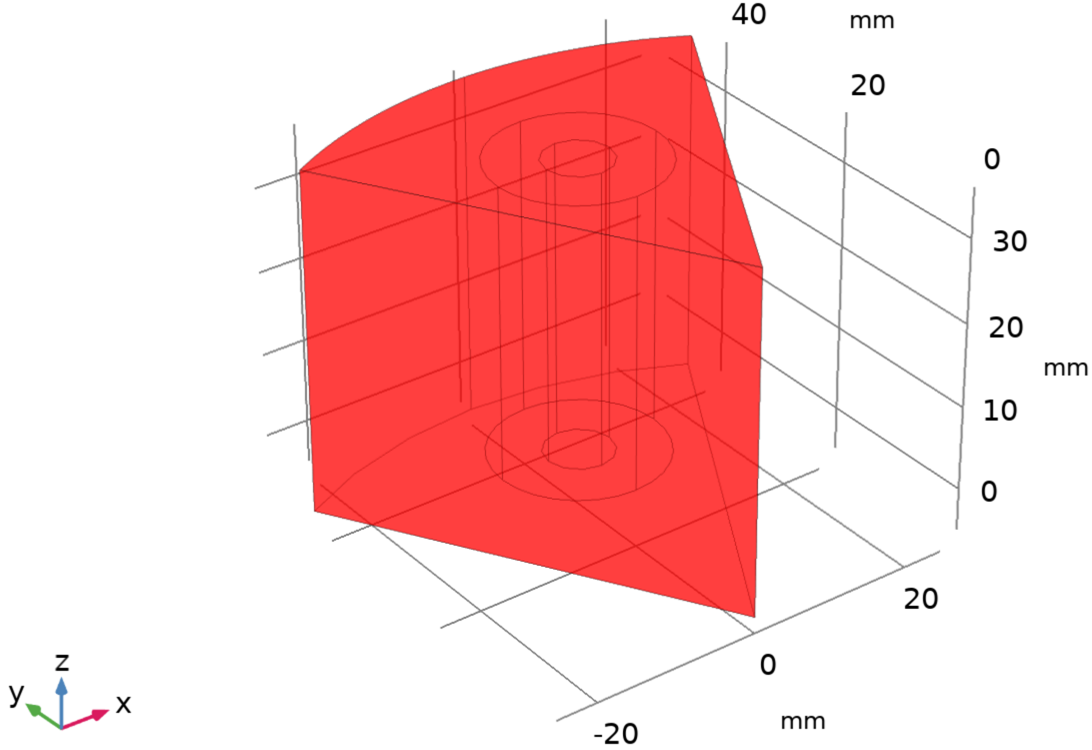
Model setup – Physics

- Maxwell's Equations
- Using three formulations with COMSOL default physics.
- A-formulation for current conducting regions (RMM)



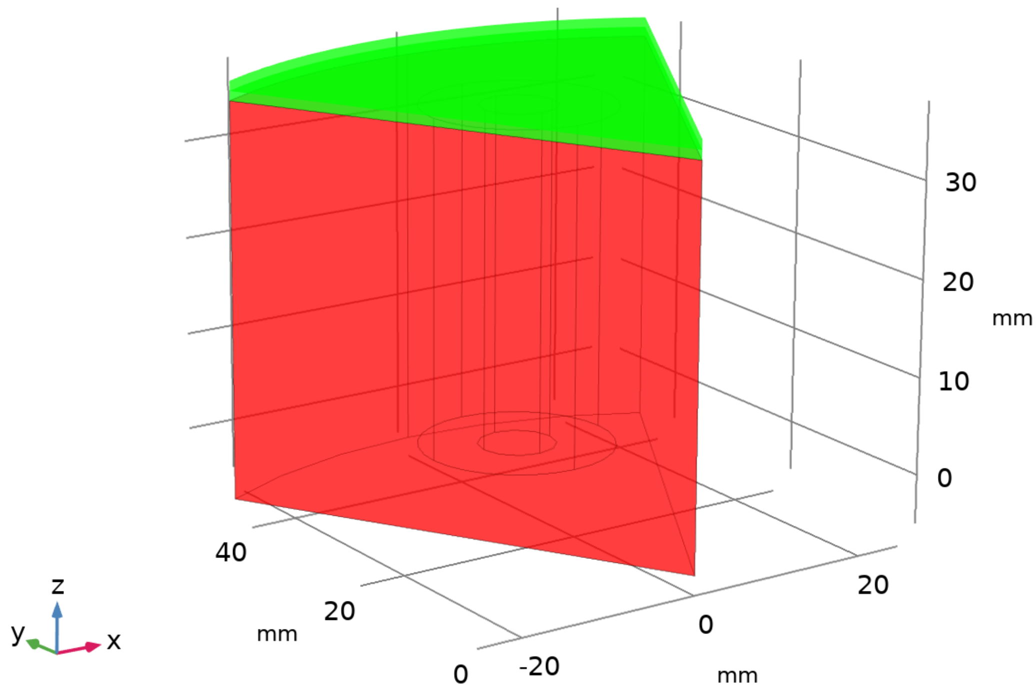
Model setup – Physics

- Maxwell's Equations
- Using three formulations with COMSOL default physics.
- A-formulation for current conducting regions and regions enclosing them. (RMM)



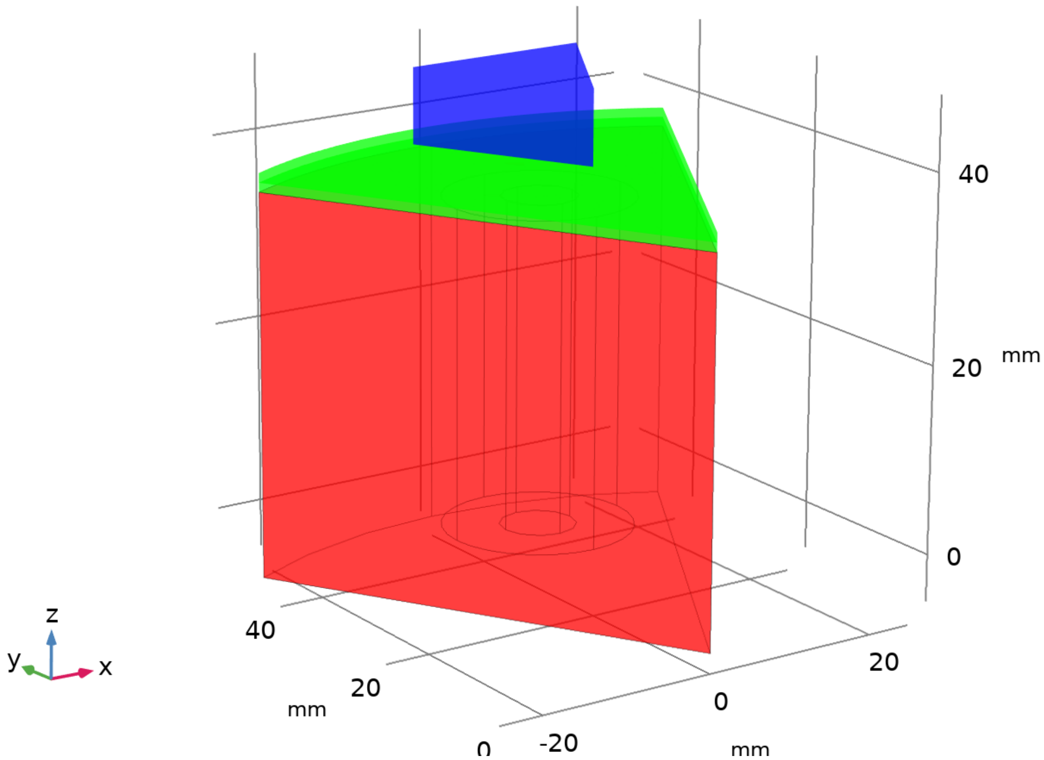
Model setup – Physics

- Maxwell's Equations
- Using three formulations with COMSOL default physics.
- A-formulation for current conducting regions and regions enclosing them. (RMM)
- Scalar Magnetic Potential for the remaining regions. (RMM)



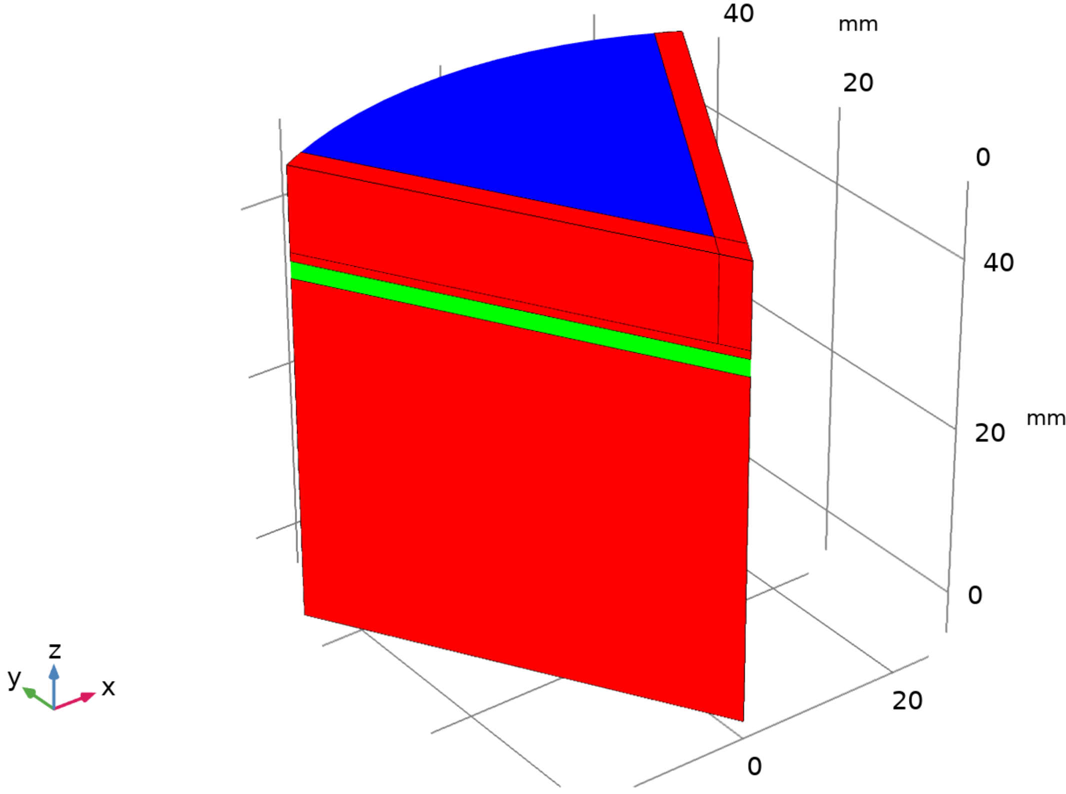
Model setup – Physics

- Maxwell's Equations
- Using three formulations with COMSOL default physics.
- A-formulation for current conducting regions and regions enclosing them. (RMM)
- Scalar Magnetic Potential for the remaining regions. (RMM)
- H-formulation for the superconductor (MFH)



Model setup – Physics

- Maxwell's Equations
- Using three formulations with COMSOL default physics.
- A-formulation for current conducting regions and regions enclosing them. (RMM)
- Scalar Magnetic Potential for the remaining regions. (RMM)
- H-formulation for the superconductor and the region enclosing it. (MFH)



Model setup – Physics

- Maxwell's Equations
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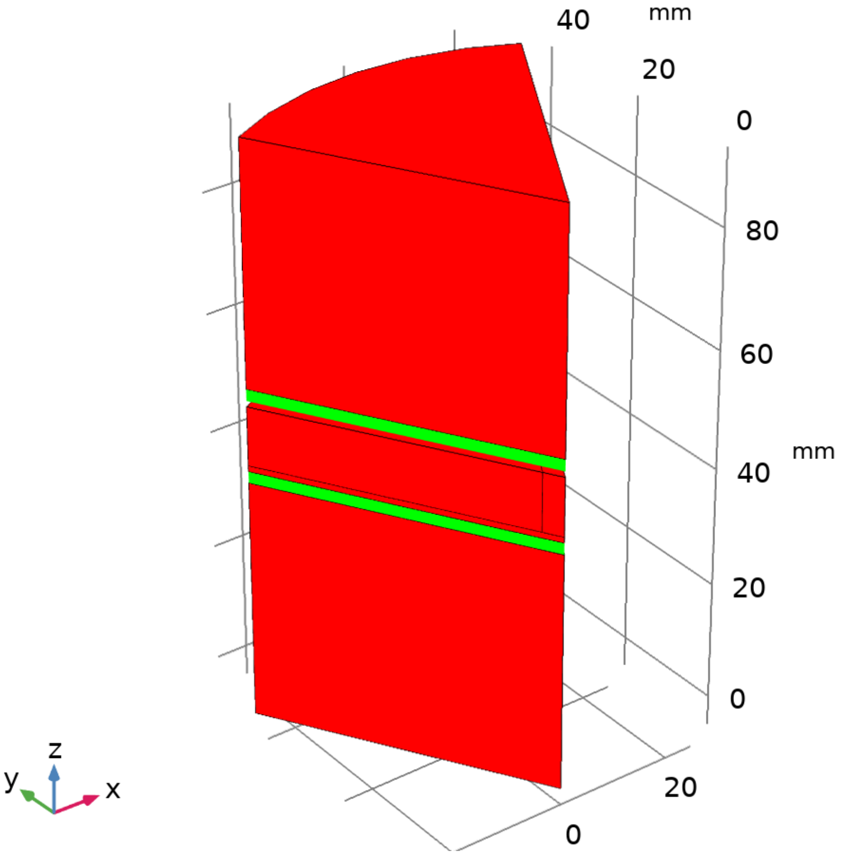


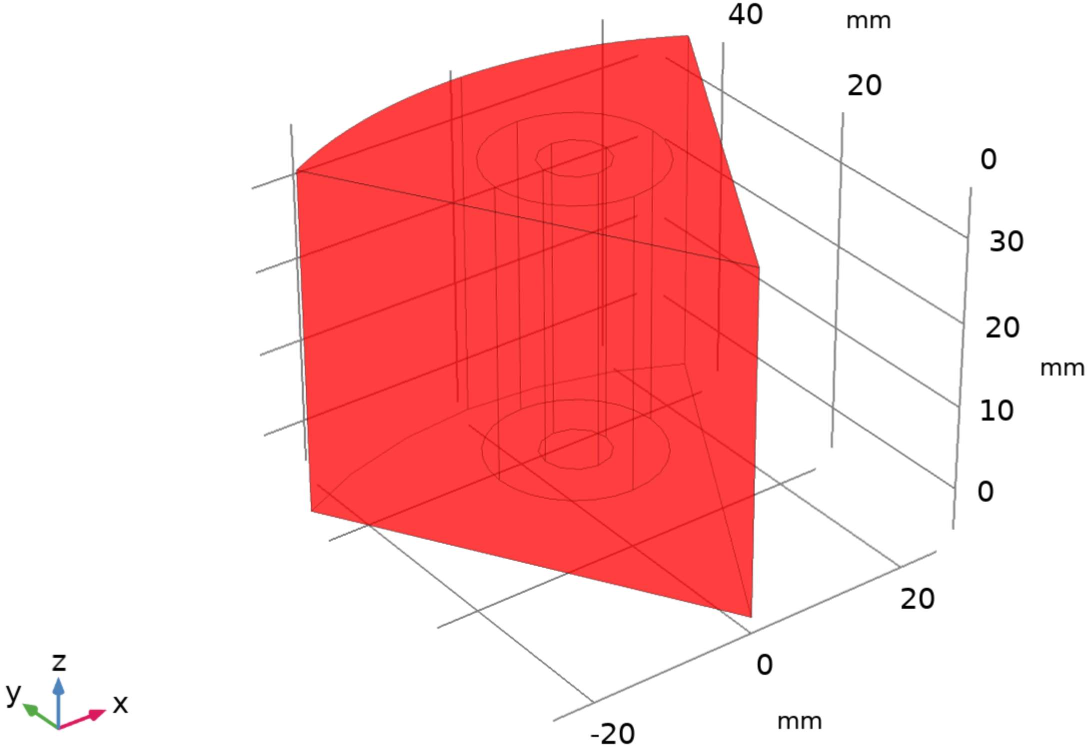
Model setup – Physics

- A-formulation solves Ampere's law

$$\nabla \times H = J$$

$$B = \nabla \times A$$

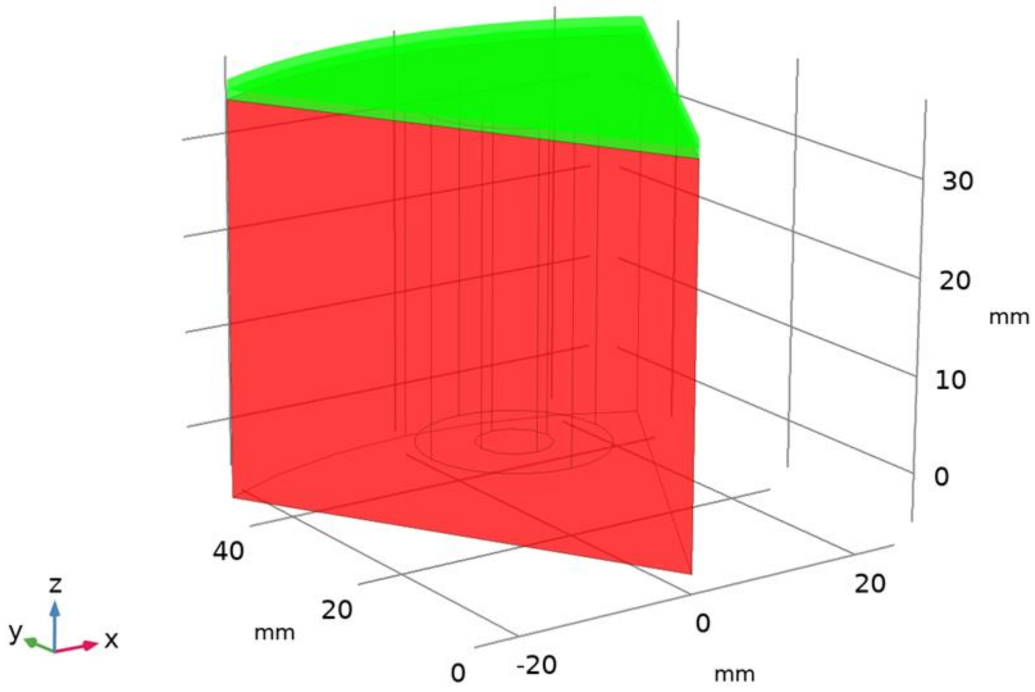
$$E = -\frac{\partial A}{\partial t}$$



Model setup – Physics

- Scalar Magnetic Potential solves Gauss's law for magnetism

$$\nabla \times B = 0$$



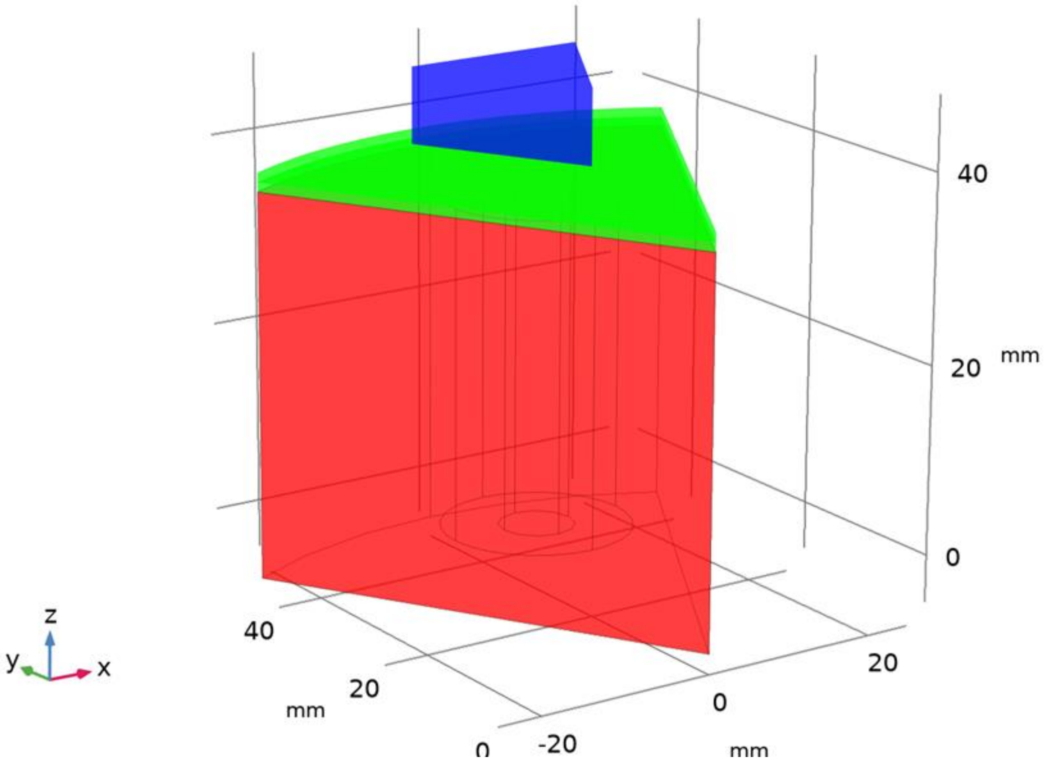
Model setup – Physics

- H-formulation solves Faraday's law

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$E = \sigma^{-1}(\nabla \times H - J_e)$$

$$J_c = \sigma E$$



Model setup – Physics

- H-formulation solves Faraday's law

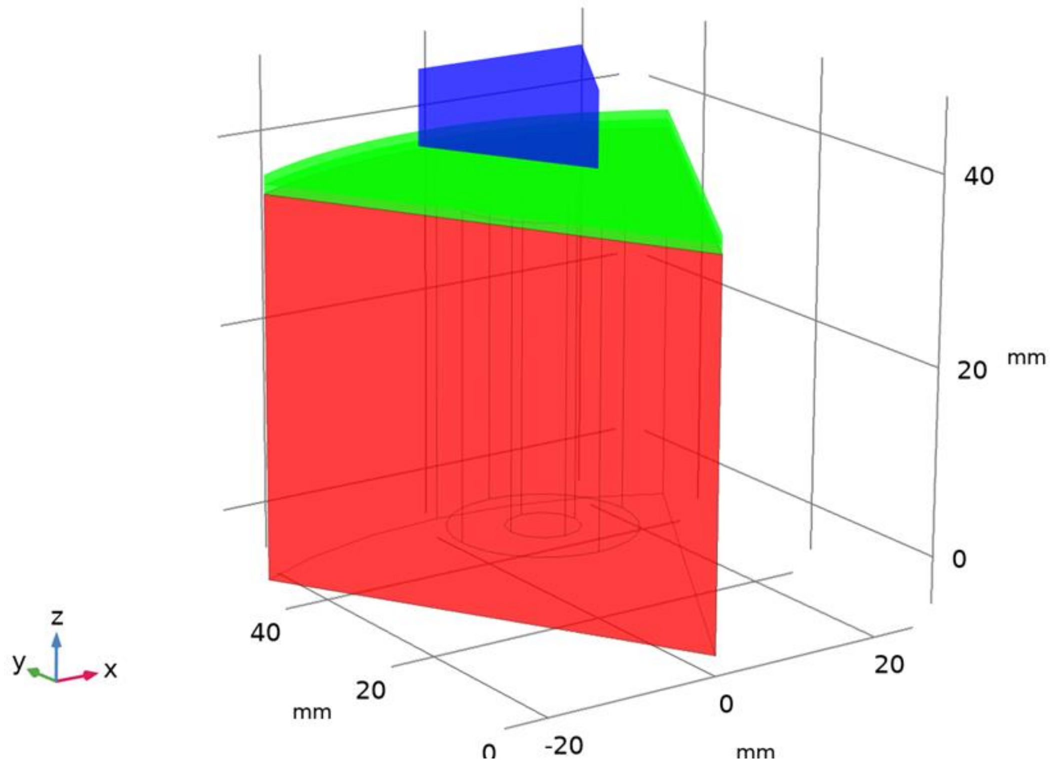
$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$E = \sigma^{-1}(\nabla \times H - J_e)$$

$$J_c = \sigma E$$

- The superconducting bulk is model using the EJ power law, with $n = 21$.

$$\rho = \frac{\varepsilon_0}{J_c}\left(\frac{J_z}{J_c}\right)^{(n-1)}$$

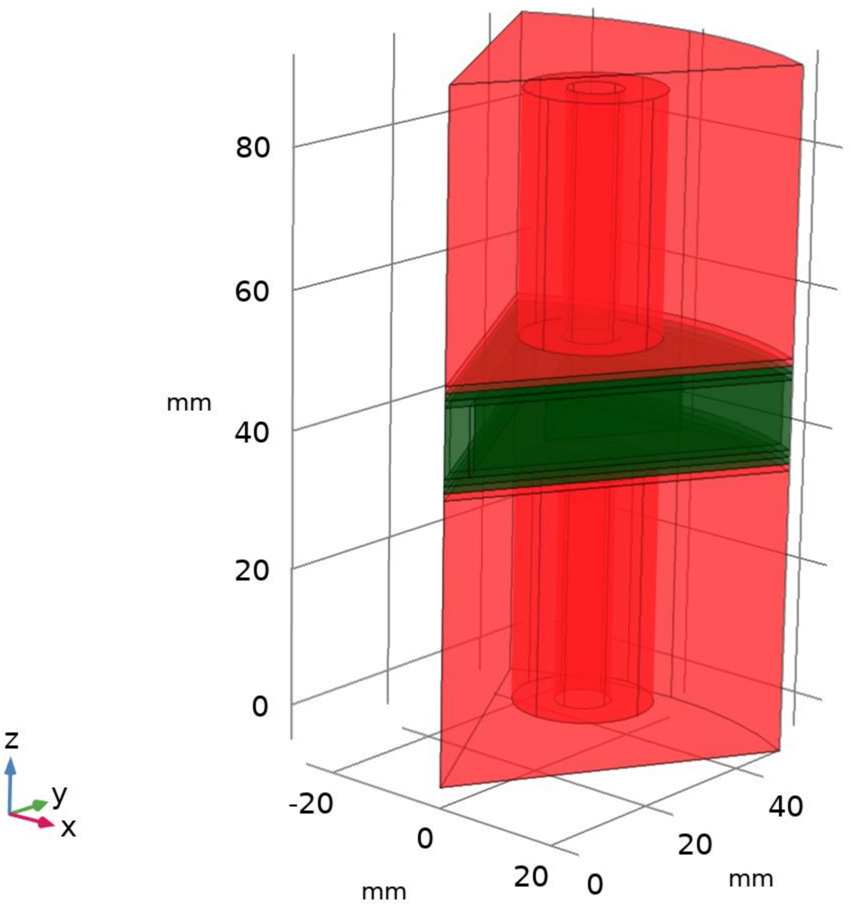


Model setup – Physics – rotational transformation

- The model is set to have a stationary part and rotating part using COMSOL default moving mesh.

$$\begin{Bmatrix} x_r \\ y_r \end{Bmatrix} = \begin{bmatrix} cos(wt) & -\sin(wt) \\ sin(wt) & cos(wt) \end{bmatrix} \begin{Bmatrix} x_g & - & x_0 \\ y_g & - & y_0 \end{Bmatrix} + \begin{Bmatrix} x_0 \\ y_0 \end{Bmatrix}$$

$$d_x = x_g - x_r$$
$$d_y = y_g - y_r$$



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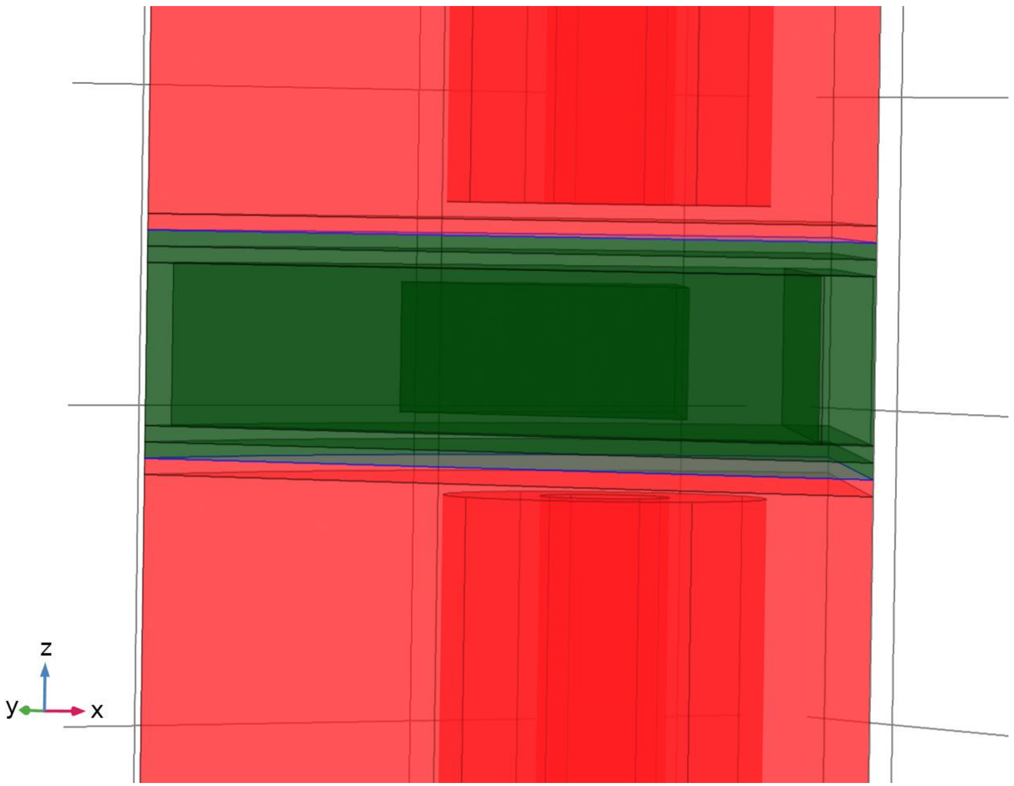
$$d_x = x_g - x_r$$
$$d_y = y_g - y_r$$

- The rotating contact is in blue.



Model setup – Physics – coupling the formulations

- To couple the formulations the boundary conditions are set similar to [4].

- For A-H:

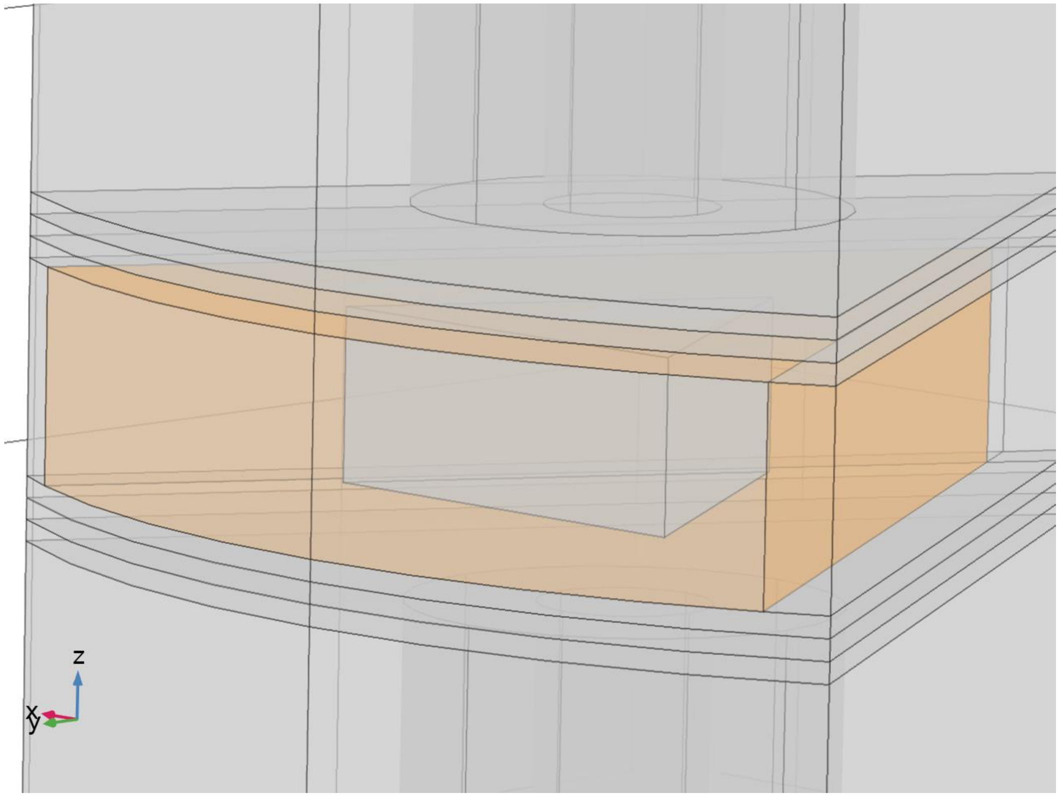
$$n \times E = n \times E_0$$

$$E_0 = \begin{Bmatrix} E_X \\ E_Y \\ E_Z \end{Bmatrix}$$

- For H-A

$$n \times H = n \times H_0$$

$$H_0 = \begin{Bmatrix} H_x \\ H_y \\ H_z \end{Bmatrix}$$



Brambilla, R., Grilli, F., Martini, L., Bocchi, M., Angeli, G., 2018. A Finite-Element Method Framework for Modeling Rotating Machines With Superconducting Windings. IEEE Transactions on Applied Superconductivity 28, 1–11.

Model setup – Physics – Boundary conditions

- For A-Formulation

Periodic

$A_{src}=A_{dst}$

If anti-periodic

$A_{src} = -A_{dst}$

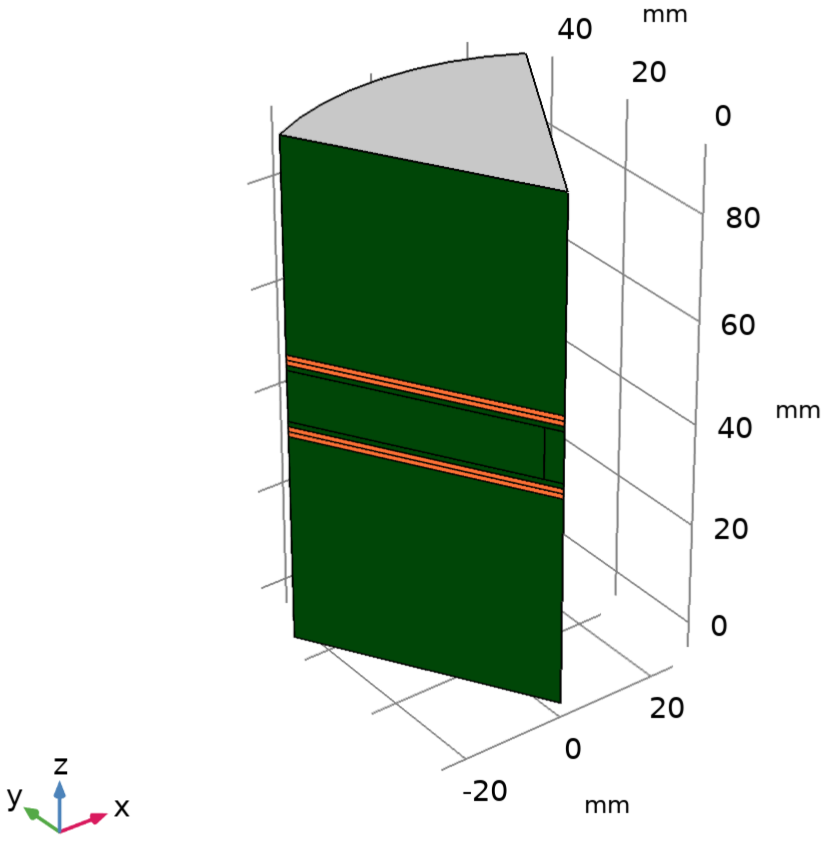
- For Scalar Magnetic Potential

Periodic

$V_{m\ src} = V_{m\ dst}$

If anti-periodic

$V_{m\ src} = -V_{m\ dst}$



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Model setup – Studies –

- Stationary – ZFC magnetization

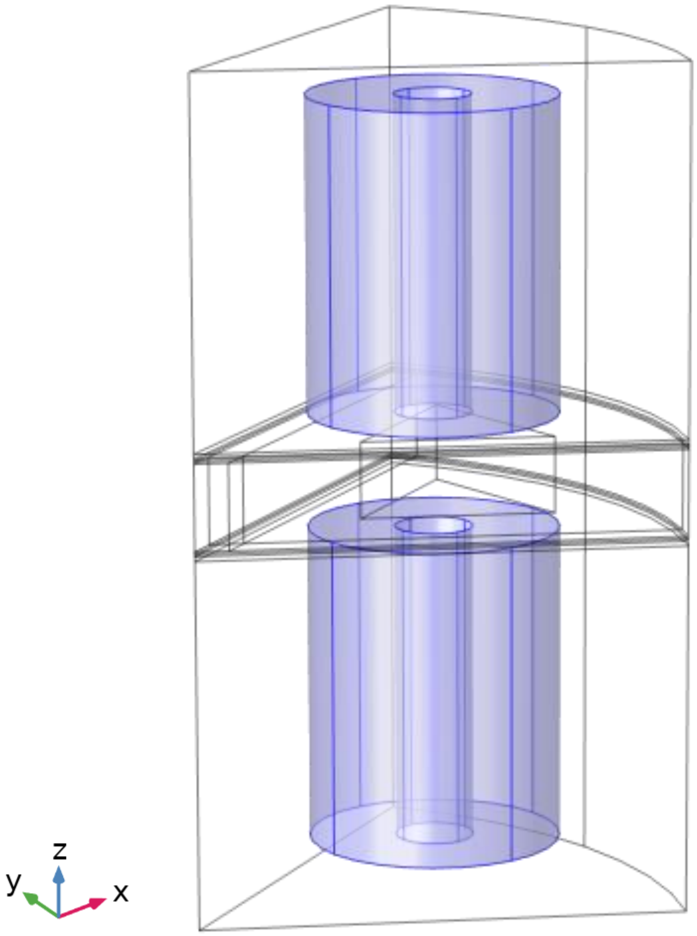
Applies a current through the coils to ramp up field for 200 s and ramp down field for 200 s.

400 s relaxation time.

- Operation - Rotation

Starts rotation at selected frequency

Applies alternating current at selected frequency.



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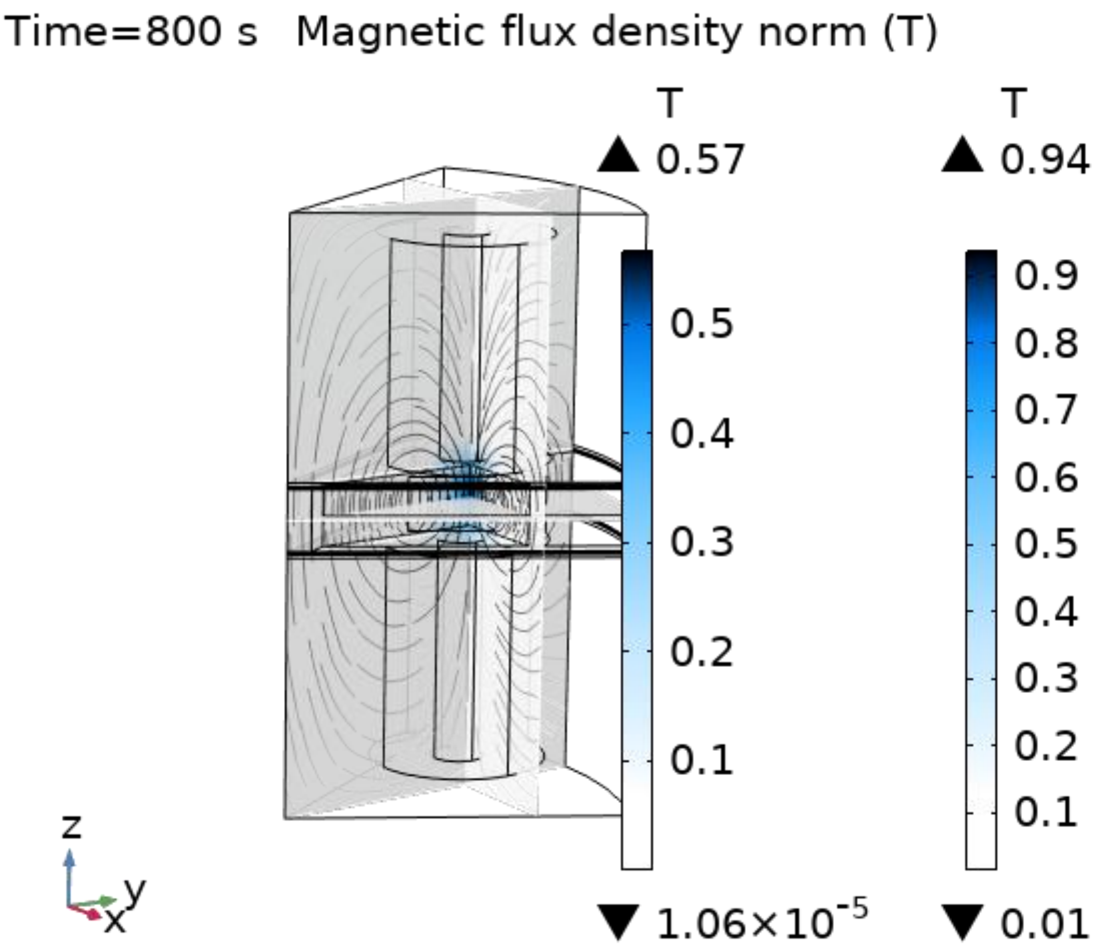
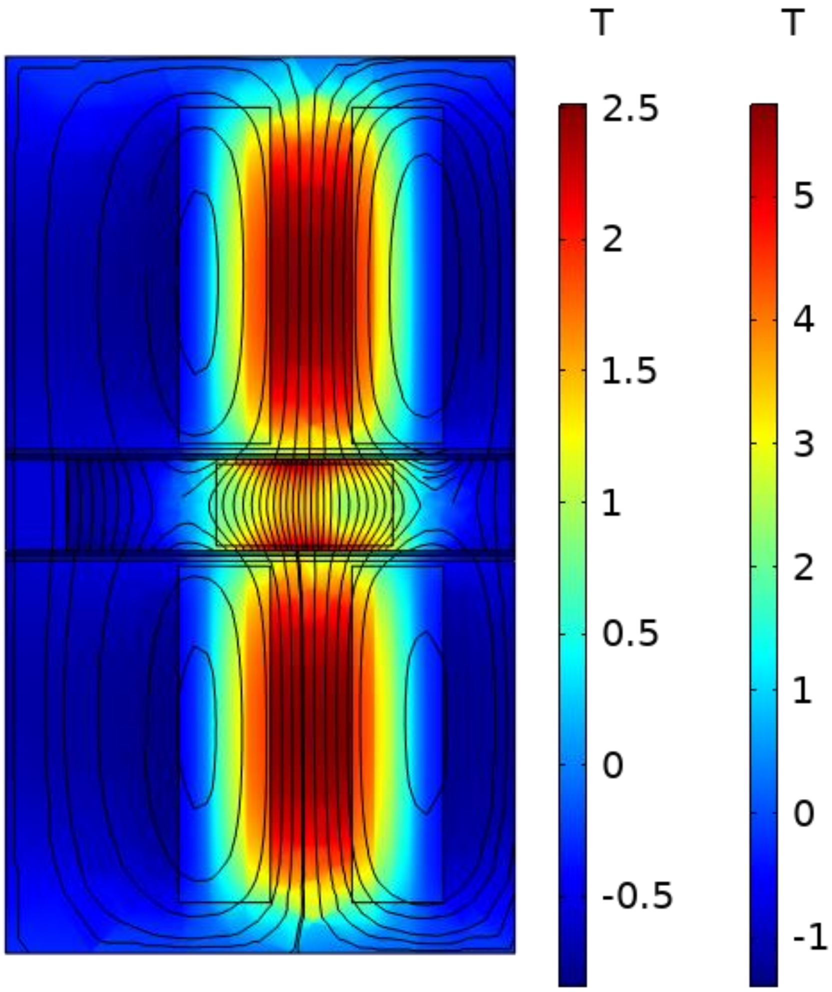
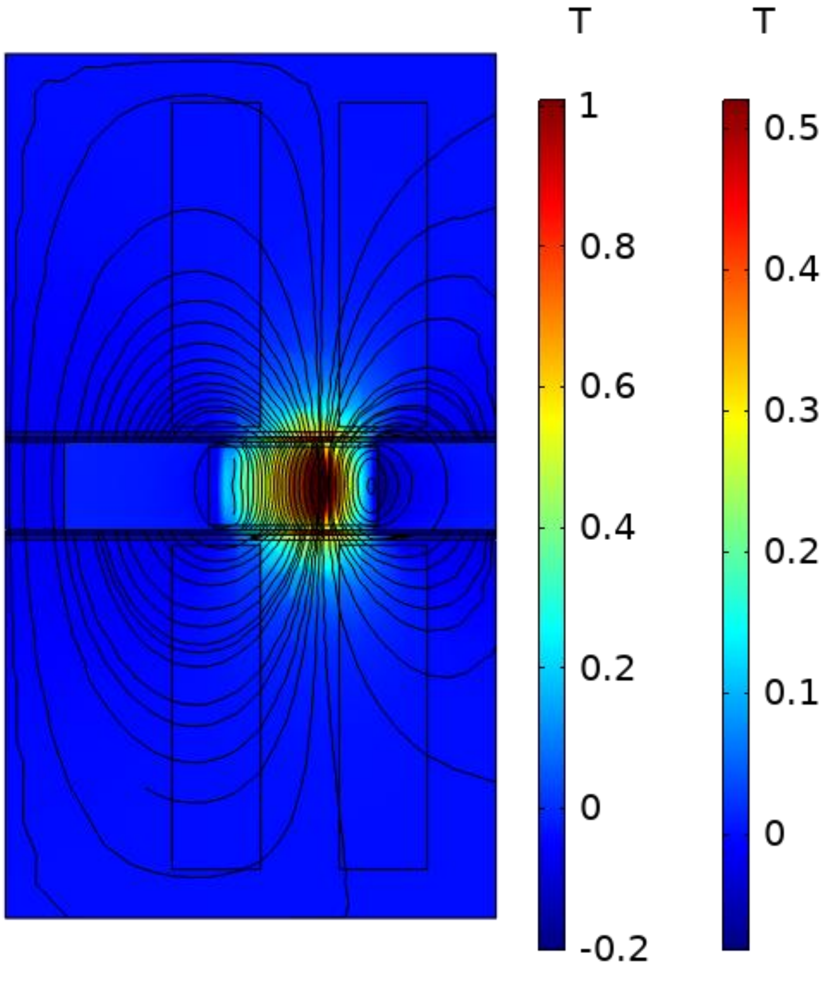
Results – Coupling H-A
Magnetic flux density continuity at 800 s.

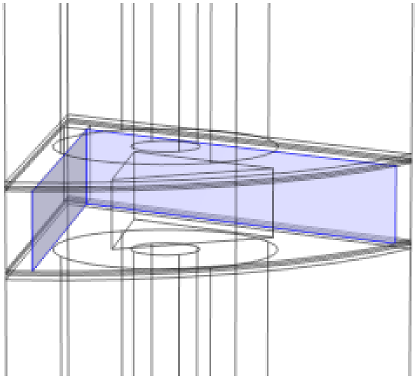


Results – Coupling H-A
Magnetic flux density continuity.
at 200 s and 800 s.

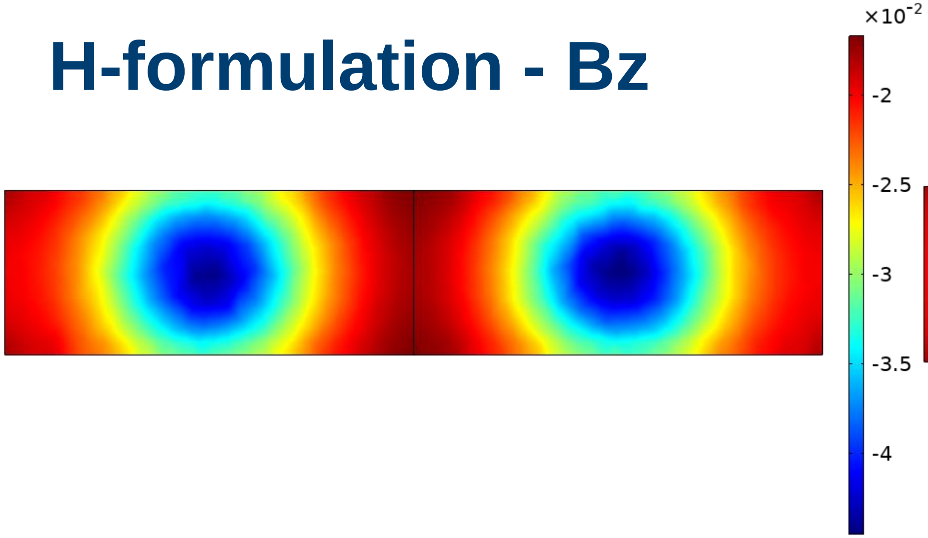




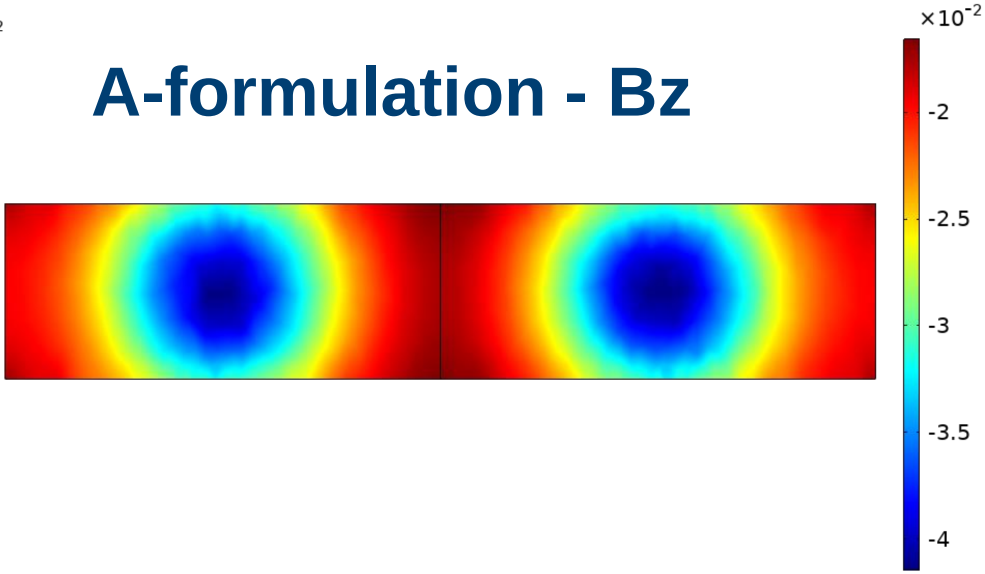
Results – Coupling H-A
Bz at H and A coupling boundaries.



H-formulation - Bz



A-formulation - Bz



Results – Coupling H-A
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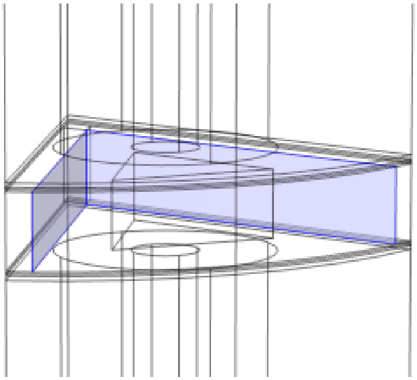
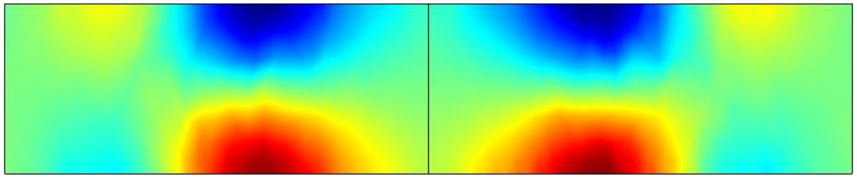
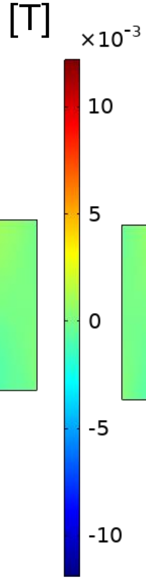


H-formulation - By





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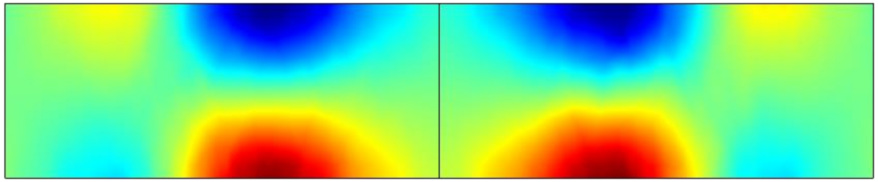
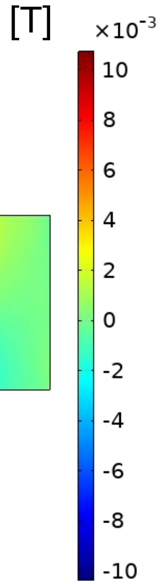
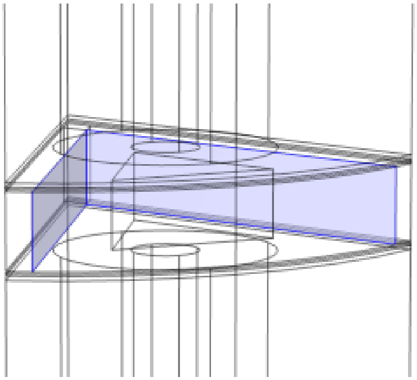
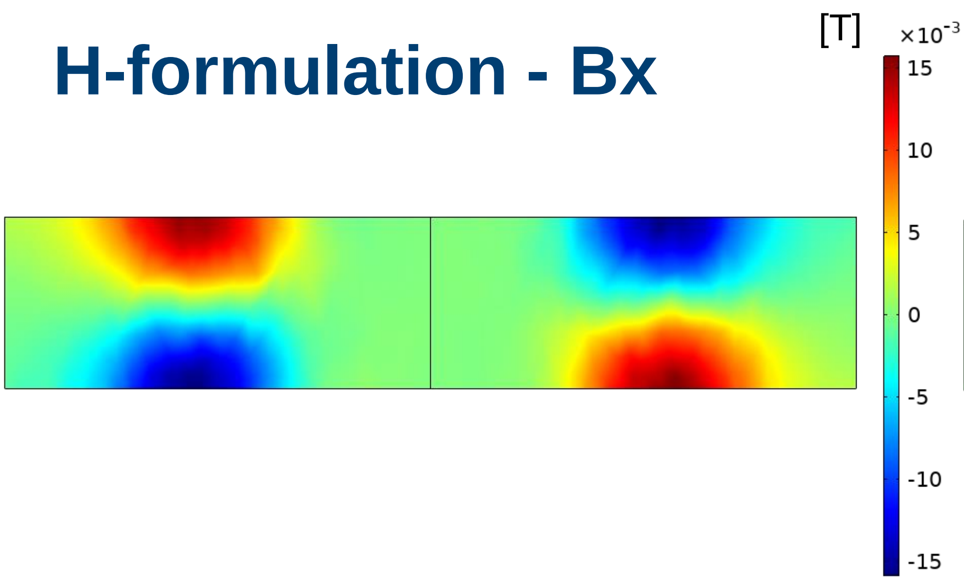




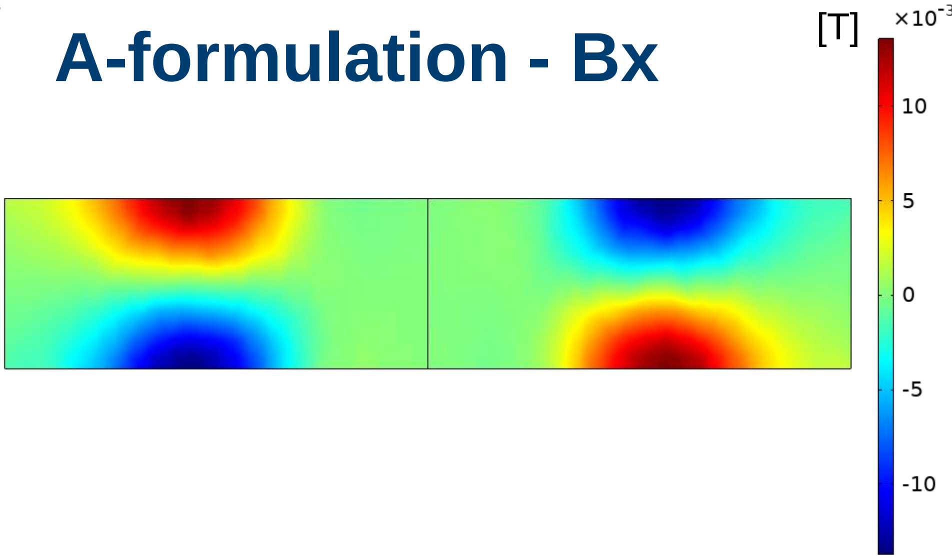
Results – Coupling H-A
Bx at H and A coupling boundaries.



H-formulation - Bx



A-formulation - Bx



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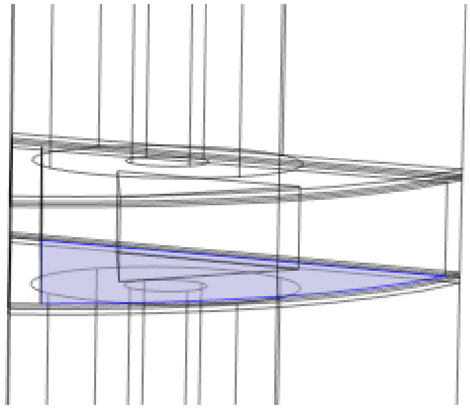
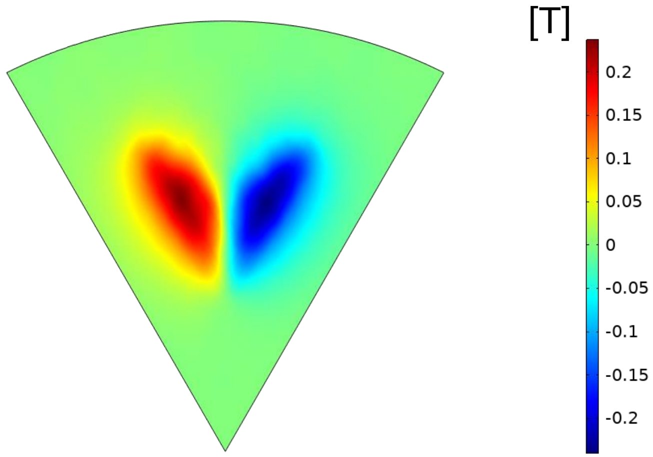


H-formulation - Bx



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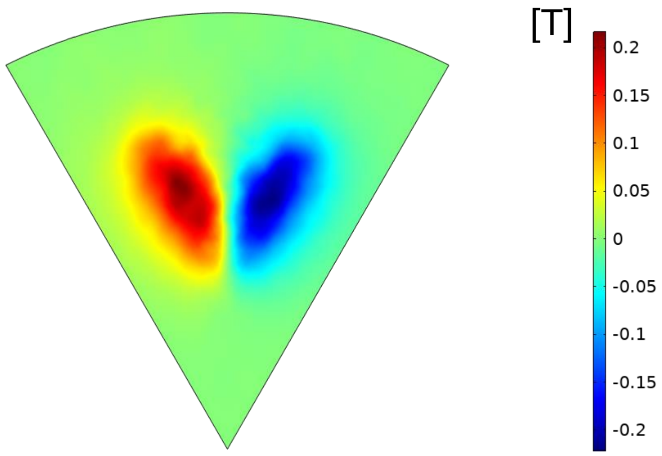
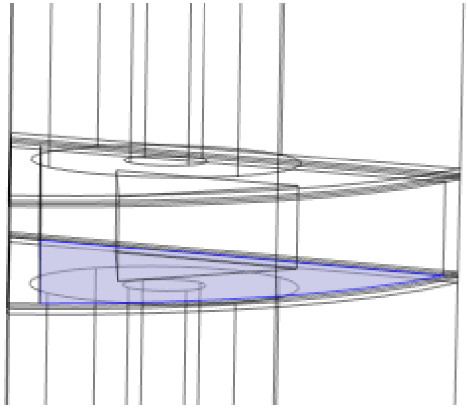
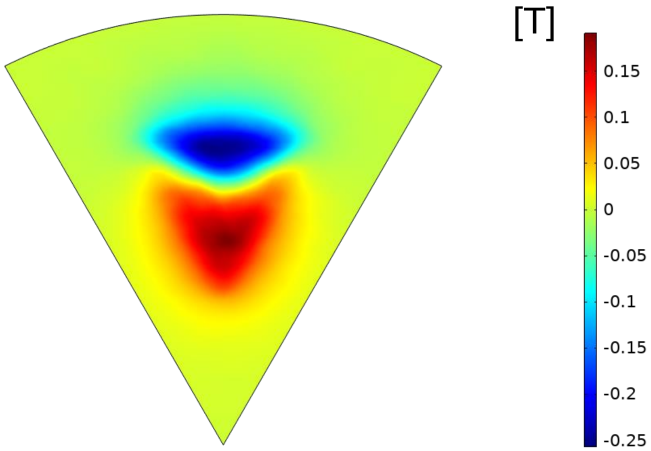


Results – Coupling H-A
By at H and A coupling boundaries.



H-formulation - By



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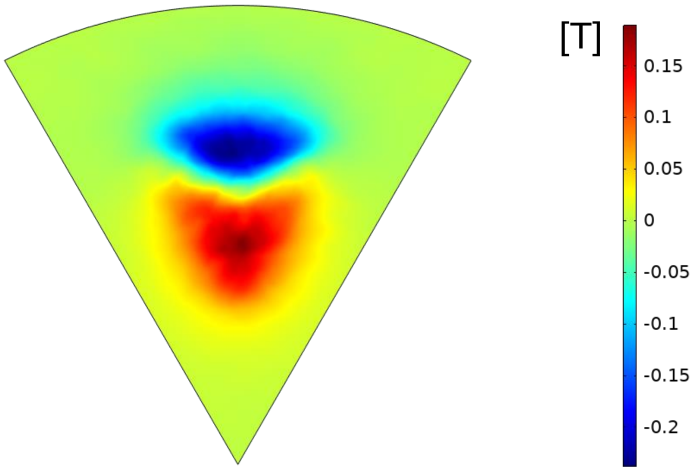
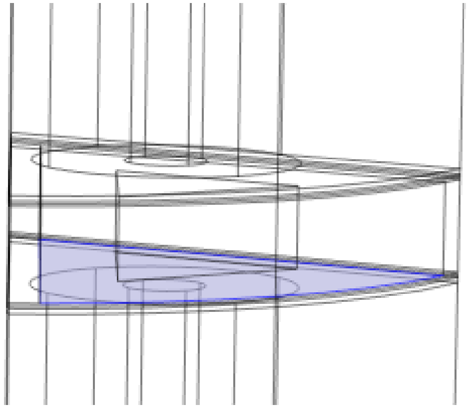
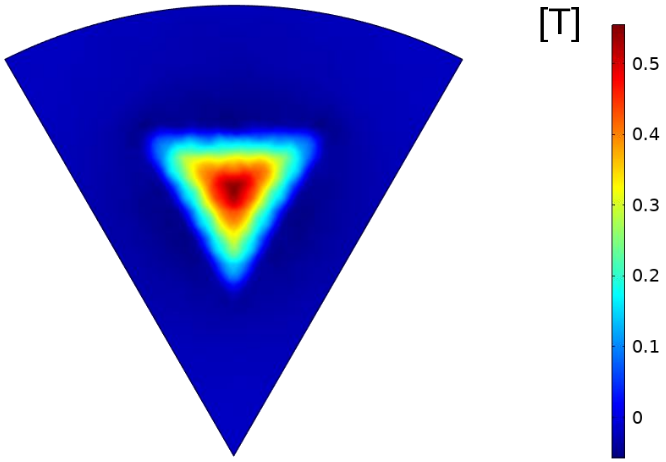


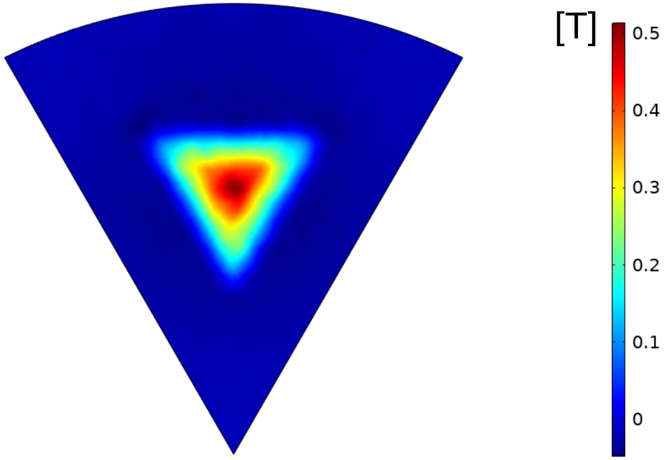
Results – Coupling H-A
Bz at H and A coupling boundaries.



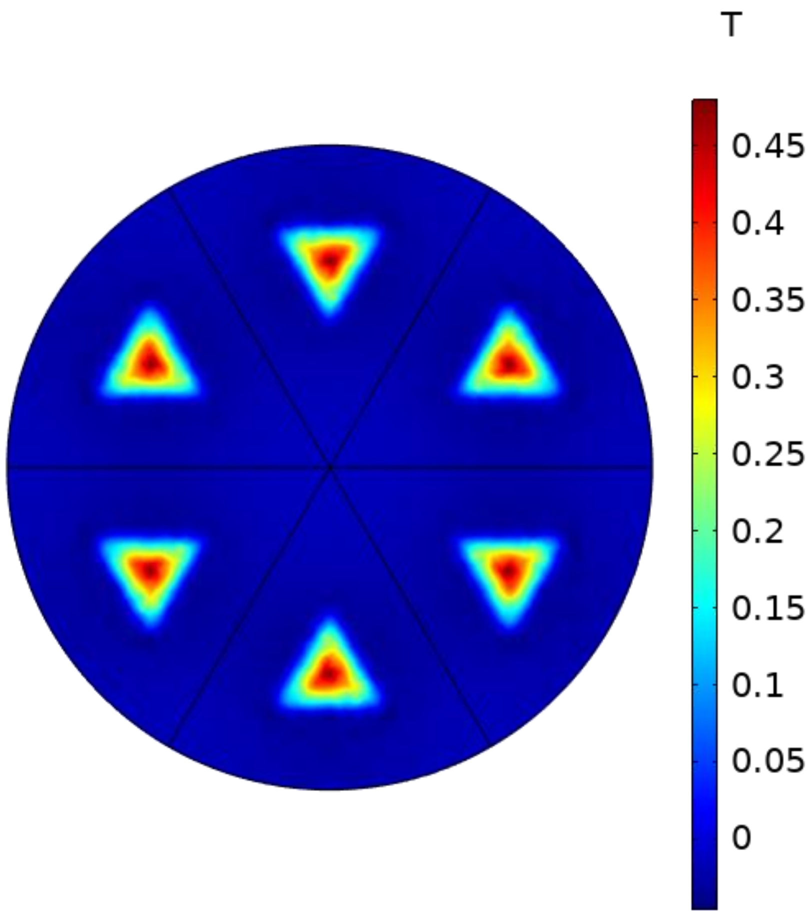
H-formulation - Bz

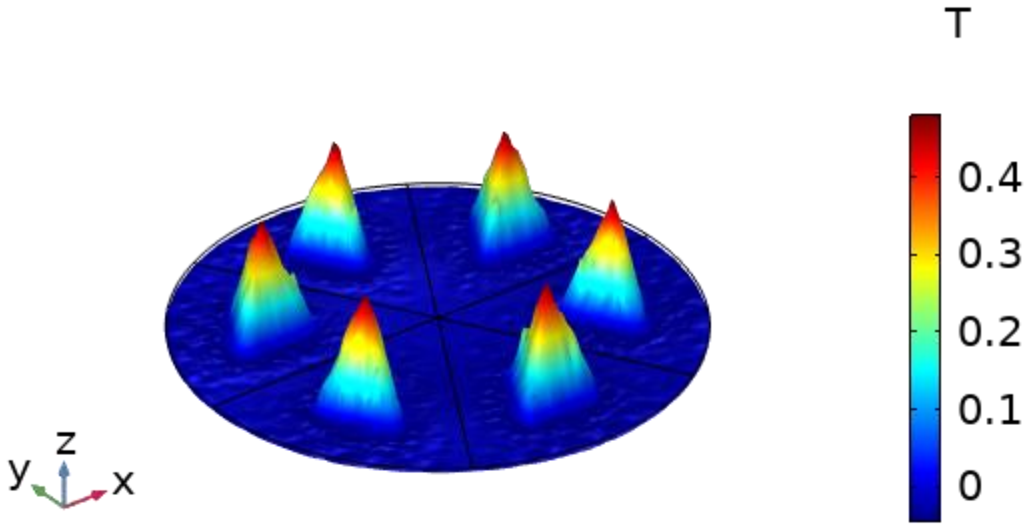


A-formulation - Bz

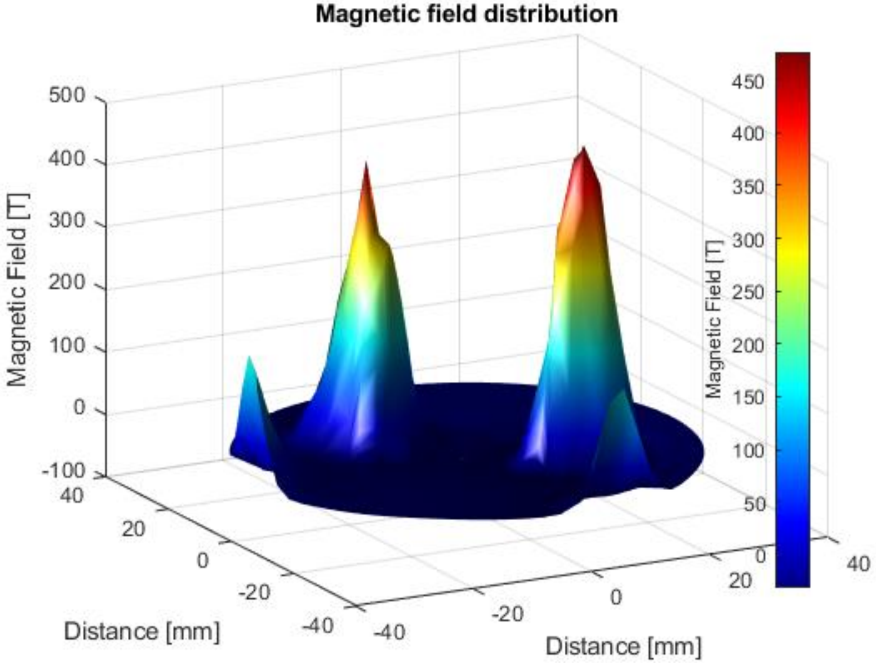


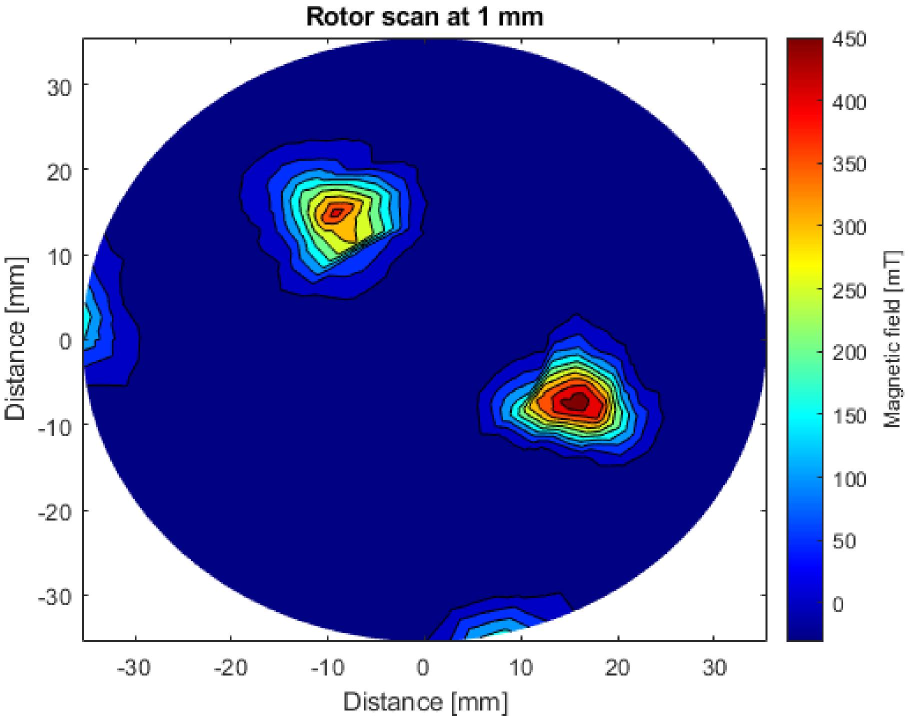
Results - Magnetic field distribution in airgap at 1 mm distance in z direction.



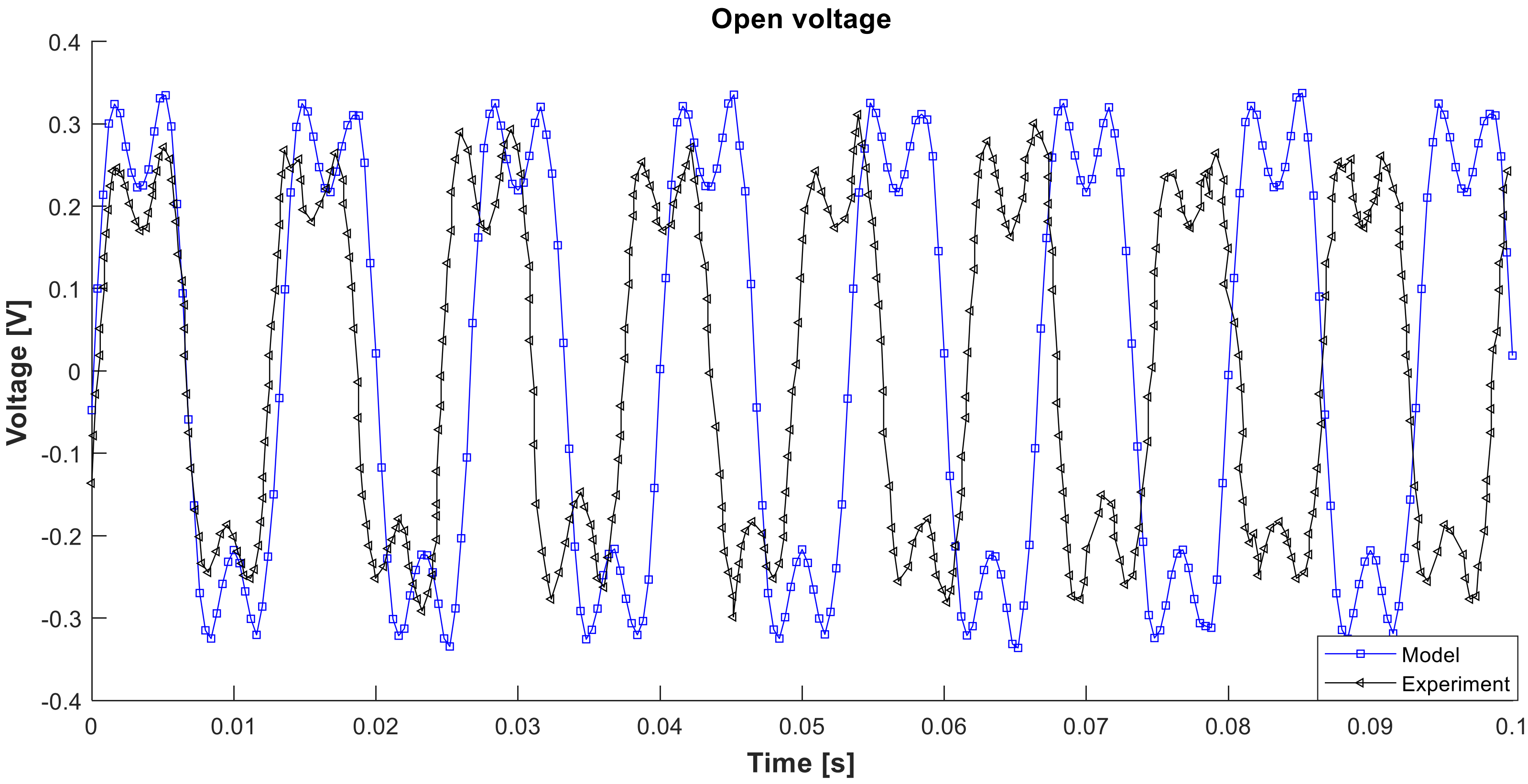


Experimental results – magnetic field distribution z direction

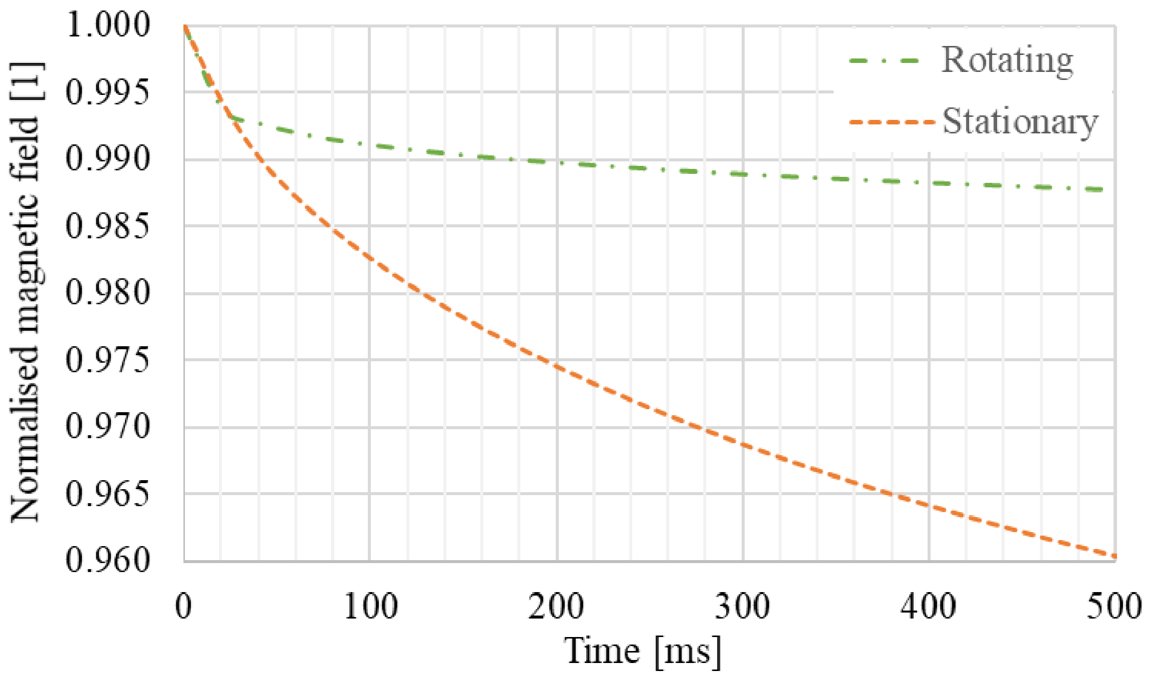




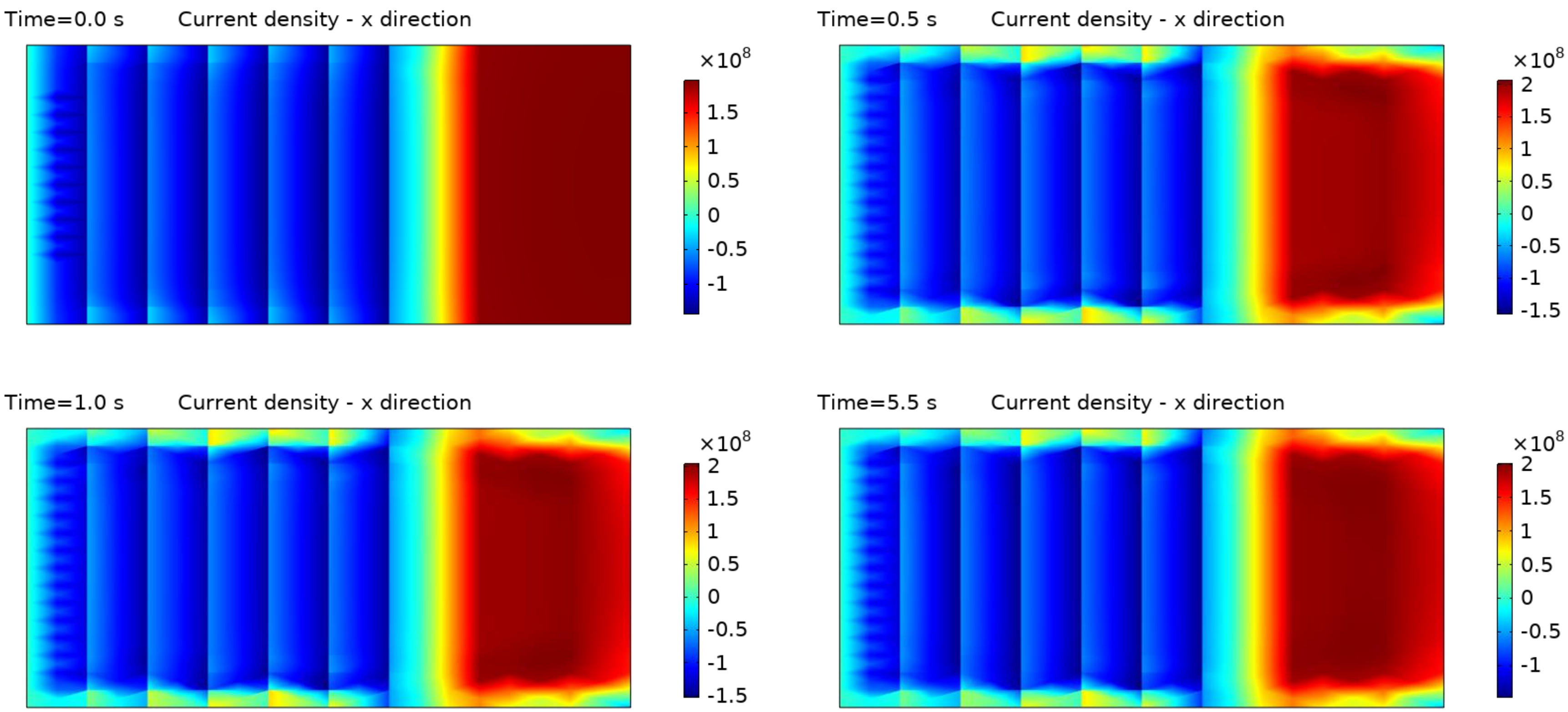
Results - Operation as a voltage generator - Model



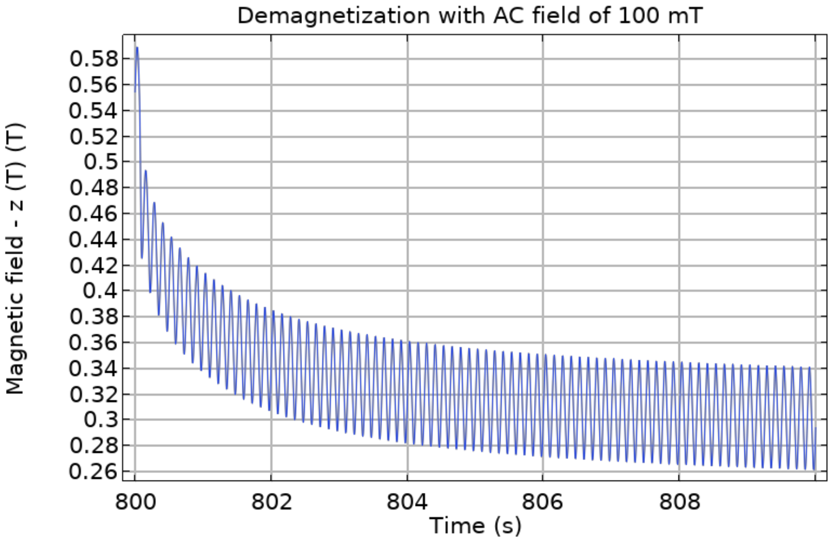
Results – 100 mT demagnetization – 8 Hz synchronous speed model

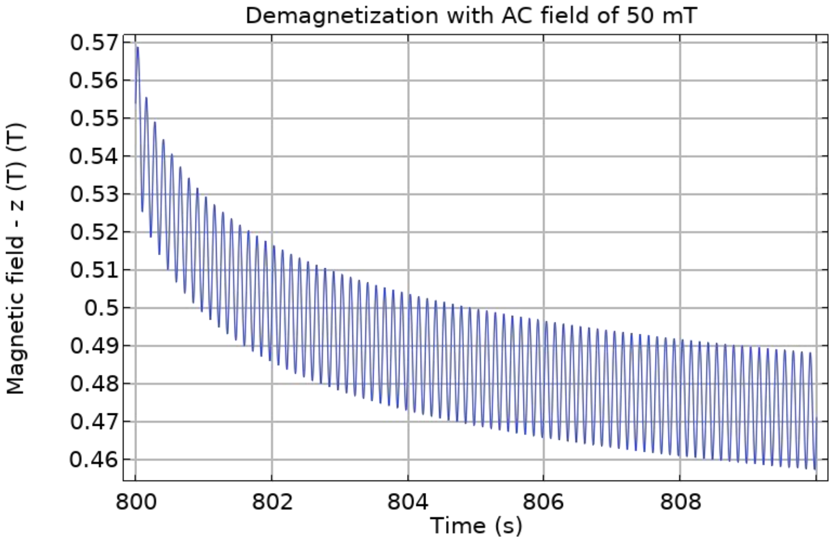


Current density in the x direction [A/m^2]

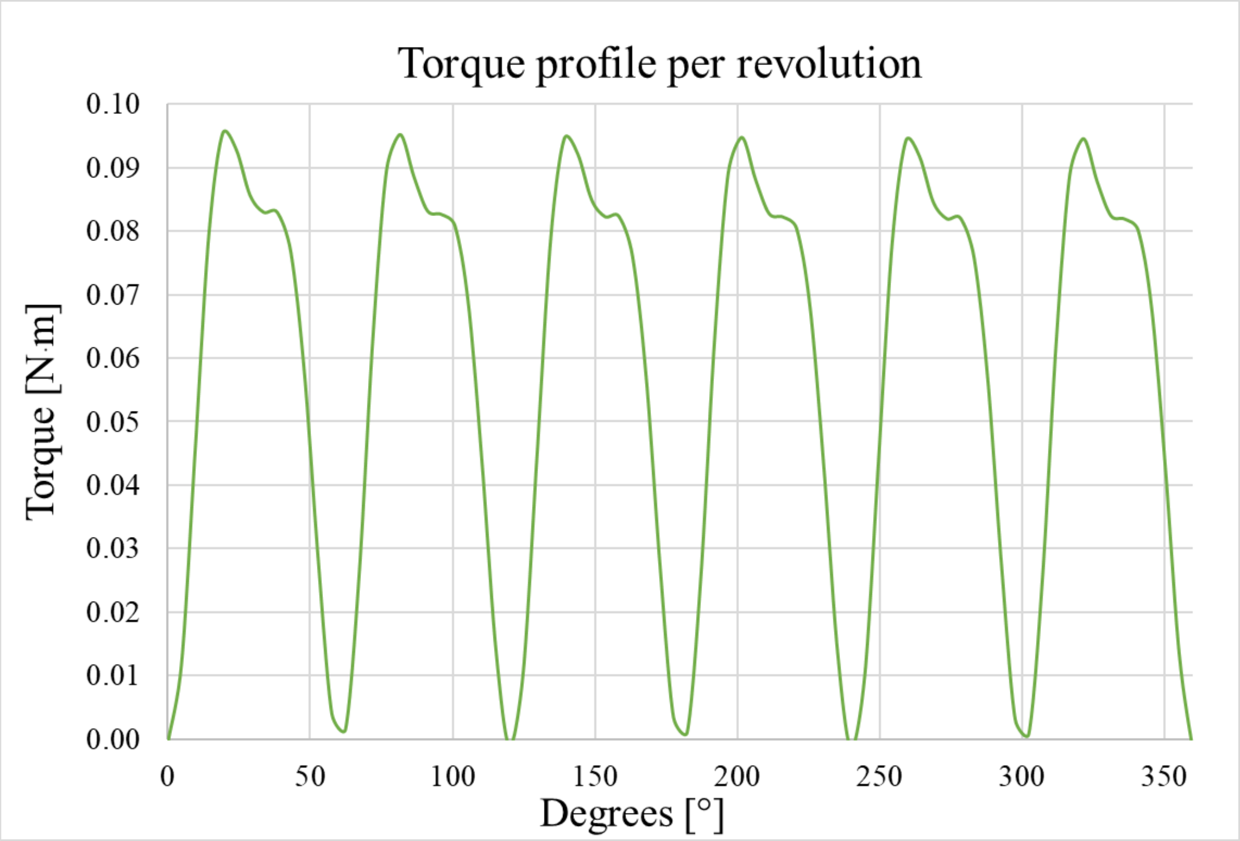


Results – Stationary demagnetization – 8 Hz 100 mT 50 and 100 mT

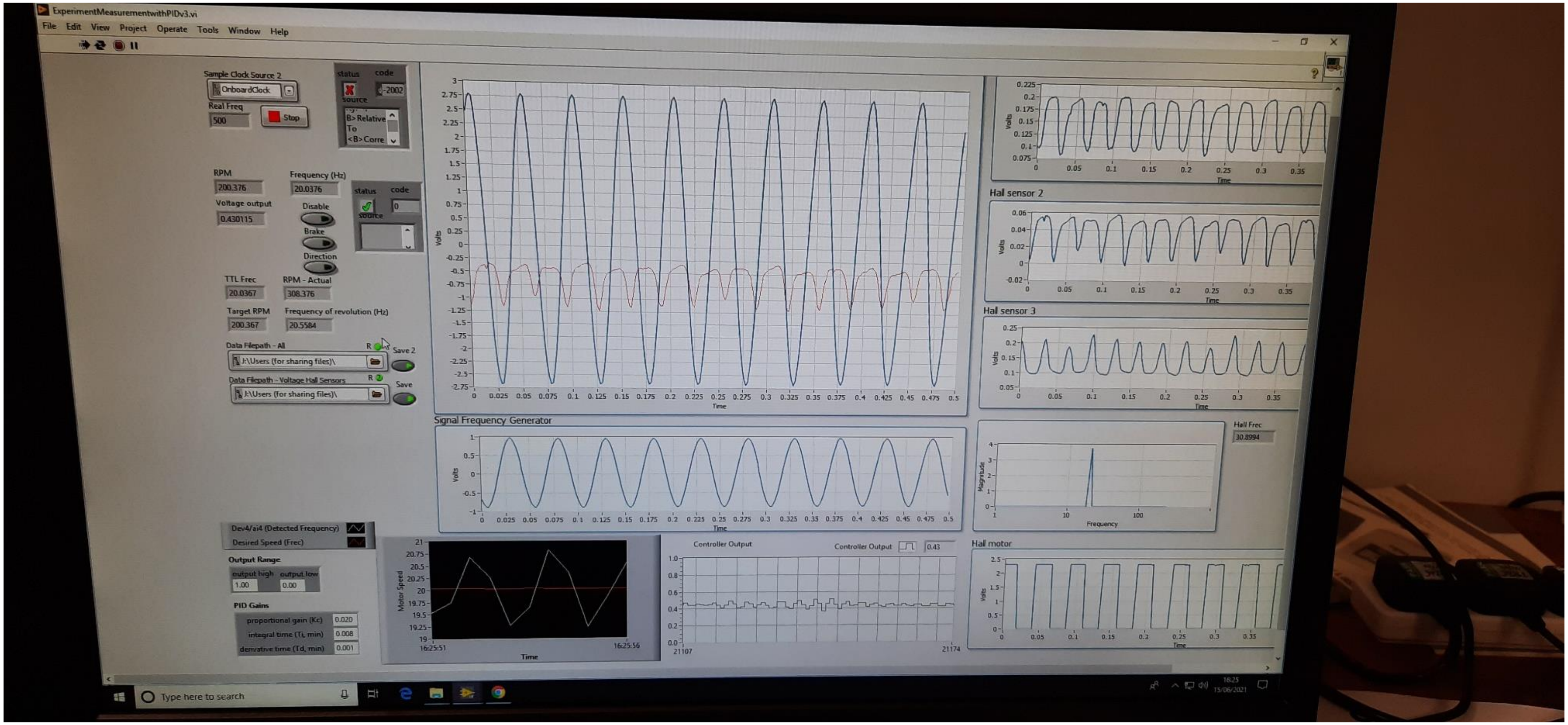




Results – Torque – model



Experiment for validation of AC losses



Conclusions

- There is evidence to think our model can reproduce the operation of a synchronous axial-flux machine and serve to predict AC losses.
- We should be able to demonstrate that losses during real operation conditions are smaller than some experiments have proposed. This since the force applied on the superconductor pushes the flux line in the direction of rotation, thus being kept in the pinning site.
- It should be possible to use this modelling approach to optimize parameters for actual commercial machines.

Acknowledgments

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Questions?