Coupled Magnetodynamic and Electric Circuit Models for Superconducting Fault Current Limiter

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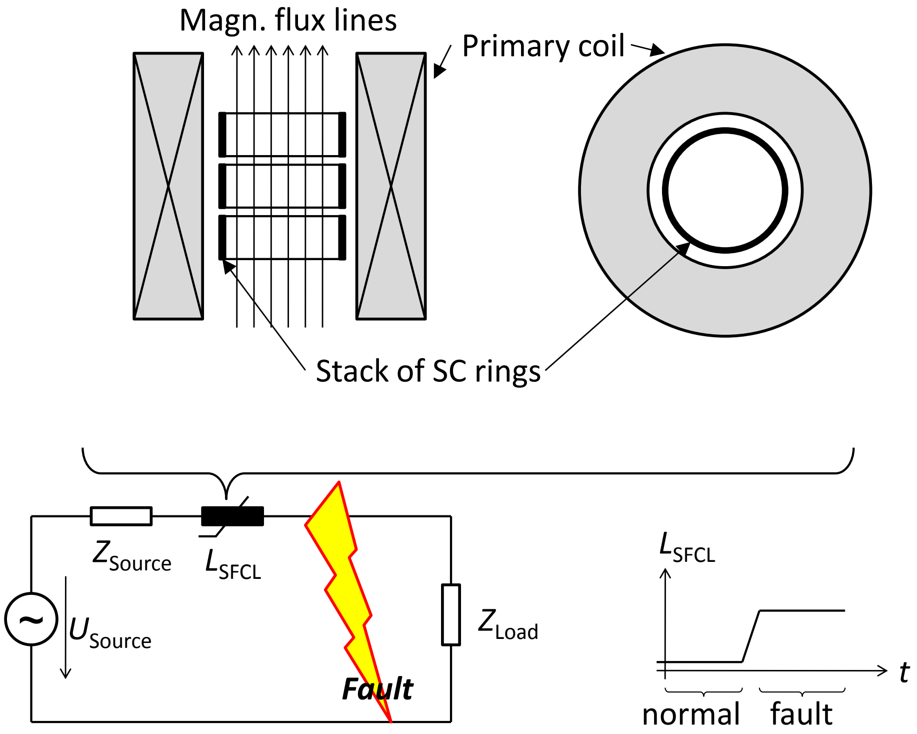
Contents

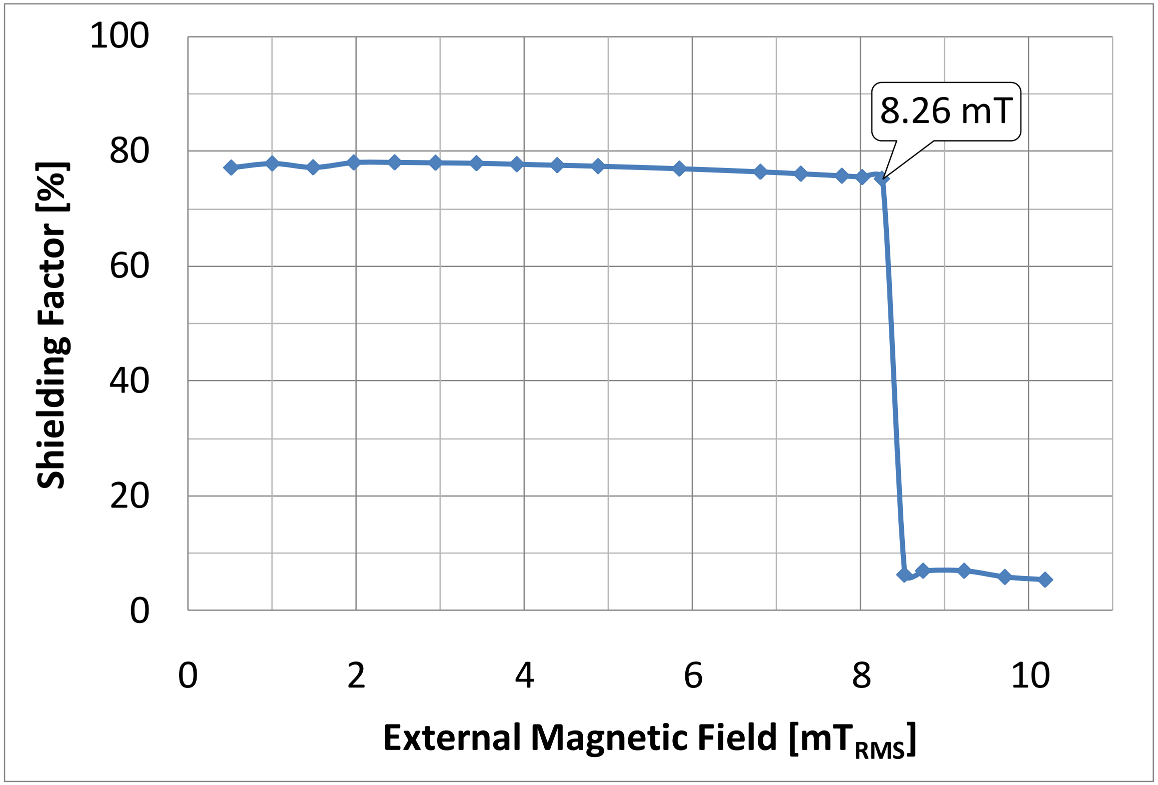
- Basics of superconducting fault current limiters (SFCL)
- Shielding properties of superconductors
- FEA magnetic model
  - Implementation of shielding properties
- Electric circuit model (“SPICE”)
- Model validation
  - Experiment with benchtop model
  - Measurements
- Conclusion

Inductive Superconducting FCL



- Problem: Increasing levels of fault currents in power grids
- SFCL limits fault current without negative impact at normal operation
  - Low voltage drop during normal operation
  - Low reactive power
- **Inductive** SFCL provide operational advantages:
  - No heat influx into cryostat through current leads
  - No Joule heating in cryostat

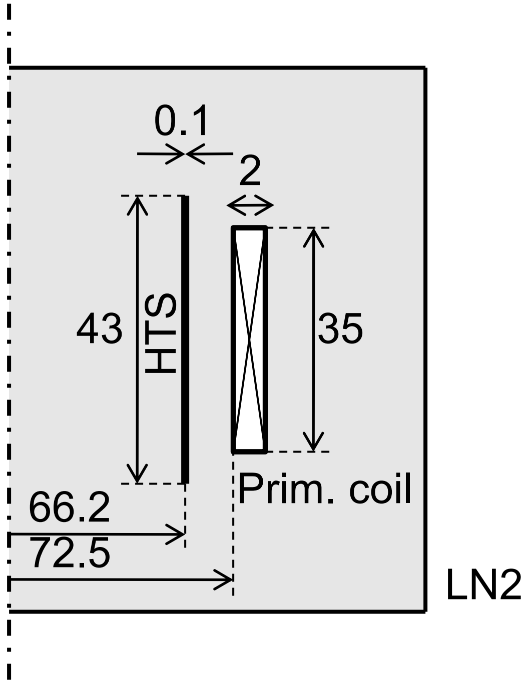
Shielding Properties of HTS



$$S = \frac{B_{\text{ext}} - B_{\text{int}}}{B_{\text{ext}}} \cdot 100\%$$

- Measured with the exact **same ring** of HTS as later used for the validation experiment
- Hall probes inside and outside the ring pick up the magnetic field
- Operation frequency differs slightly from 60 Hz to reduce noise

Finite Element Model



$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \mathbf{H} - \sigma\, \mathbf{v} \times \mathbf{B} = \mathbf{J}_\mathbf{e}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

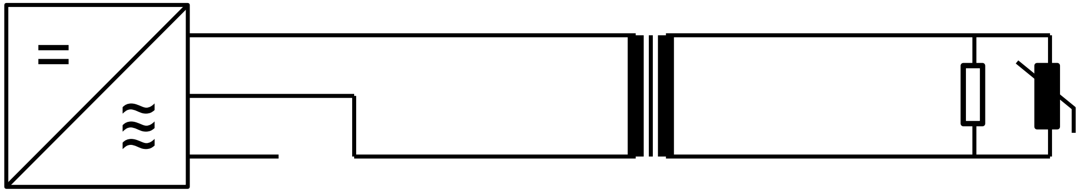
- Shielding properties of HTS **modeled by conductivity** of HTS
  - Exact value of conductivity is not critical
  - Factor 100 lower due to increased thickness in model

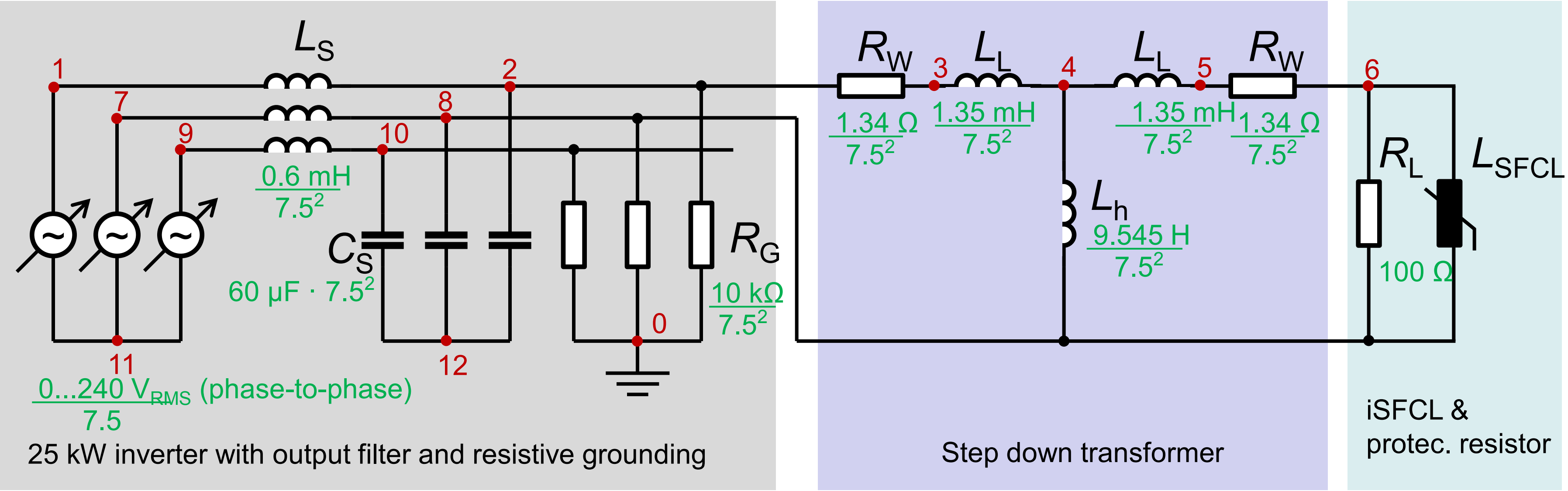
$$\sigma = \begin{cases} 2.5 \cdot 10^{14}\ \mathrm{S/m} & \text{in normal operation,} \\ 2.5 \cdot 10^{0}\ \mathrm{S/m} & \text{in quench/fault operation.} \end{cases}$$

- Primary coil: Multi-turn coil domain with 60 turns of 1 mm Cu wire
- Liquid nitrogen (LN2) in open bath at 77 K ($\mu_r = 1$; $\sigma = 0$ S/m)

iSFCL for FEA Validation: Equivalent Circuit

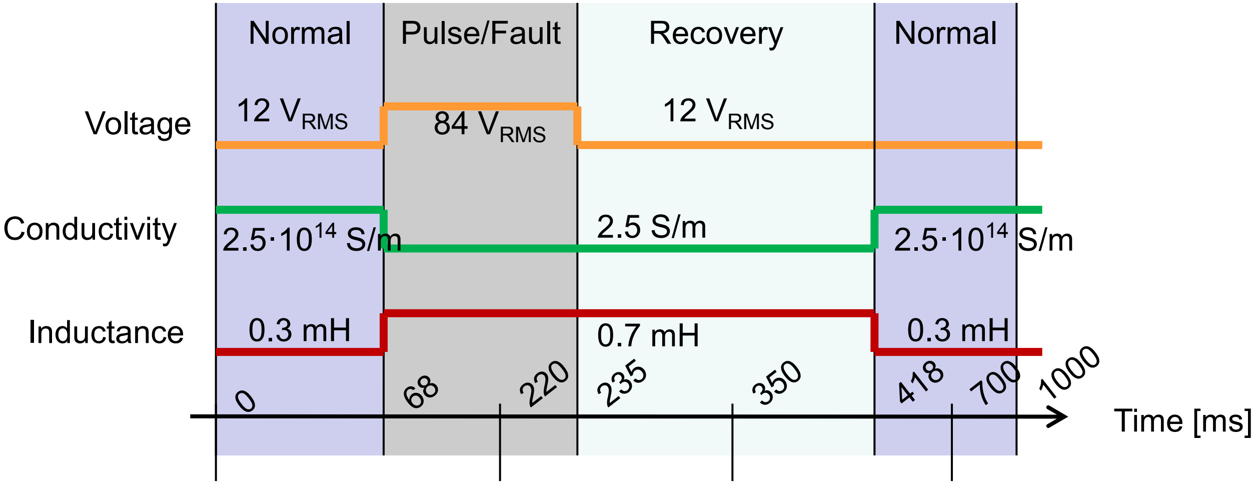
- Electric circuit with lumped elements (“SPICE”), coupled to the FEA model
- Transformer ratio: 240 V : 32 V = 7.5





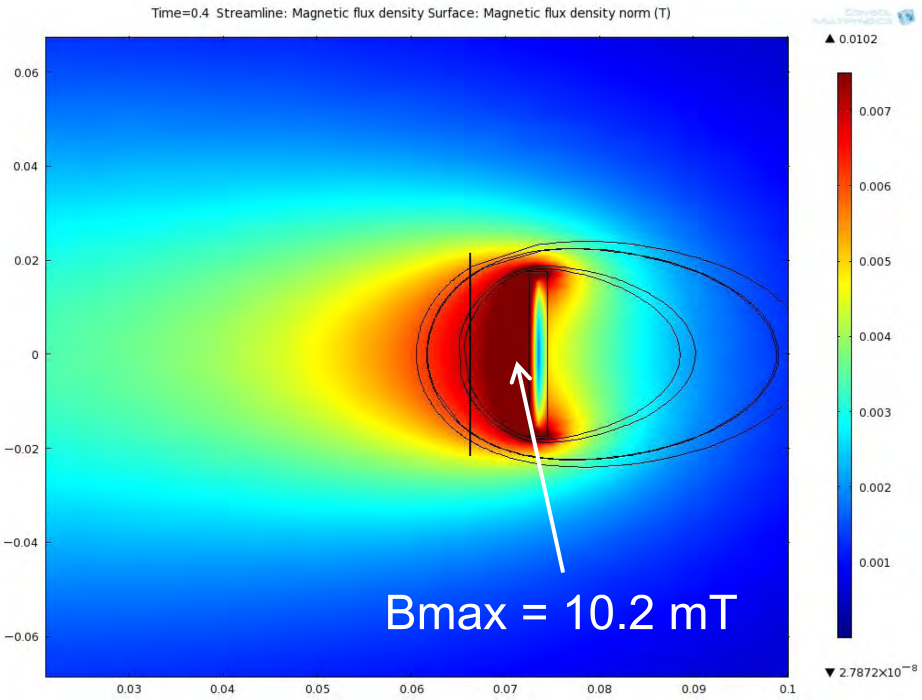
iSFCL for FEA Validation: Pulse Pattern

- Input parameters
  - Applied voltage (pulse of 7× nominal simulates a fault situation)
  - HTS conductivity
- Output parameters
  - Inductance of the iSFCL as a function of time



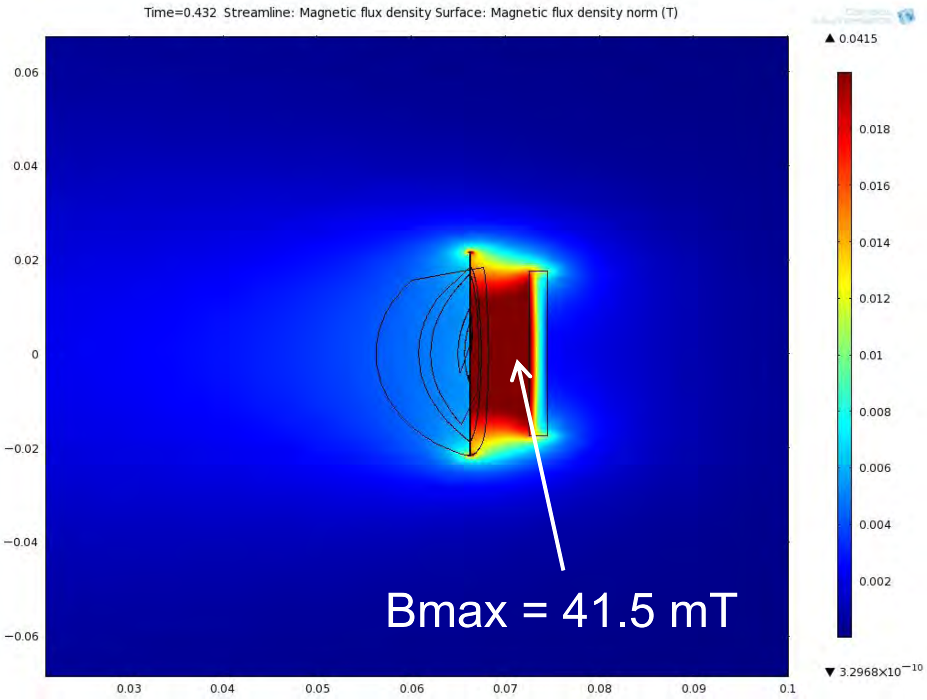
iSFCL for FEA Validation: Magnetic Flux Density

a) After fault but before recovery of superconduction (quenched)



L = 0.7 mH

b) Normal operation (shielding)

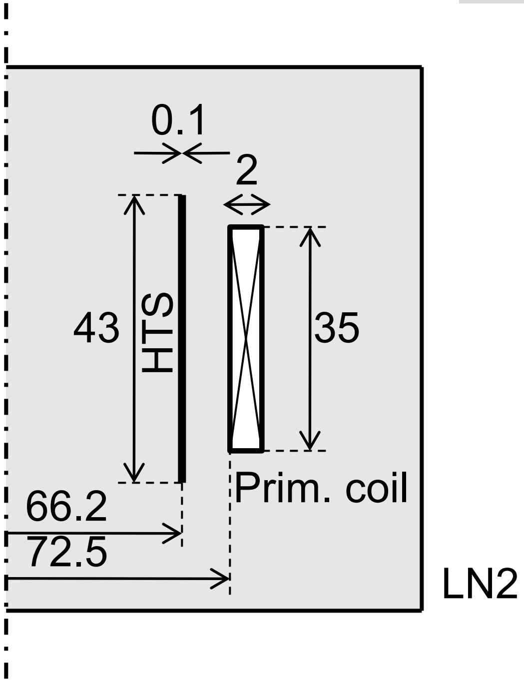


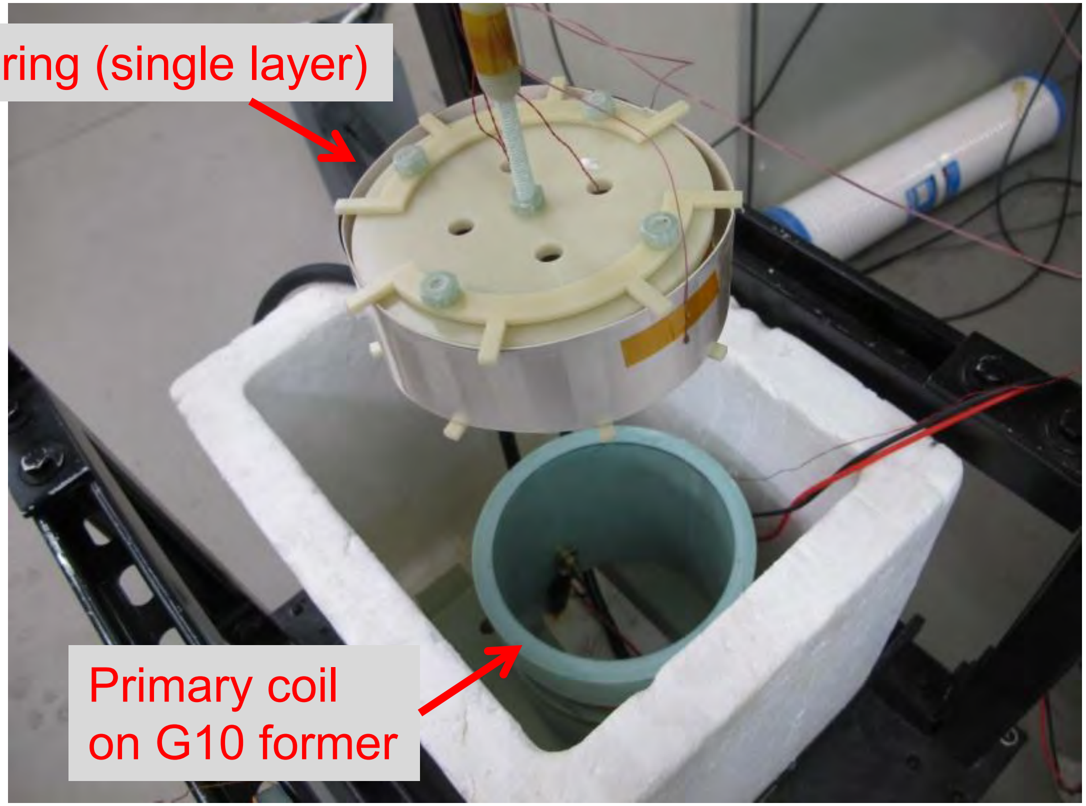
L = 0.3 mH

iSFCL for FEA Validation: Construction

- Primary purpose of this **small-scale** iSFCL:

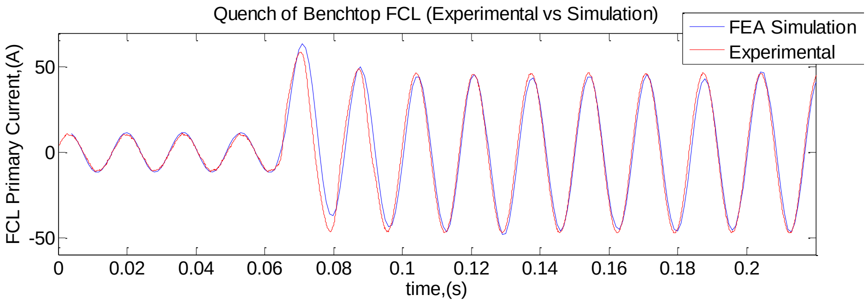
  Validation of FEA model (i.e. conductivity-based magnetic shielding)

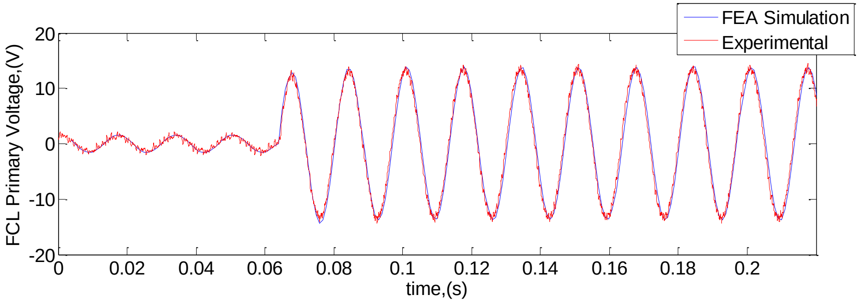


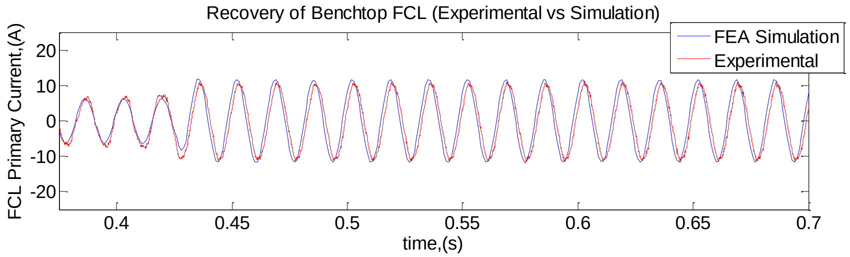

HTS ring (single layer)

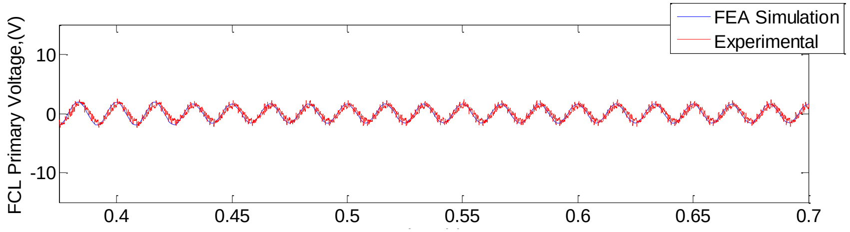
Primary coil on G10 former

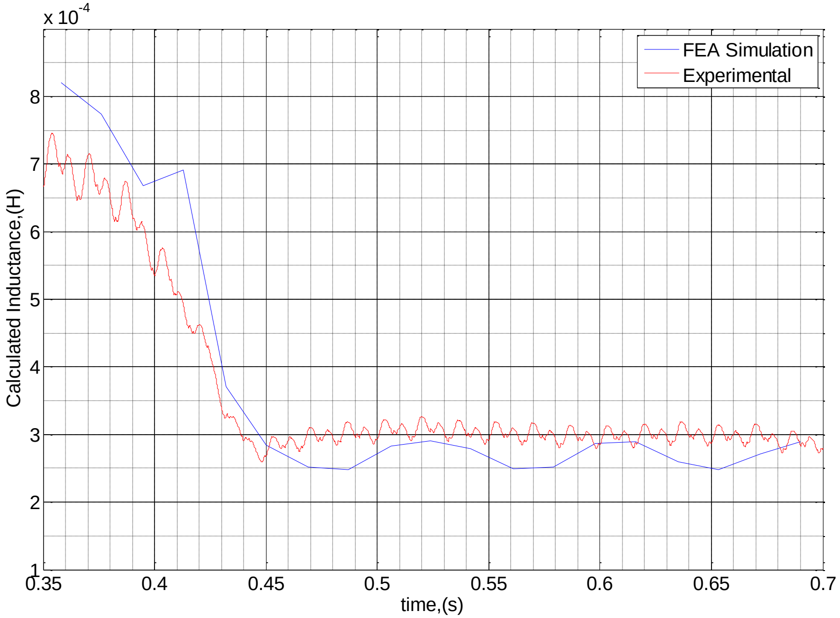
iSFCL for FEA Validation: Voltage, Current, and Inductance











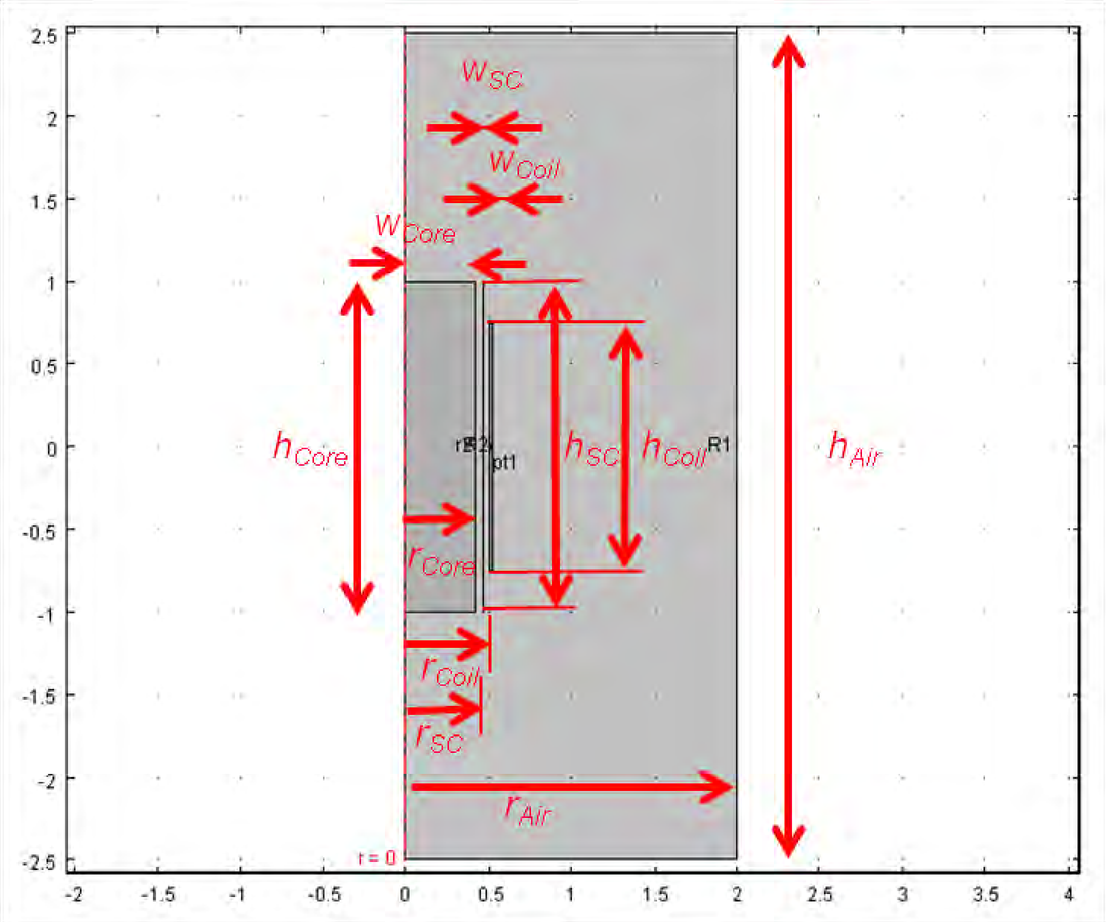
- FEA results compared to measurements around instant of fault (above, left), instant of recovery (above, right), and ratio of inductance (right)
- Convincing agreement of model and measurement

Conclusion

- HTS conductivity as input parameter to the FEA model is a valid technique to simulate basic magnetic properties
  - Model can be used for parametric studies
- Coupling with circuit model allows interaction with grid components
  - Enables power hardware-in-the-loop tests
- Computational very efficient
  - A couple of minutes to calculate on a PC
  - Would allow to implement geometry of higher complexity
- Regarding the air core iSFCL...
  - Ratio of inductance is limited to approx. 1.5 ~ 3 (depends on geometry of primary coil, cryostat wall thickness, and height to diameter ratio)
  - Insertion of an iron core (e.g. I-core) boosts the ratio to 5 ~10

Additional Slides

Coreless Model: Parameters



- Geometry
  - $r_{Air} = 2$ m; $h_{Air} = 5$ m
  - $r_{Coil} = 0.5$ m; $h_{Coil} = 1.5$ m; $w_{Coil} = 0.02$ m
  - $r_{SC} = 0.4$ m; $h_{SC} = 2$ m; $w_{SC} = 1$ mm
  - Optional: $r_{Core} = 0.42$ m; $h_{Core} = h_{SC}$
  - $N = 65$
  - $A_{Coil} = 240\ \text{mm}^2$
- Material
  - Air, HTS, and primary coil: $\varepsilon_r = 1$; $\mu_r = 1$; $\rho = \{10^{-15}; 1\}\ \Omega\text{m}$
  - Iron core: $\varepsilon_r = 1$; $\mu_r = 4000$; $\rho = 1\ \Omega\text{m}$
- Load current in the coil
  - $f = 50$ Hz; $I_{coil} = \{0.5 ; 20\}$ kA; $I_{tot} = N \cdot I_{coil}$

Coreless Model: Equations and BCs

Governing equations

$$\nabla \cdot \mathbf{J} = 0$$

$$\nabla \times \mathbf{H} = \mathbf{J}$$

$$\mathbf{J} = \sigma\mathbf{E} + j\omega\mathbf{D} + \begin{pmatrix} 0 \\ I_{tot}/A_{coil} \\ 0 \end{pmatrix}$$

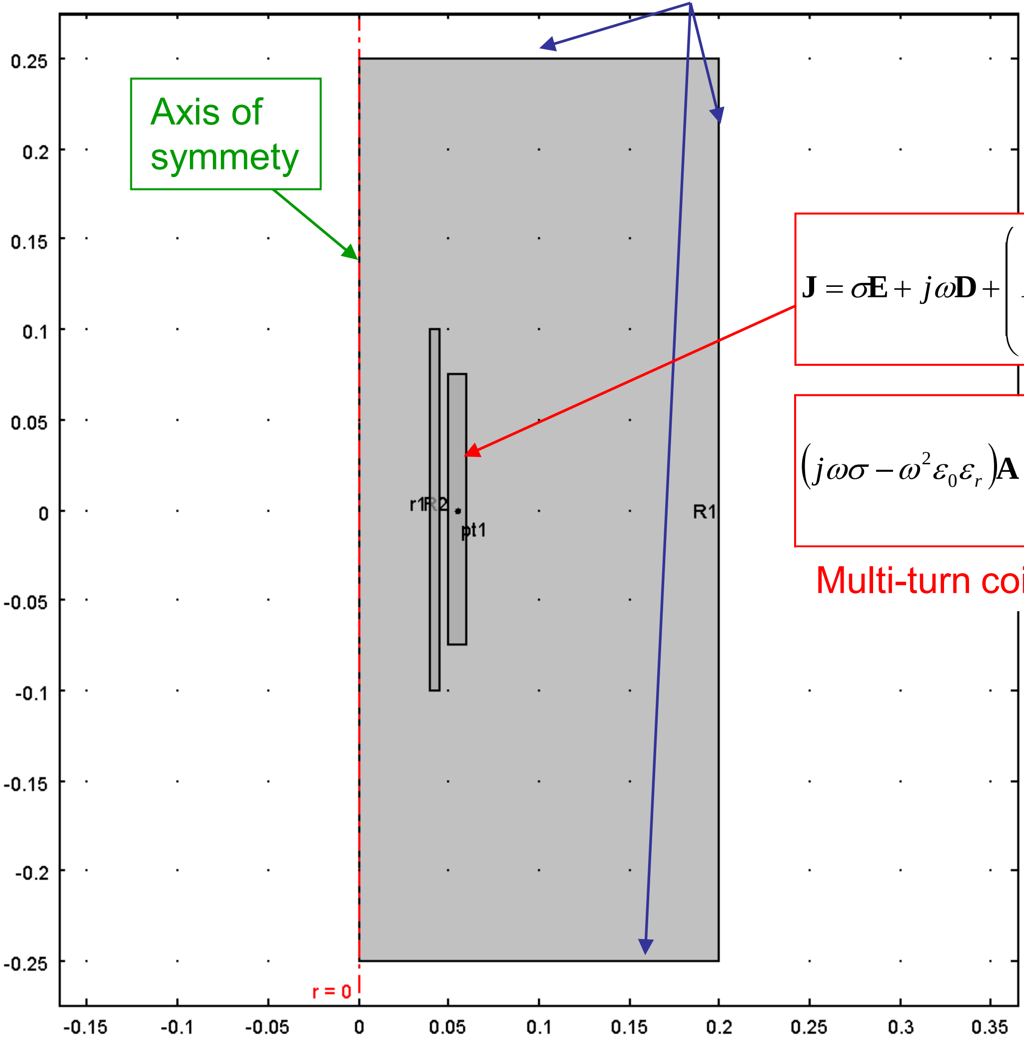
$$\mathbf{E} = -\nabla V - j\omega\mathbf{A}$$

$$\mathbf{B} = \nabla \times \mathbf{A}$$

Material equations

$$\mathbf{D} = \varepsilon_0\varepsilon_r\mathbf{E}$$

$$\mathbf{B} = \varepsilon_0\varepsilon_r\mathbf{H}$$



$$\mathbf{n} \times \mathbf{A} = 0$$
$$-\mathbf{n} \cdot \mathbf{J} = 0$$

Magnetic and electric insulation

Axis of symmety

$$\mathbf{J} = \sigma\mathbf{E} + j\omega\mathbf{D} + \begin{pmatrix} 0 \\ I_{tot}/A_{coil} \\ 0 \end{pmatrix}$$

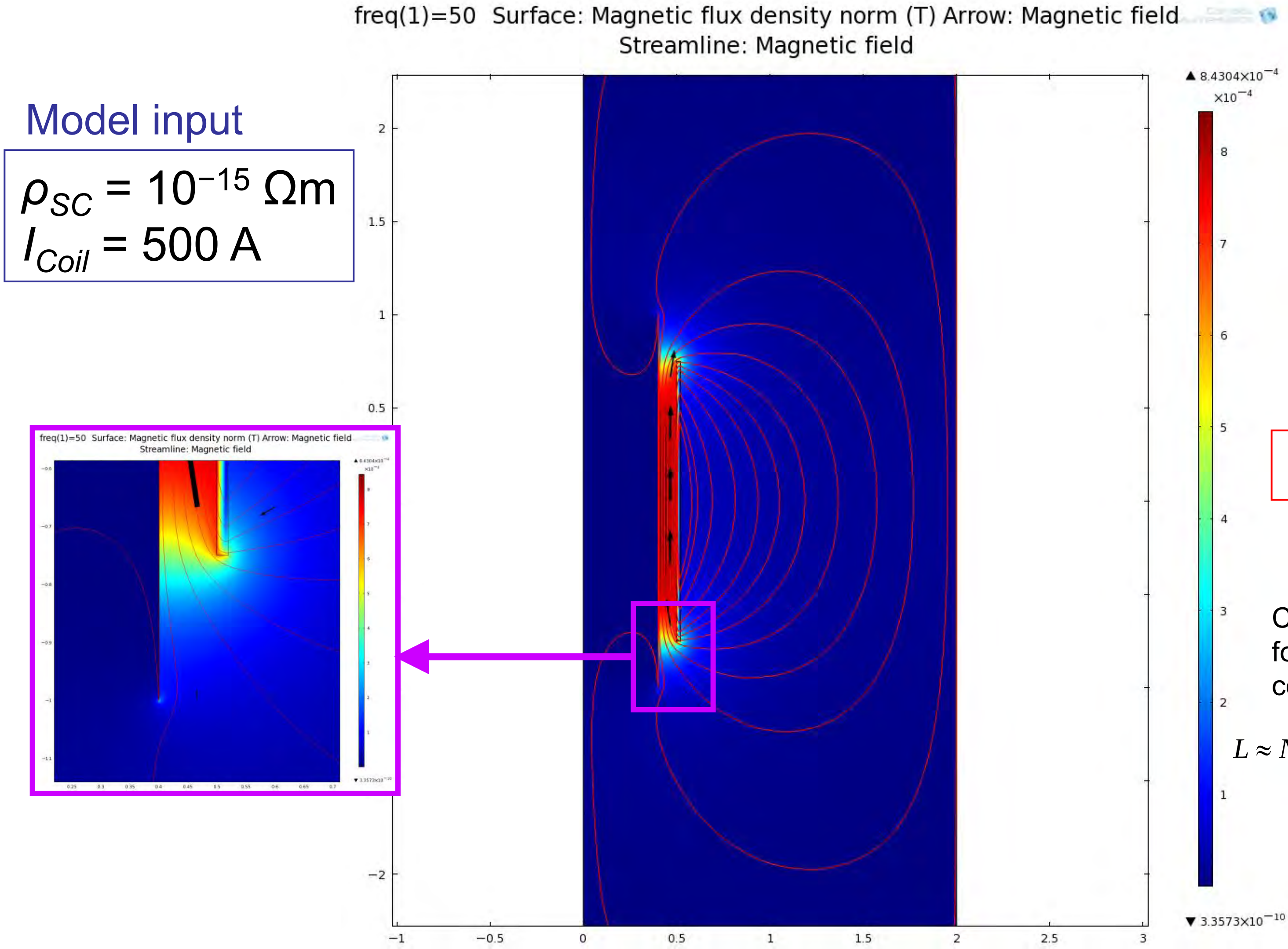
External current density

$$\left(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r\right)\mathbf{A} + \nabla \times \mathbf{H} - \sigma\mathbf{v} \times \mathbf{B} = \begin{pmatrix} 0 \\ I_{tot}/A_{coil} \\ 0 \end{pmatrix}$$

Multi-turn coil domain

All vectors are in cylindrical coordinates

Coreless Model: No-Fault Condition



Model input

$\rho_{SC} = 10^{-15}\ \Omega\text{m}$

$I_{Coil} = 500\text{ A}$

Model output

$L_{Coil} = 0.96\text{ mH}$

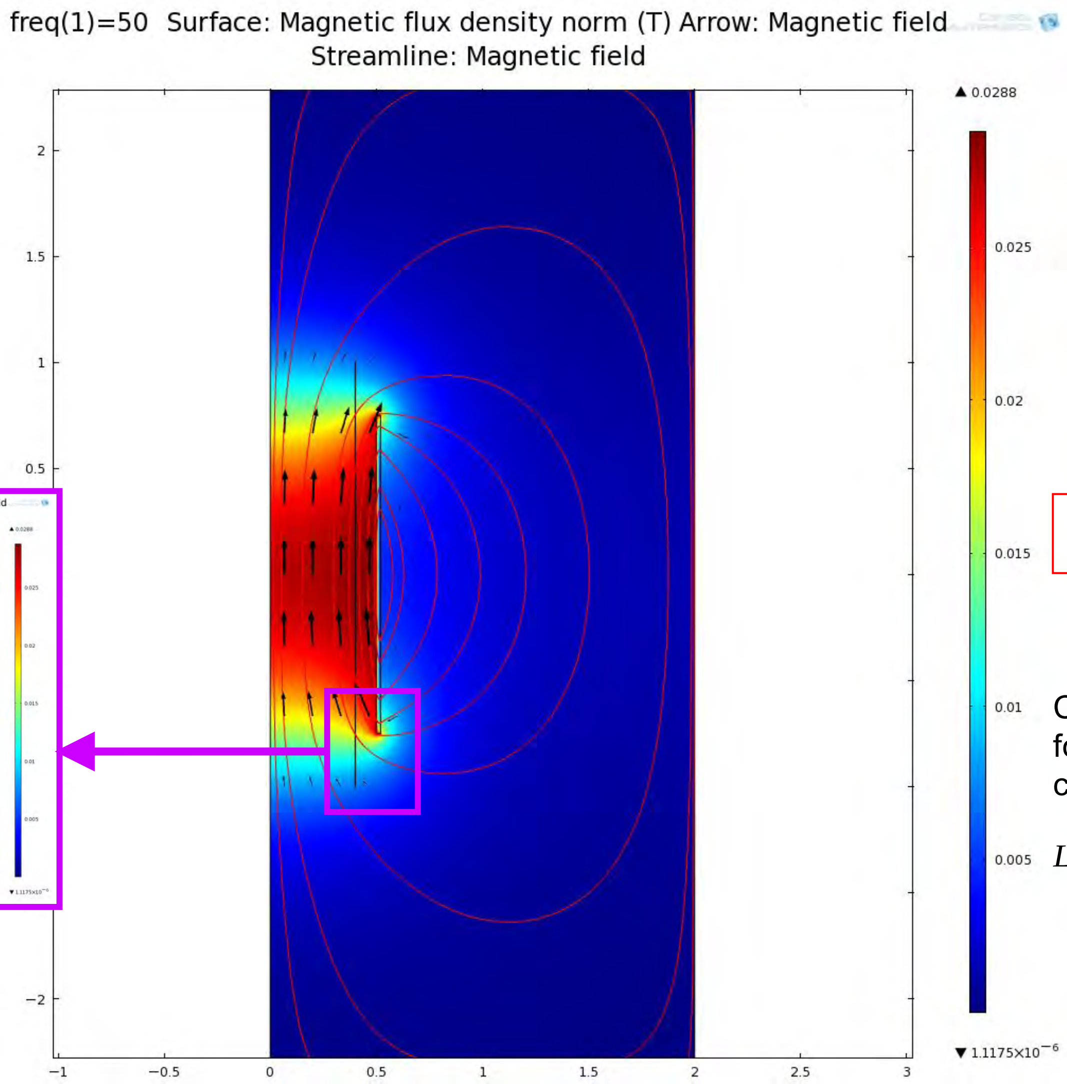
Cross-validation by adapted formula for long cylindrical coil:

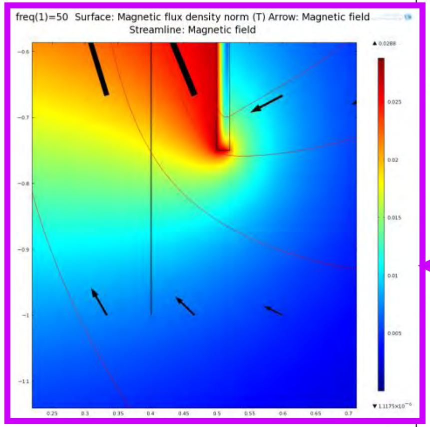
$$L \approx N^2 \mu_0 \frac{\pi \cdot \left(r_{Coil}^{\ 2} - r_{SC}^{\ 2}\right)}{h_{Coil}} = 1.00\text{ mH}$$

Coreless Model: Fault Condition

Model input

$\rho_{SC} = 1\ \Omega\text{m}$
$I_{Coil} = 20\ \text{kA}$





Model output

$L_{Coil} = 2.19\ \text{mH}$

Cross-validation by simple formula for long cylindrical coil:

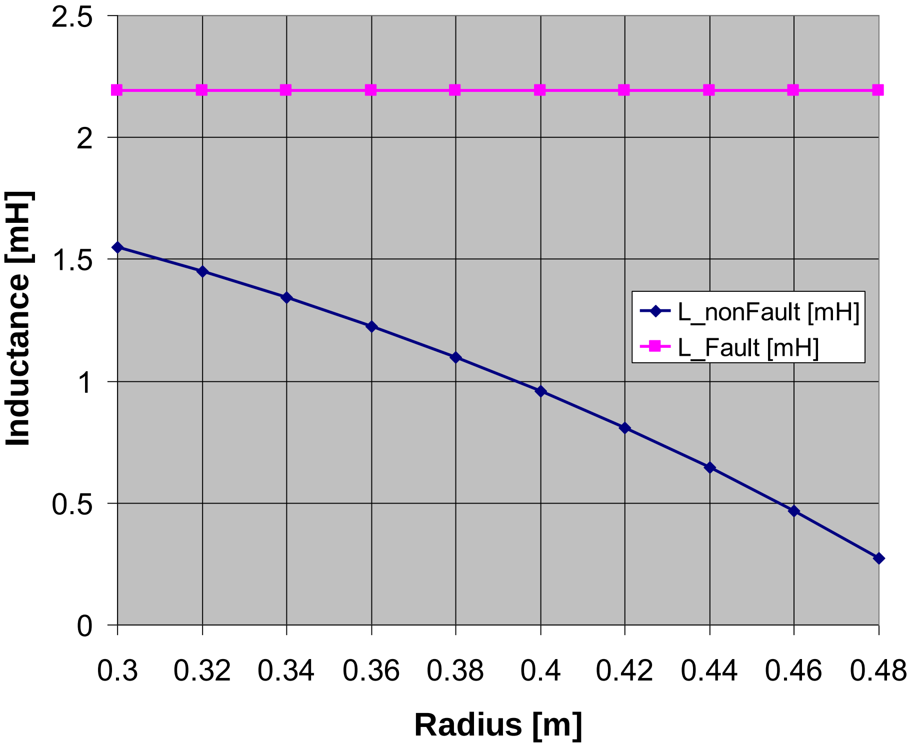
$$L \approx N^2 \mu_0 \frac{\pi \cdot r_{Coil}^2}{h_{Coil}} = 2.78\,\text{mH}$$

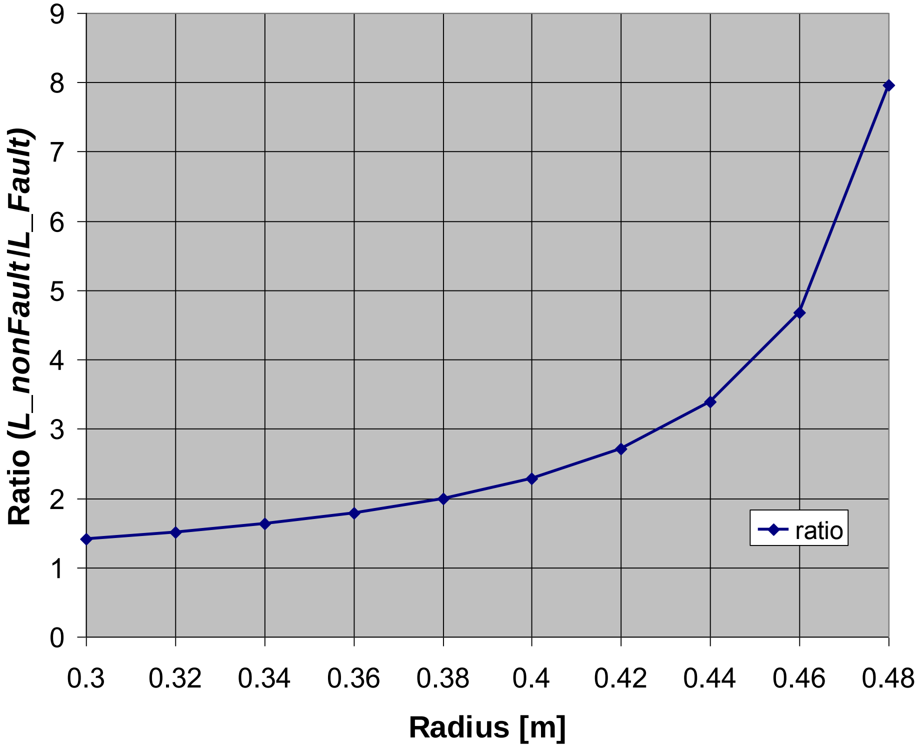
Coreless Model: Inductance Ratio wrt. Gap Distance

- Primary winding: r_{Coil} = 0.5 m (const)
- SC stack radius: r_{SC} = {0.30, 0.32, ...0.48} m

Corresponds to 2 cm gap

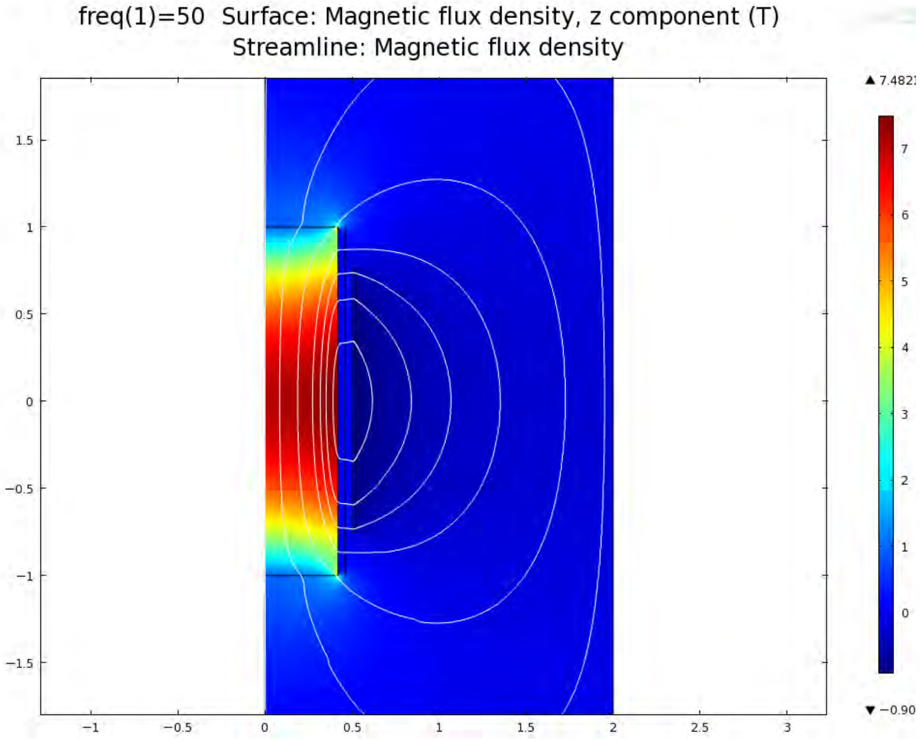
Corresponds to 20 cm gap





Model with Iron Core

Quenched state (20 kA; 1 Ωm)

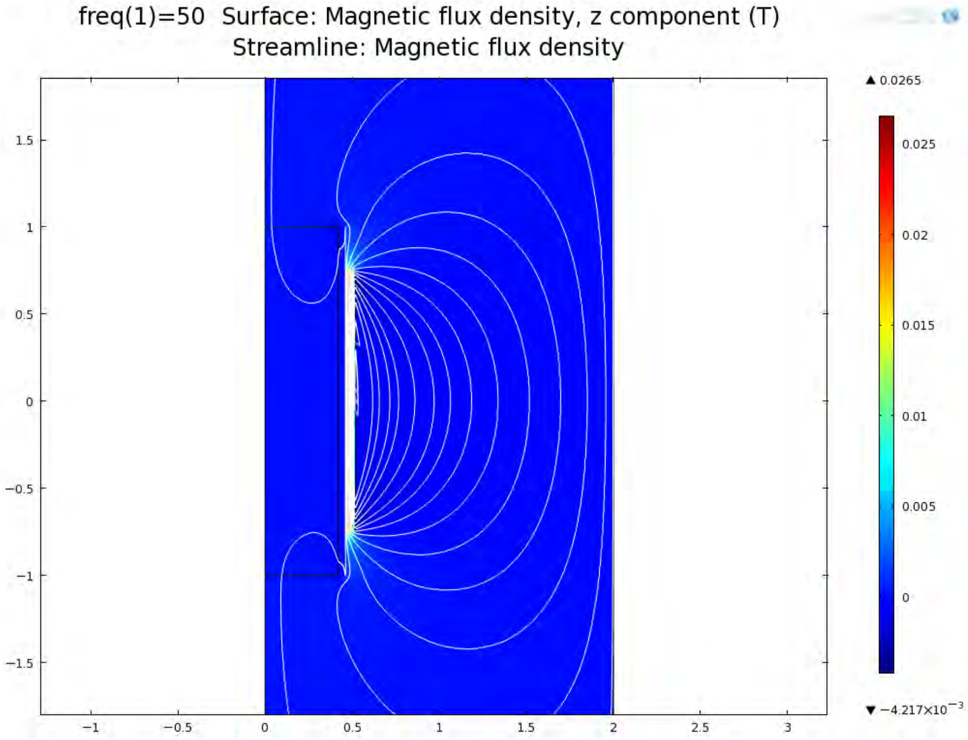

freq(1)=50 Surface: Magnetic flux density, z component (T)
Streamline: Magnetic flux density

Gap $r_{Coil} - r_{SC}$ = 40 mm

L_{Coil} = 11.4 mH

Inductance ratio: 25.2

Normal state (500 A; 10^{-15} Ωm)


freq(1)=50 Surface: Magnetic flux density, z component (T)
Streamline: Magnetic flux density

$r_{Coil} - r_{SC}$ = 40 mm

L_{Coil} = 0.452 mH