Current Return: The Path of Least IMPEDANCE

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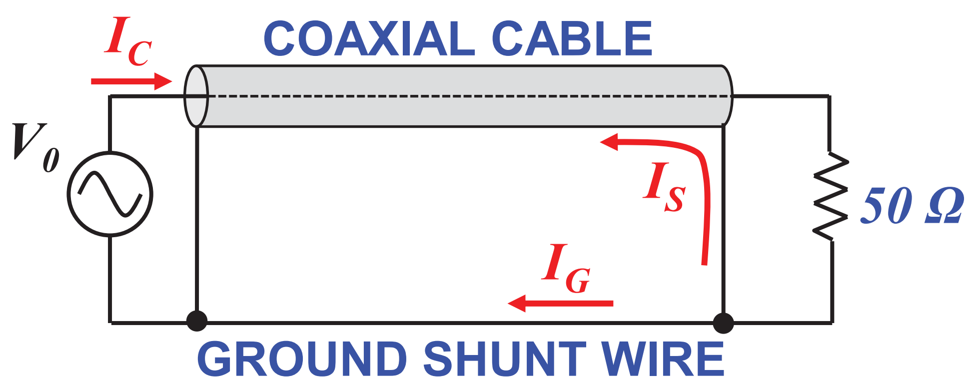
Kirchhoff's Current Law

- **All currents return to their sources following path of least IMPEDANCE**
  - NOT always path of least resistance
- **Currents do NOT return to ground**
  - They may use ground as the return path to their source, if that is the path of least impedance

BIG Rule of Thumb for EMC: "Follow the current"

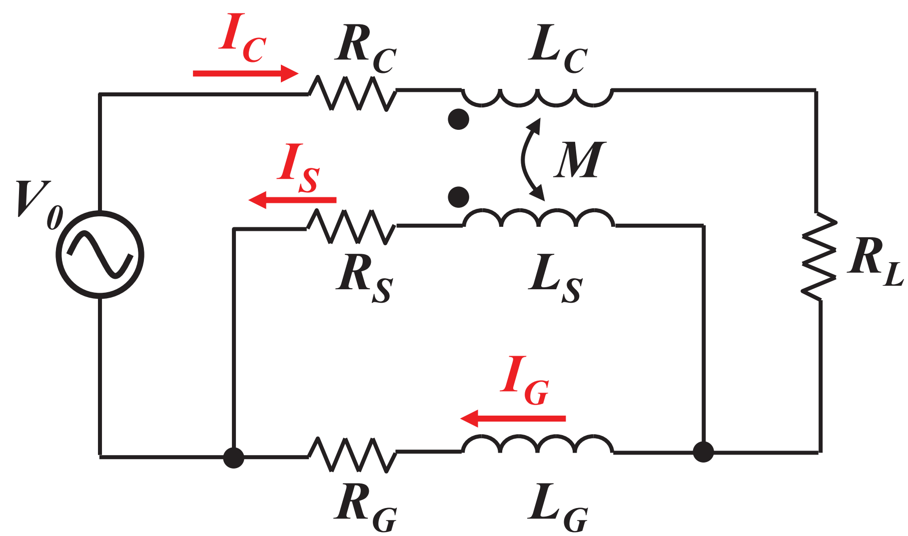
Current Return Path Test Setup

- Which path will the return current take?



I_C = *center conductor current*
I_S = *shield return current*
I_C = *ground shunt wire return current*

Equivalent Circuit



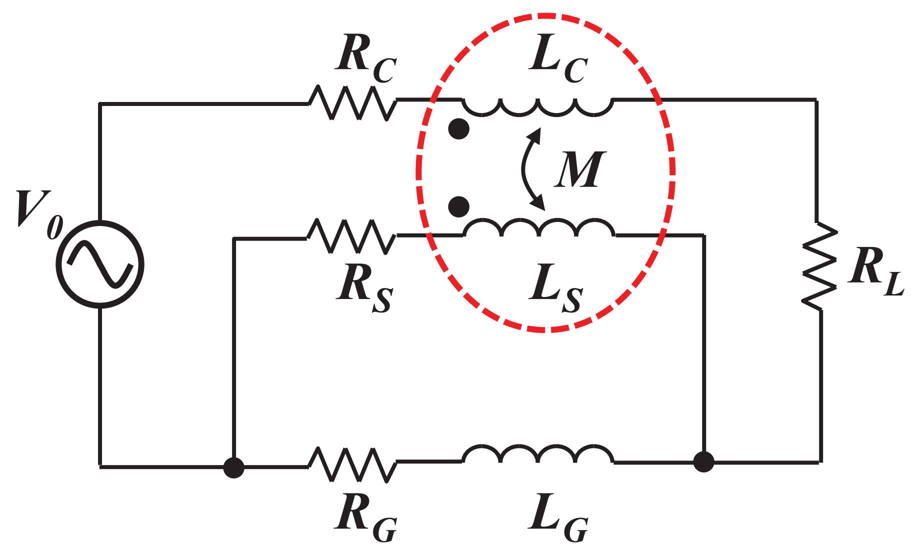
I_C = *center conductor current*

I_S = *shield return current*

I_G = *ground wire return current*

$$I_C = I_S + I_G$$

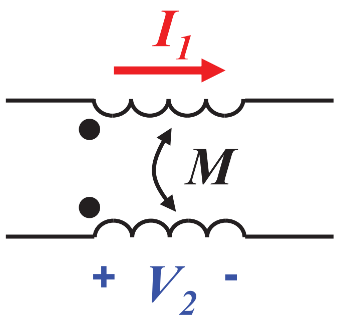
Equivalent Circuit



M = mutual inductance between center conductor and shield

$$M = L_C = L_S$$

A Word About Mutual Inductance

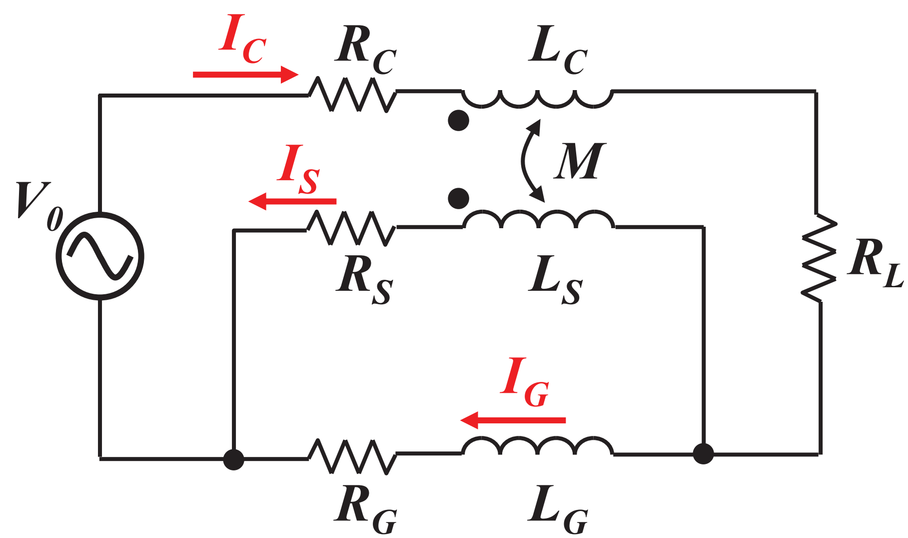


$$V_2 = M\frac{dI_1}{dt} = j\omega M I_1$$

Mutual inductance between 2 circuits means:
Current in circuit 1 induces emf (potential) in circuit 2

- *Magnitude according to equation above*
- *Sign according to dot convention above*

Circuit Analysis



$$V_0 = I_C(R_C + R_L + j\omega L_C) - I_S(j\omega M) + I_S(R_S + j\omega L_S) - I_C(j\omega M)$$

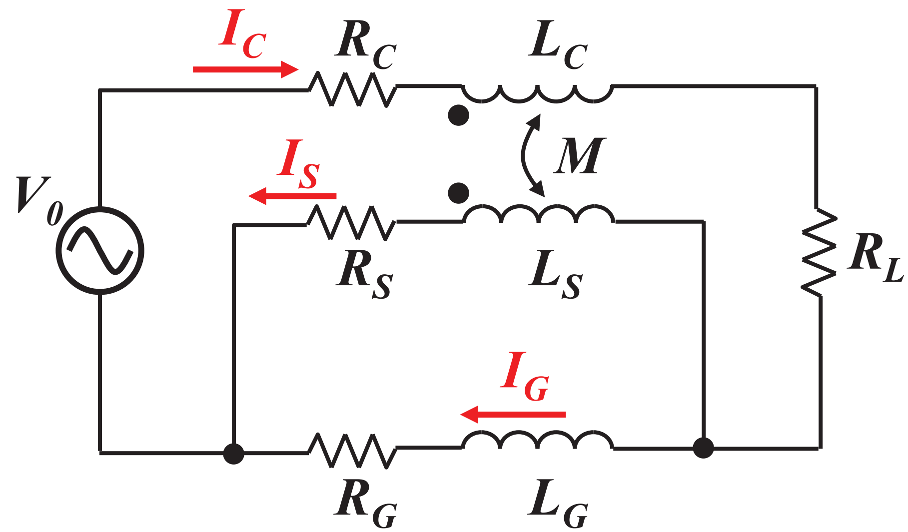
$$V_0 = I_C(R_C + R_L + j\omega L_C) - I_S(j\omega M) + I_G(R_G + j\omega L_G)$$

$$0 = I_S(R_S + j\omega L_S) - I_C(j\omega M) - I_G(R_G + j\omega L_G)$$

$$I_S(R_S + j\omega L_S) = I_C(j\omega M) + I_G(R_G + j\omega L_G)$$

$I_C = I_S + I_G$ $\quad$ $M = L_S$

Circuit Analysis (cont.)



Solving for I_S/I_C:

$$I_S(R_S + j\omega L_S) = I_C(j\omega L_S) + (I_C - I_S)(R_G + j\omega L_G)$$

$$I_S[(R_S + R_G) + j\omega(L_S + L_G)] = I_C[(R_G + j\omega(L_S + L_G))]$$

$$\frac{I_S}{I_C} = \frac{[R_G + j\omega(L_S + L_G)]}{[(R_S + R_G) + j\omega(L_S + L_G)]}$$

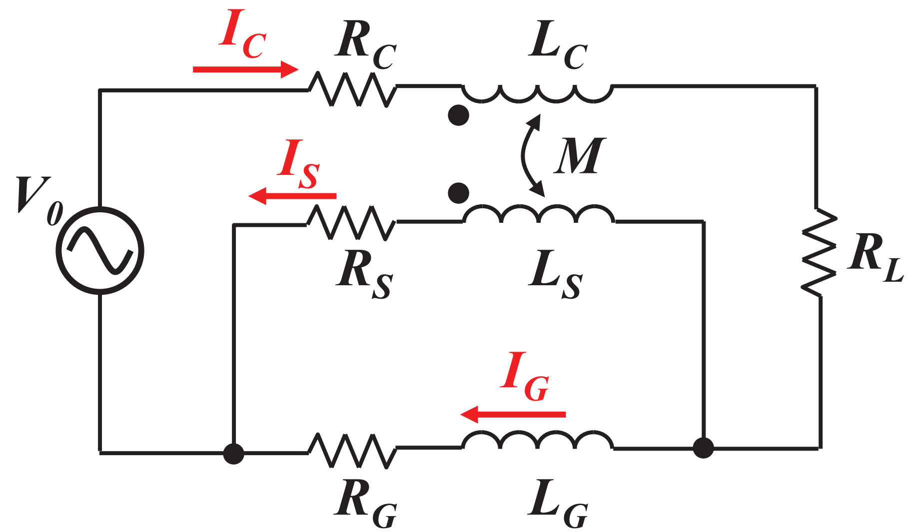
Solving for I_G/I_C:

$$(I_C - I_G)(R_S + j\omega L_S) = I_C(j\omega L_S) + I_G(R_G + j\omega L_G)$$

$$I_C R_S = I_G[(R_S + R_G) + j\omega(L_S + L_G)]$$

$$\frac{I_G}{I_C} = \frac{R_S}{[(R_S + R_G) + j\omega(L_S + L_G)]}$$

Circuit Analysis (cont.)



Shield return current:

$$\frac{I_S}{I_C} = \frac{\left[R_G + j\omega(L_S + L_G)\right]}{\left[(R_S + R_G) + j\omega(L_S + L_G)\right]}$$

Ground wire return current:

$$\frac{I_G}{I_C} = \frac{R_S}{\left[(R_S + R_G) + j\omega(L_S + L_G)\right]}$$

At low frequencies:

$$\frac{I_S}{I_C} \approx \frac{R_G}{R_S + R_G}$$

At low frequencies:

$$\frac{I_G}{I_C} \approx \frac{R_S}{R_S + R_G}$$

Resistive divider

At high frequencies:

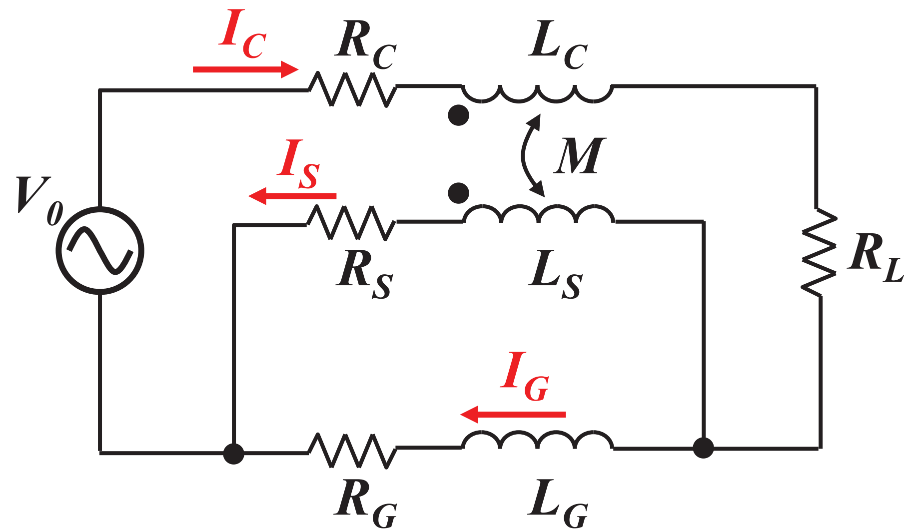
$$\frac{I_S}{I_C} \approx \frac{j\omega(L_S + L_G)}{j\omega(L_S + L_G)} \approx 1$$

At high frequencies:

$$\frac{I_G}{I_C} \approx \frac{R_S}{j\omega(L_S + L_G)} \approx 0$$

Virtually all current returns on shield

Circuit Analysis (cont.)



Ratio of shield current to ground wire current:

$$\frac{I_S}{I_G} = \frac{\left[R_G + j\omega\left(L_S + L_G\right)\right]}{R_S}$$

$I_S = I_G$ when:

$$\sqrt{R_G{}^2 + \left[2\pi f_c\left(L_S + L_G\right)\right]^2} = R_S$$

$$f_c = \frac{\sqrt{R_S{}^2 - R_G{}^2}}{2\pi\left(L_S + L_G\right)}$$

Test #1 Setup Parameters

Shield return path:

R_S *(measured) = 96 mΩ*

L_S / l *= 0.25 μH/m (from RG-58 coaxial cable datasheet)*

l *= 4.8 m*

L_S *= 1.2 μH*

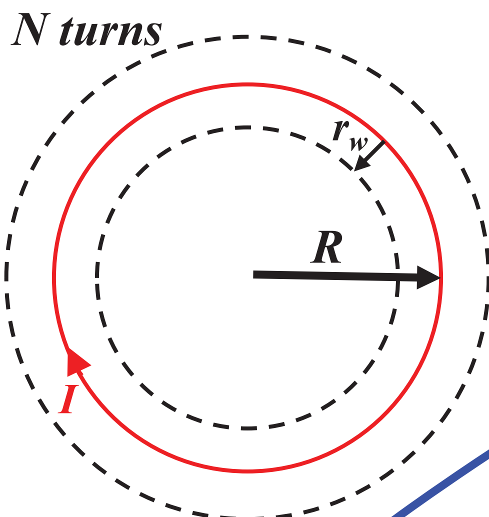
Ground wire return path:

R_G *(measured) = 15 mΩ*

L_G *= 24.4 μH (next slides)*

Inductance of Circular Loop

- From Missouri University of Science and Technology inductance calculator
  - http://emclab.mst.edu/inductance/



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

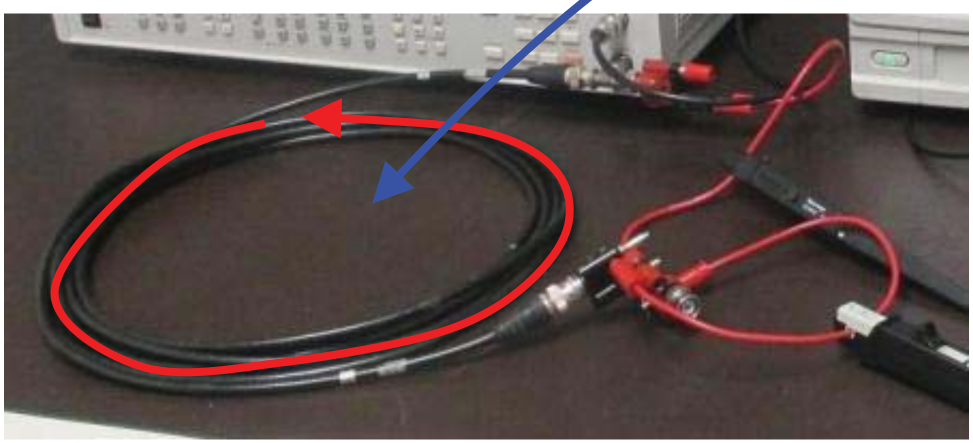
N = ~5.5

$\mu_r = 1$

$\mu_0 = 4\pi \times 10^{-7}$ *H/m*

R = 6 inches = 15 cm

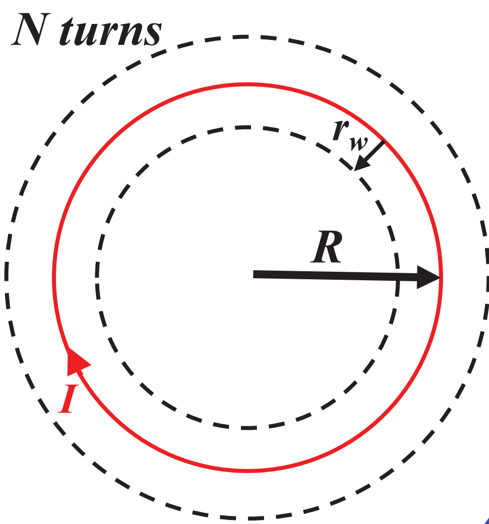
r_w *= 0.25 cm (shield radius)*



$L_{coil} = \sim 23.8\ \mu H$

Inductance of Circular Loop (cont.)

- Coiled cable in series with loop completing connections to signal generator:



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

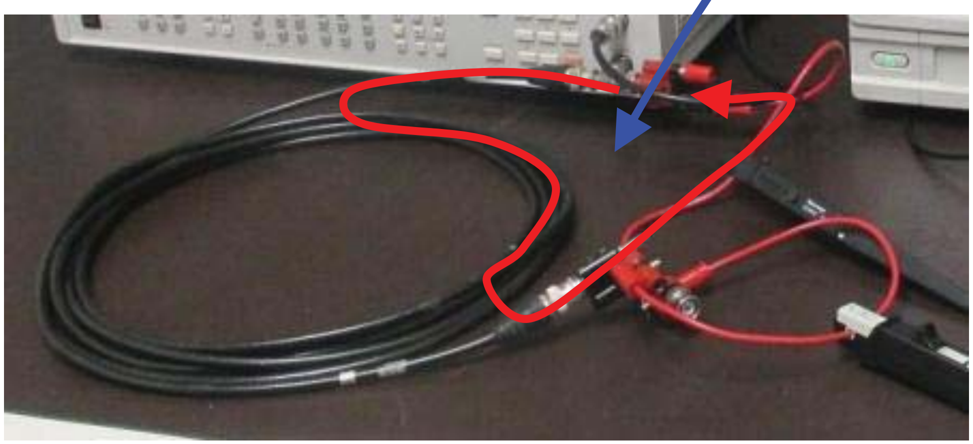
$N = 1$

$\mu_r = 1$

$\mu_0 = 4\pi \times 10^{-7}$ H/m

$R_{eff} = 12$ cm

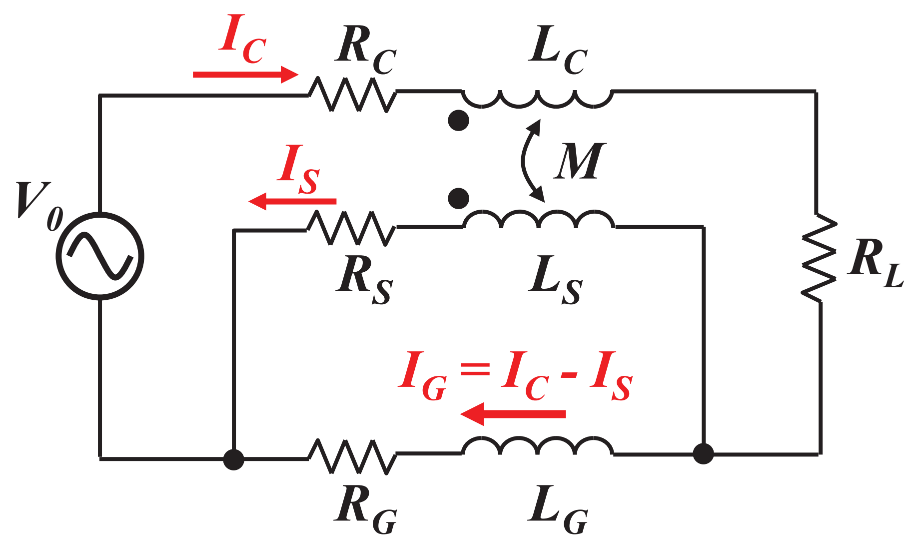
$r_w = 0.25$ cm (shield radius)



$L_{gen} = \sim 0.6\ \mu H$

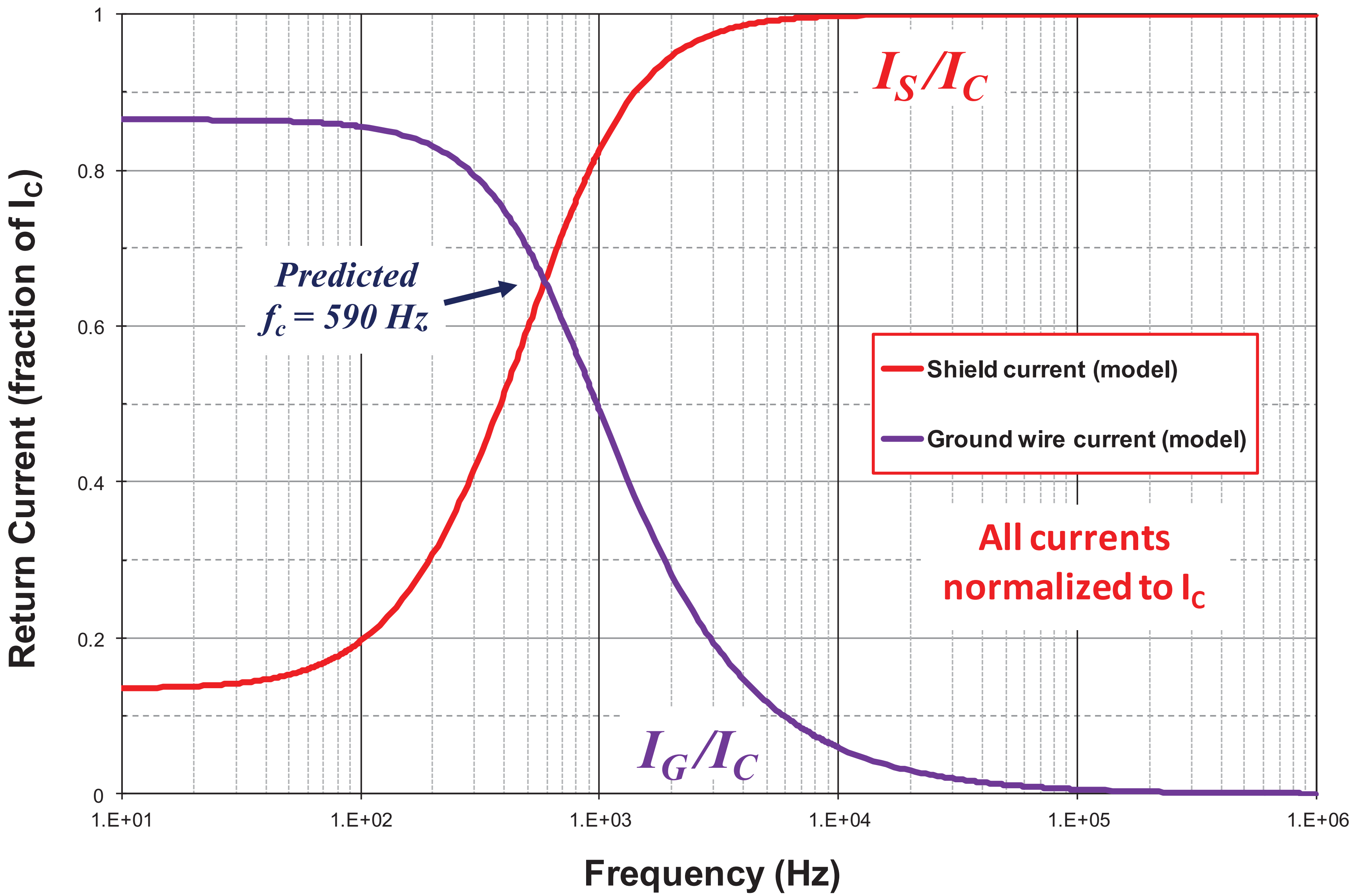
$L_G = L_{coil} + L_{gen} = 24.4\ \mu H$

Why Do We Use the Shield Radius?

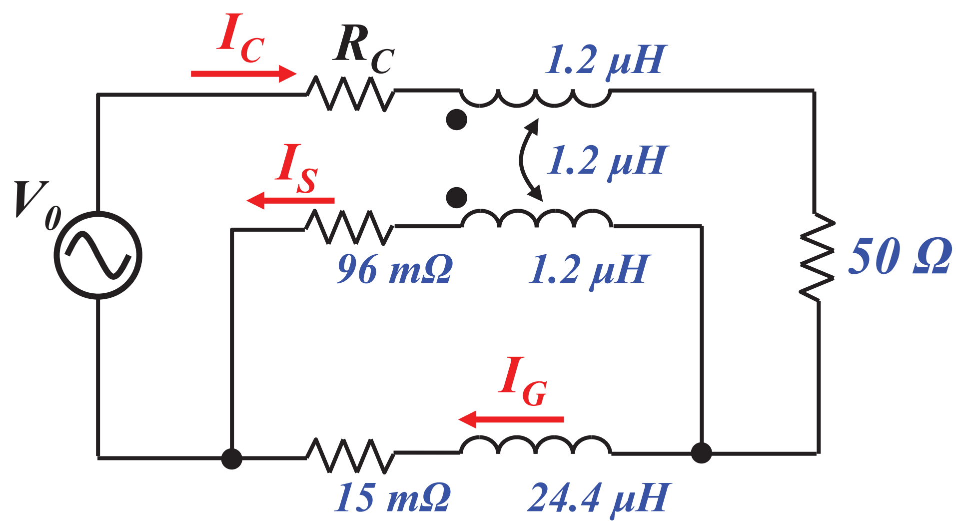


We use the shield radius because the current in the large loop is the net current from the coax, i.e. that gets past the shield

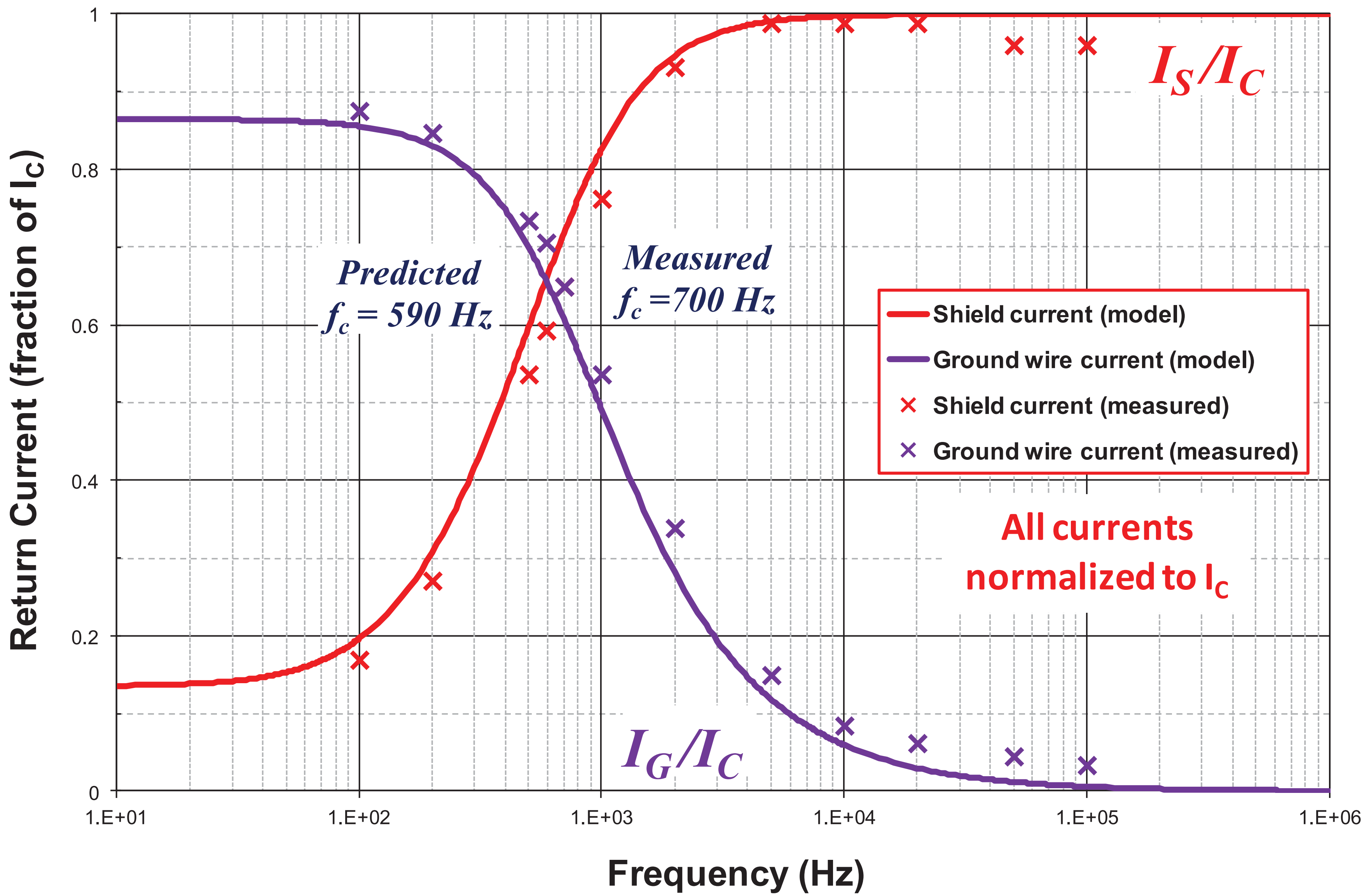
Return Currents – Model for Test #1



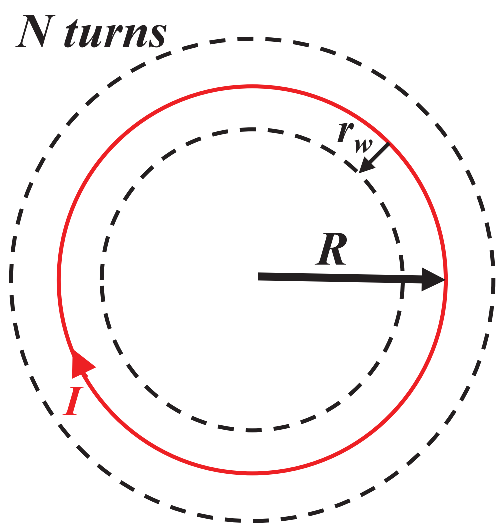
Updated Equivalent Circuit



Test #1: Measured vs. Model



Test #2: 3.5-Turn Loop



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

$N = \sim 3.5$

$\mu_r = 1$

$\mu_0 = 4\pi \times 10^{-7}$ H/m

R = 9 inches = 23 cm

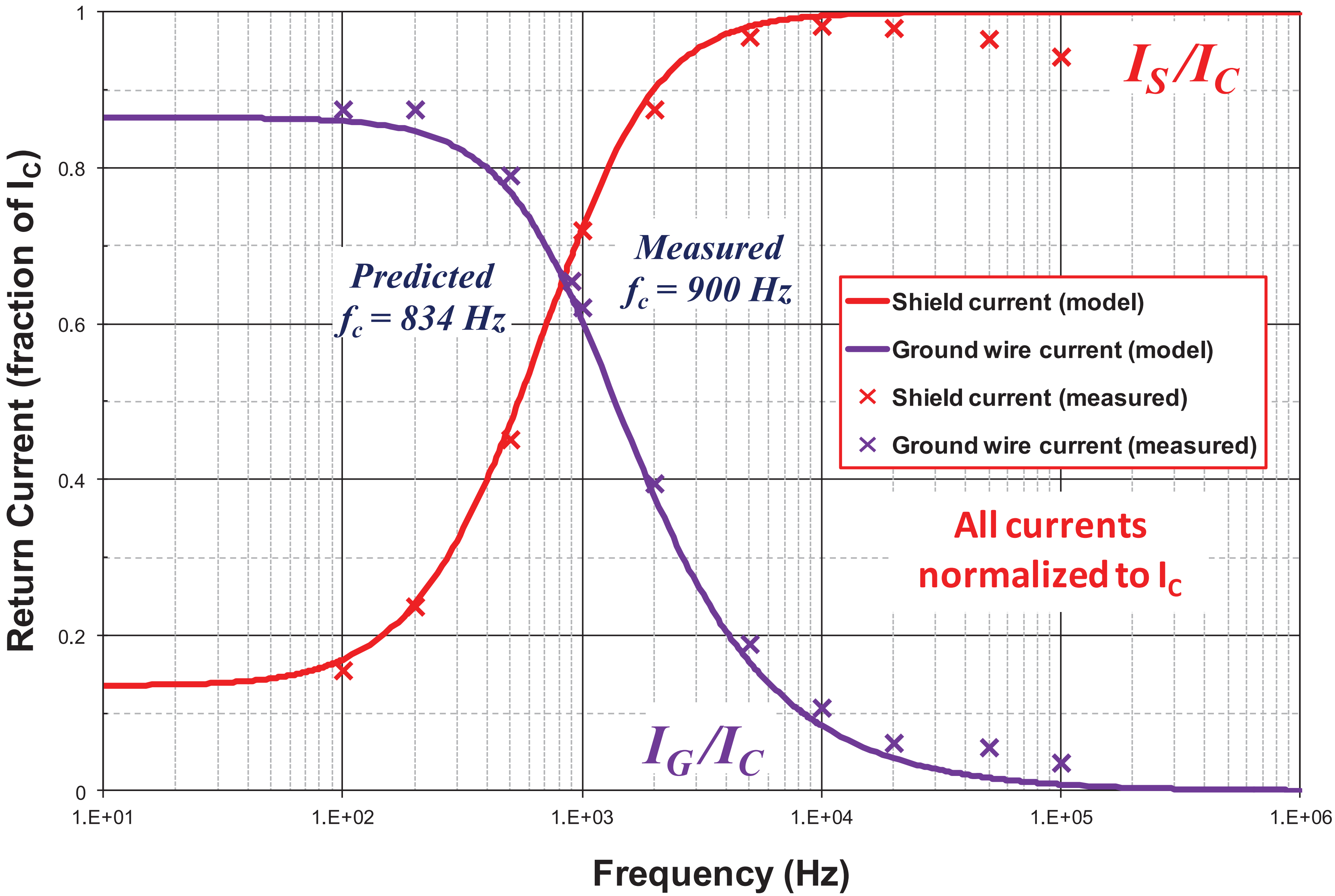
$r_w = 0.25$ cm (shield radius)

$L_{coil} = \sim 16.3\ \mu H$

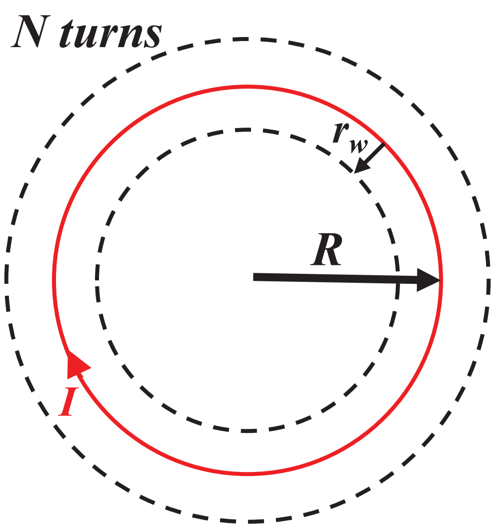
$L_{gen} = \sim 0.6\ \mu H$ (same as before)

$$L_G = L_{coil} + L_{gen} = 16.9\ \mu H$$

Test #2: Measured vs. Model



Test #3: 1-Turn Loop



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

$N = 1$

$\mu_r = 1$

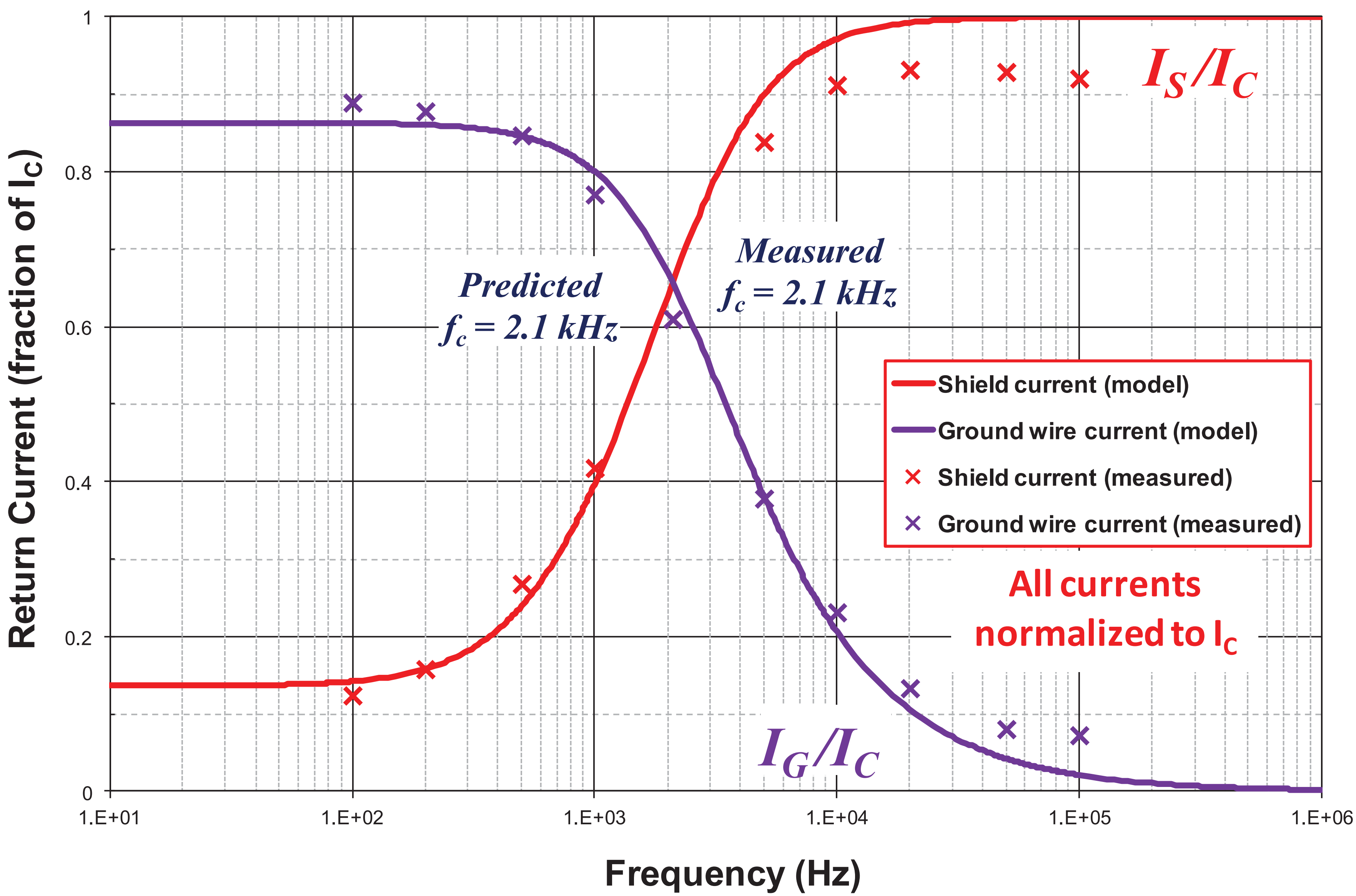
$\mu_0 = 4\pi \times 10^{-7}$ H/m

Reff = 5 m / 2π = ~80 cm

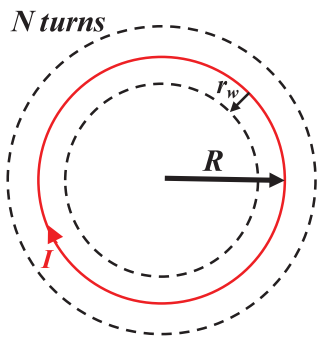
r_w = 0.25 cm (shield radius)

$$L_G = 5.9\ \mu H$$

Test #3: Measured vs. Model



Why Doesn't the Ground Wire Current Go To Zero?



$$L_{loop} \approx N^2 \mu_r \mu_0 R \left(\ln \frac{8R}{r_w} - 2 \right)$$

$N = 1$

$\mu_r = 1$

$\mu_0 = 4\pi \times 10^{-7}$ H/m

$R = \sim 5$ cm

$r_w = 0.05$ cm

$L_G = \sim 300$ nH

THE INDUCTANCE OF THIS LOOP LIMITS THE SHIELD CURRENT AT HIGHER FREQUENCIES

Observations/Summary

- **Measured data shows good agreement with model**
  - At low frequencies, current forms resistive divider with all available paths
  - At high frequencies, impedance is dominated by inductance (loop area)
- **High inductance (large loop areas) increases likelihood of ground bounce and magnetic coupling (crosstalk) between circuits**
- **Practical implications for circuit and system design:**
  - Provide deliberate low inductance (small loop area) return paths for high frequency currents
  - Cabling: twisted pairs, coax
  - PC board: return (-) trace immediately adjacent to send (+) trace
  - Do NOT route traces over splits in ground plane
  - Video type signals
    - Video signals tend to be “bursty”; mix of high and low frequency content
    - High frequency content will return on the shield; low frequency content will not
    - Shield isn't a shield at low frequencies, and thus the low frequency video signal mixes in with ground noise which pollutes the video signal

Questions/Comments

- **Contact:**
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