Designing with EMC in Mind

How to Apply Shielded Cables to Solve More Problems than You Create

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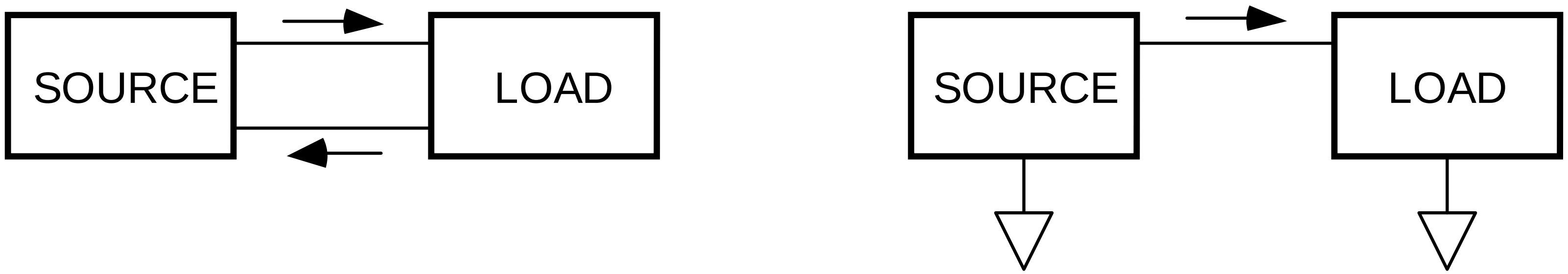
The Job

Designing for electromagnetic compatibility (EMC) is primarily the orchestration of return current flow.

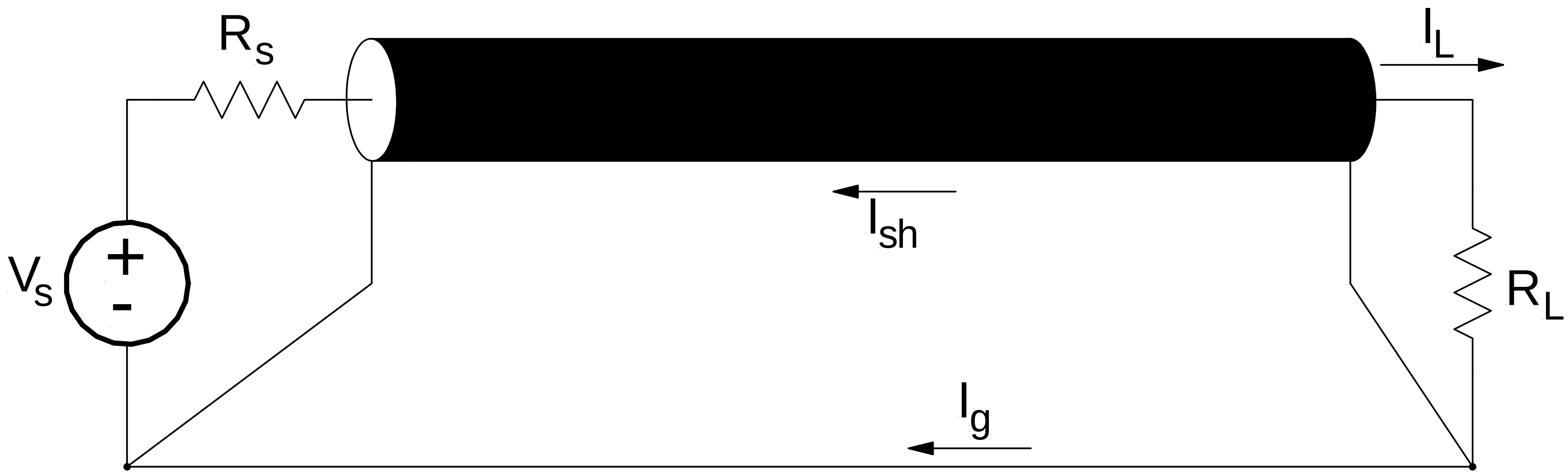


Topics

- Return Current Behavior
- Cable shields
- Cable grounding
- Ground-loop and common-mode coupling
- Common-mode emissions from cables
- Transfer impedance
- Bringing cables through shield walls

The Key

The successful application of cables depends on a knowledge of the return current flow.



The Rules

- At low frequencies, the return current apportions itself among paths according to the resistances involved.

- At high frequencies, the return current apportions itself among paths according to the inductances involved.

The Good News

- The return current apportions itself in such a way that it incurs the smallest voltage drop possible on its way back to the source.
- That is, the return current seeks the minimum impedance.

$$\vec{E} = -\nabla V \qquad\qquad P = \tfrac{1}{2}\Re e\left\{VI^*\right\}$$

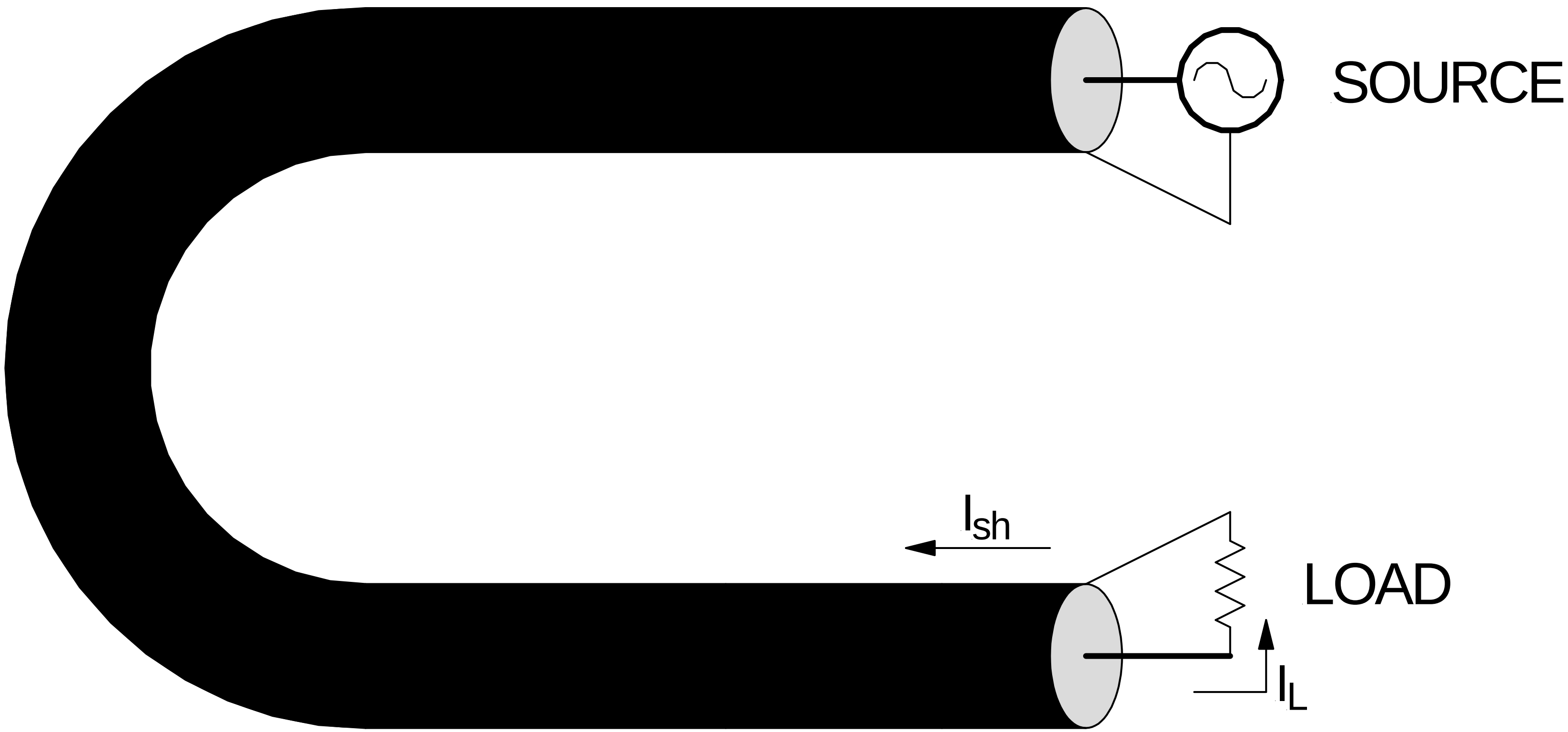
In Other Words

- At low frequencies, current apportions itself so that the net resistance seen in the aggregate of the paths it travels on the way back to the source is the smallest available.

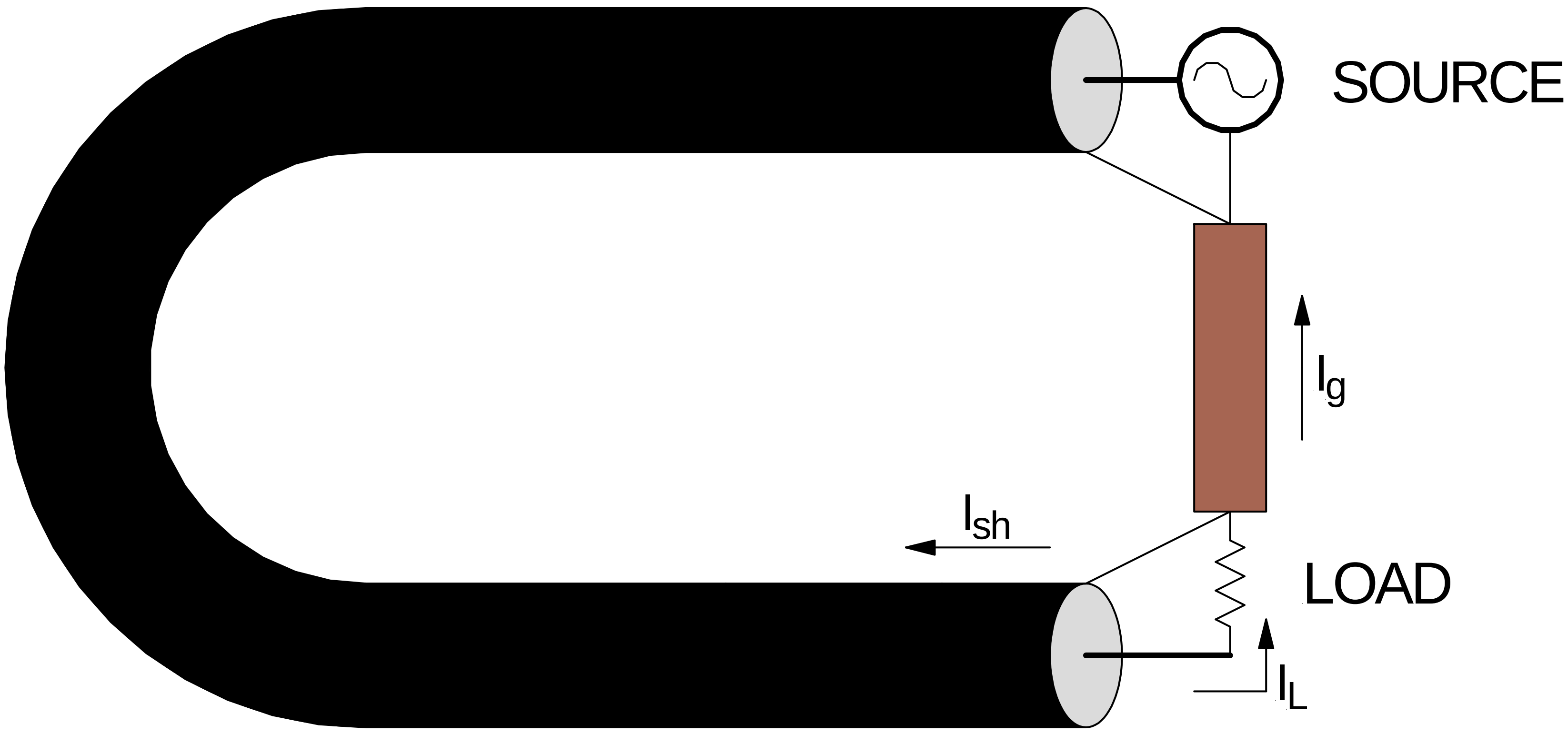
- At high frequencies, current apportions itself so that the net inductance seen in the aggregate of the paths it travels on the way back to the source is the smallest available.

$$\psi = LI$$

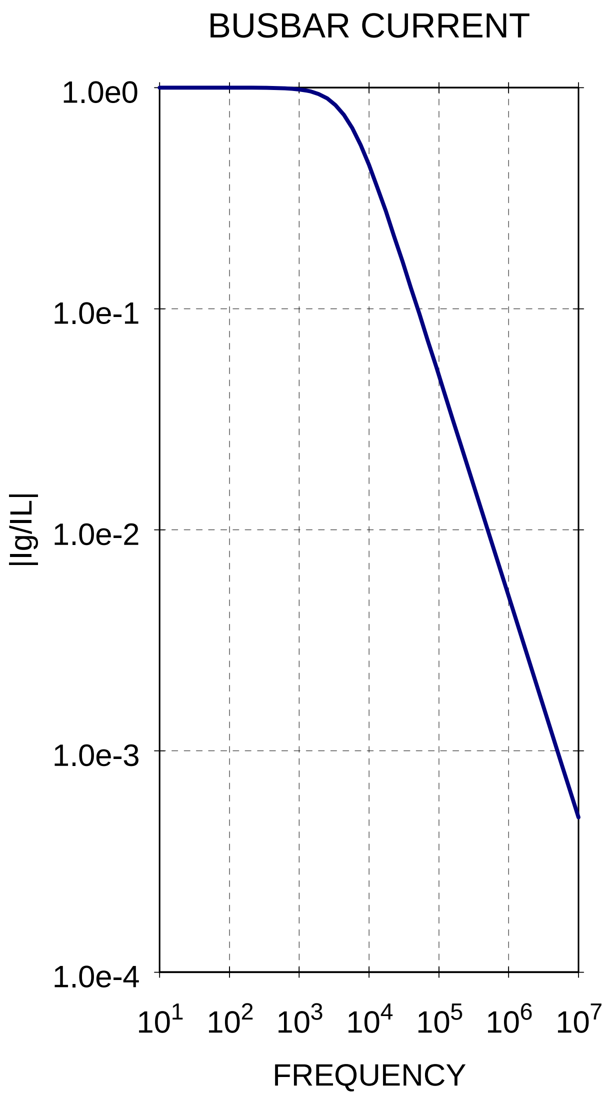
Cable - One Return Path

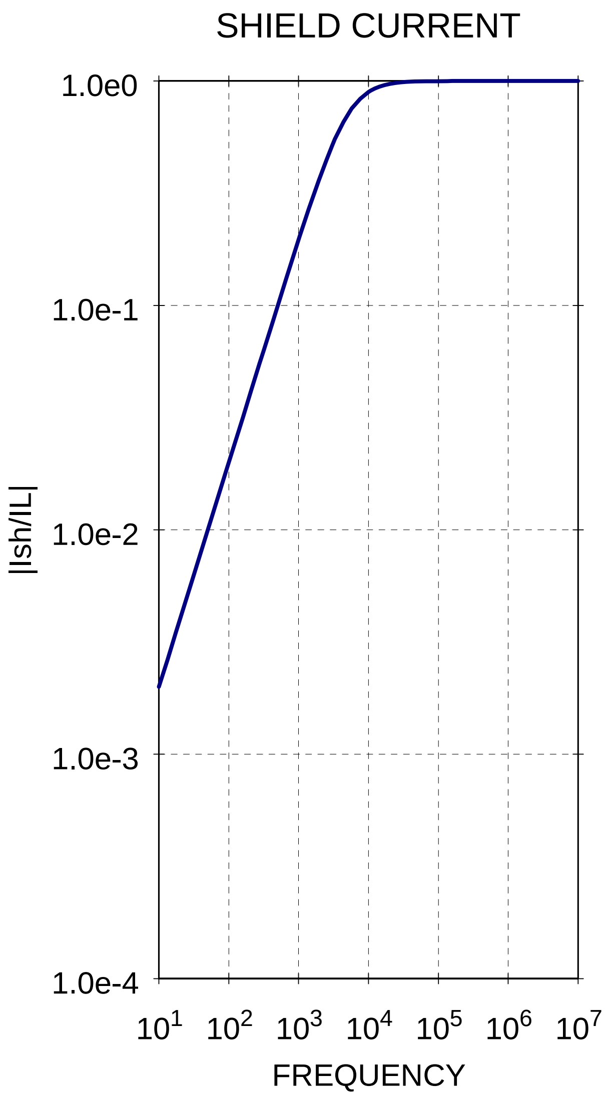


Cable - Two Return Paths

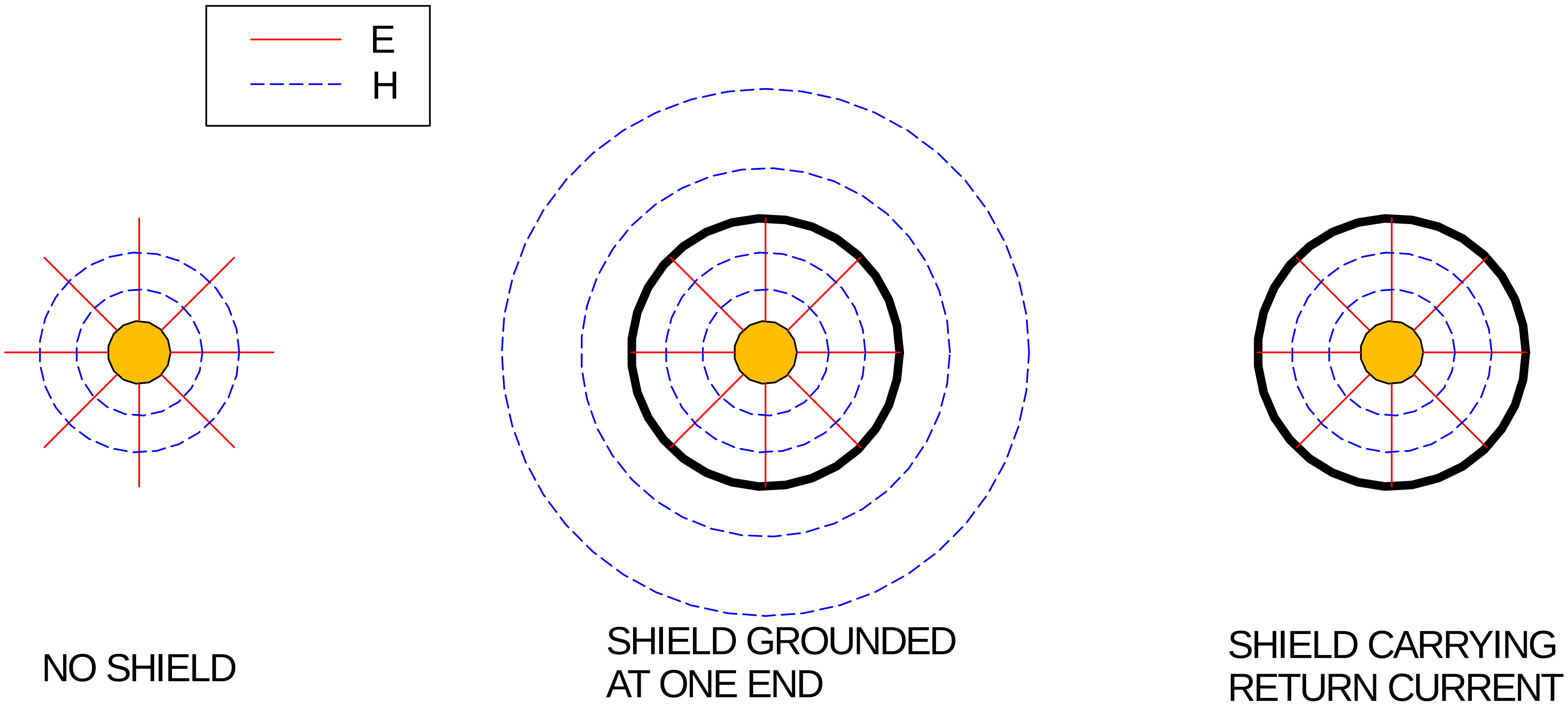


Current Distribution

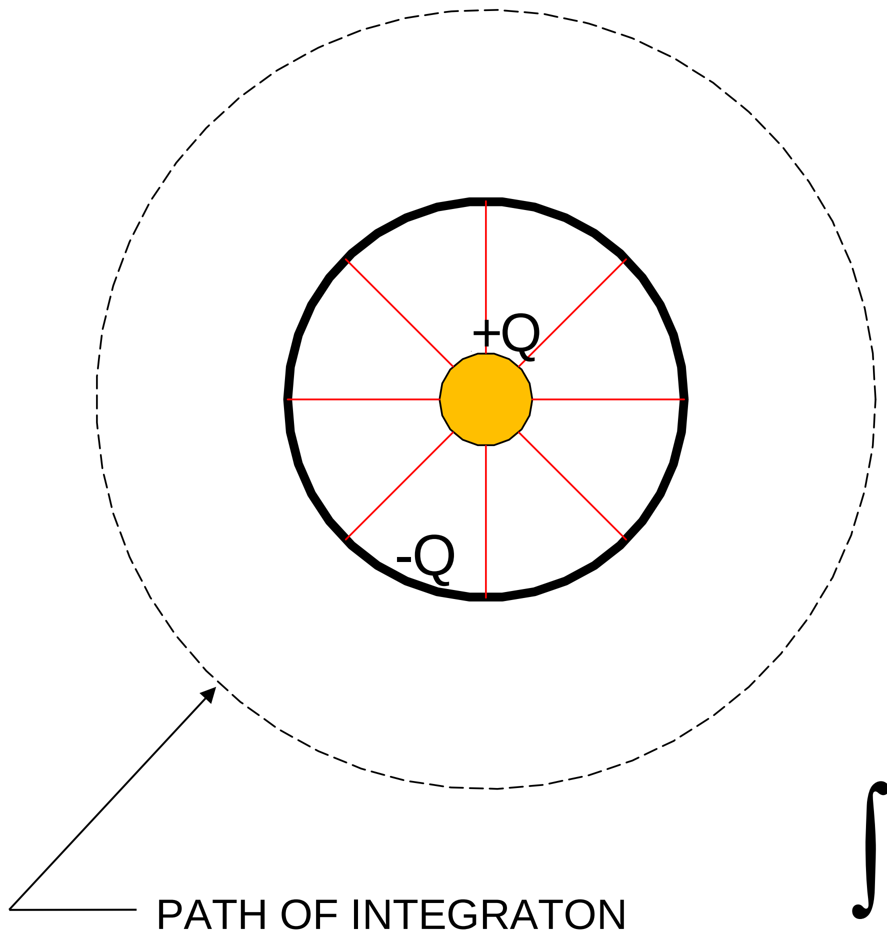




Shielded Cable

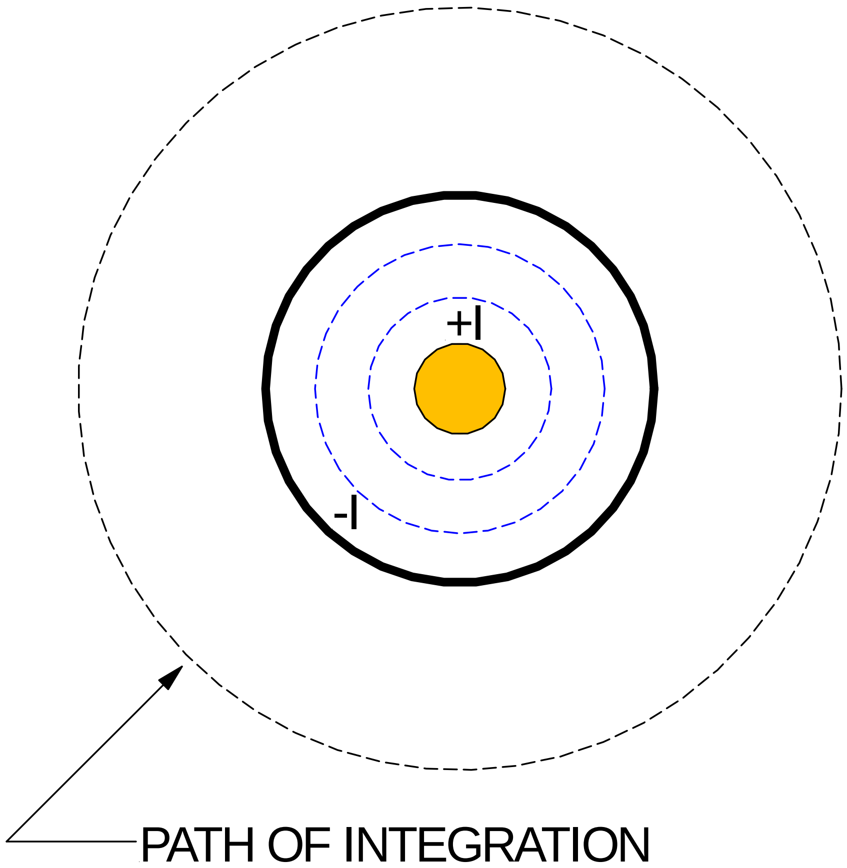


Gauss's Law



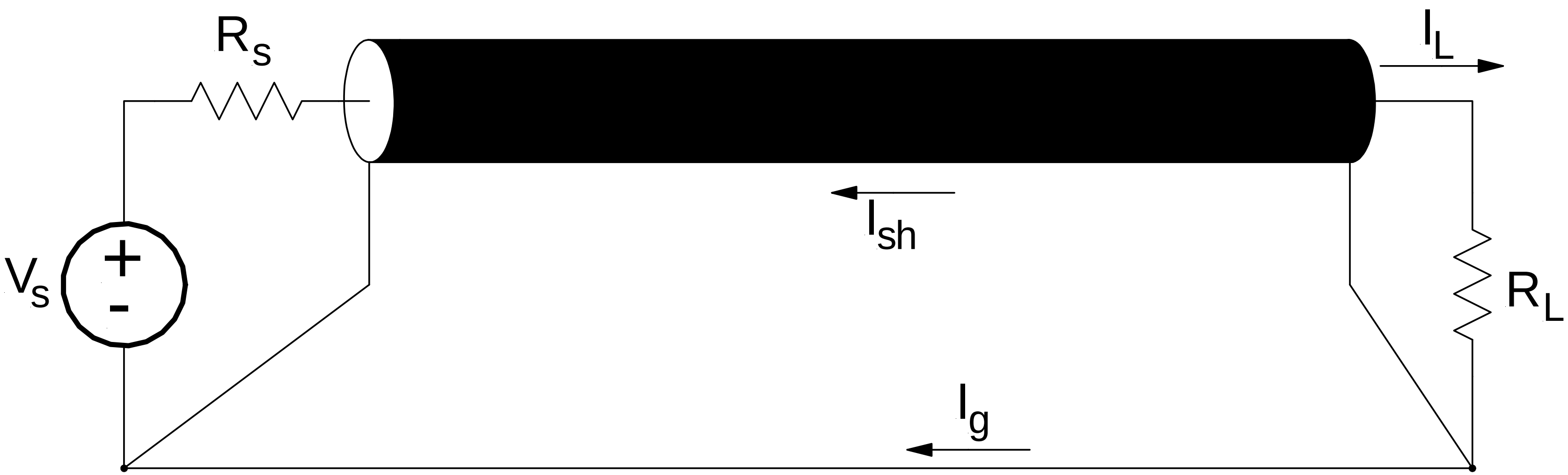
$$\iint \varepsilon\, \vec{E} \cdot d\vec{S} = Q_{enclosed}$$

Ampere's Law



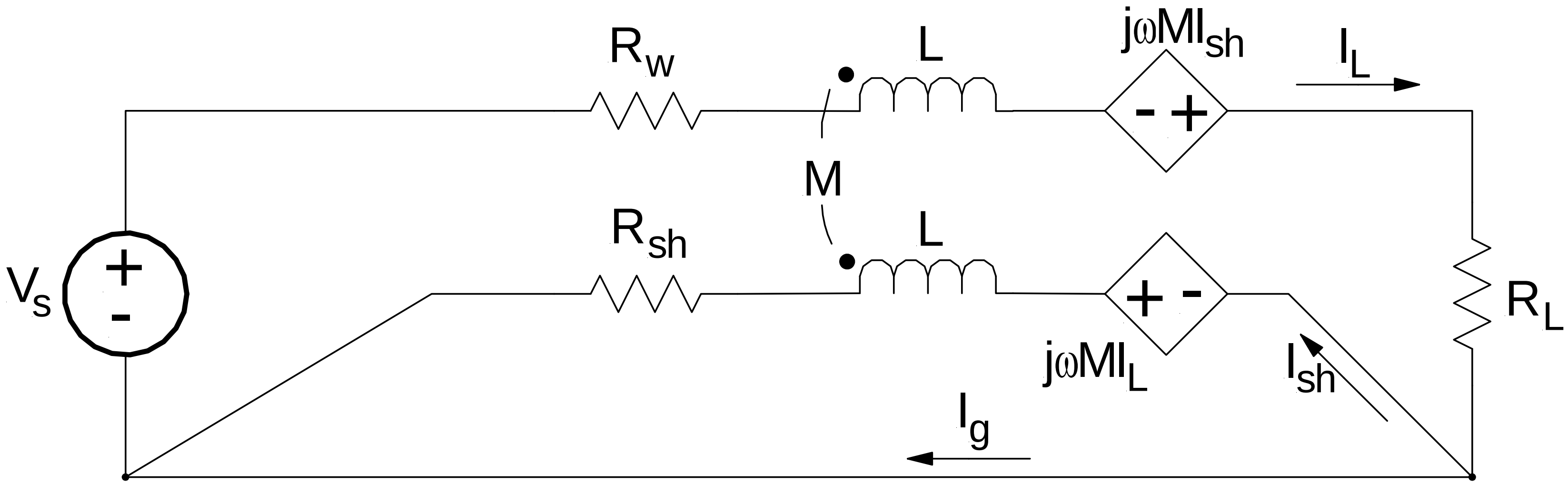
$$\oint \vec{H} \cdot d\vec{\ell} = I_{enclosed}$$

Return Current Flow



WHERE DOES THE RETURN CURRENT FLOW?

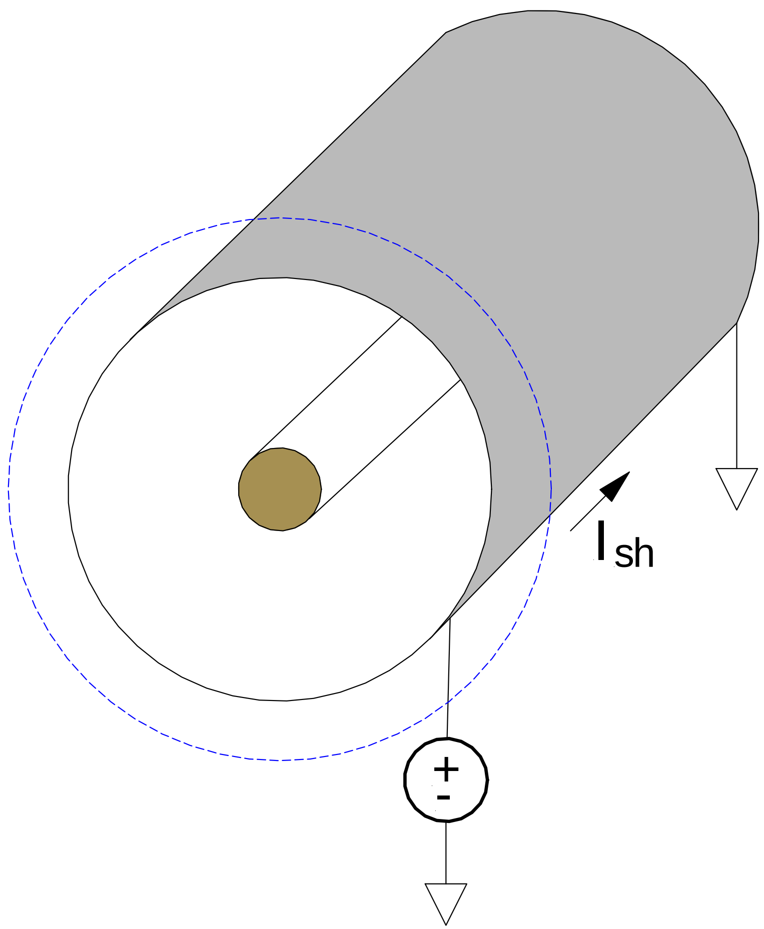
Analysis of Shield Cutoff



$$I_{sh} R_{sh} + j\omega L\, I_{sh} - j\omega M I_L = 0$$

$$\frac{I_{sh}}{I_L} = \frac{j\omega M}{R_{sh} + j\omega L}$$

Magnetic Coupling



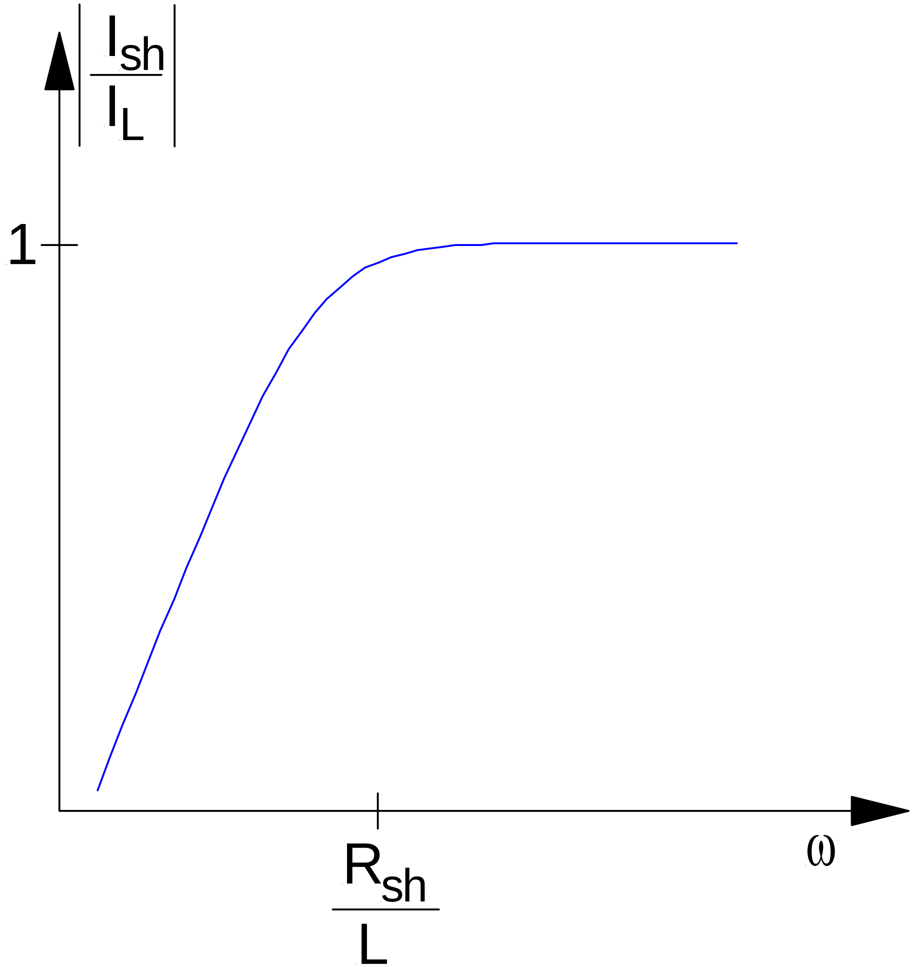
M = L

Shield Current

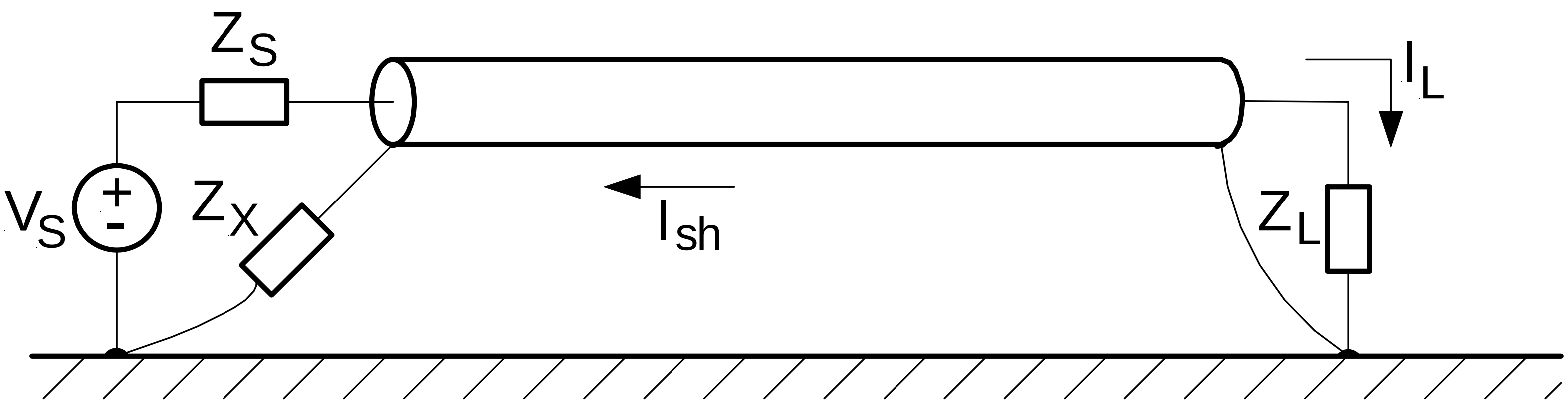
$$\frac{I_{sh}}{I_L} = \frac{j\omega L}{R_{sh} + j\omega L}$$

SHIELD CUTOFF FREQUENCY

$$f_c = \frac{R_{sh}}{2\pi L}$$



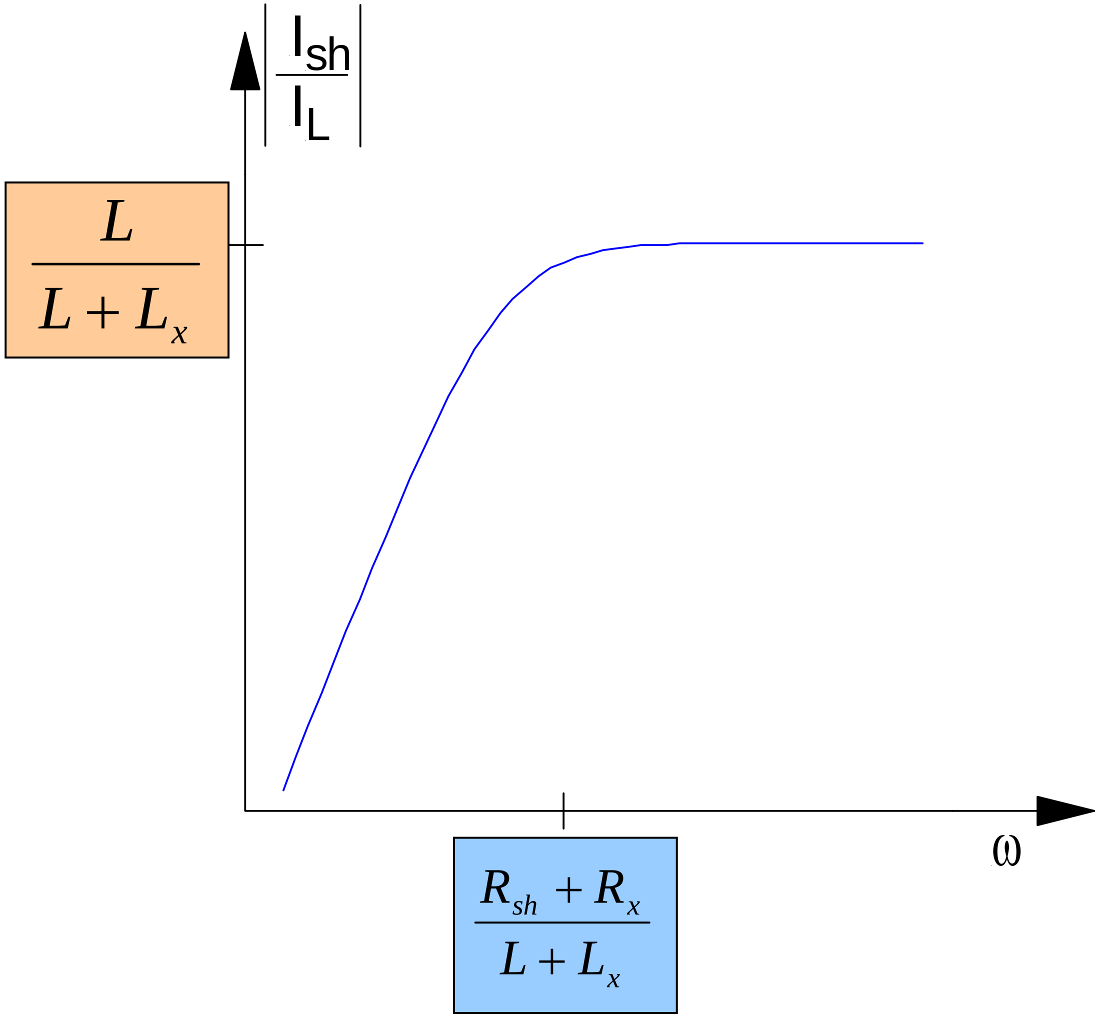
Poor Shield Grounding



$$Z_x = R_x + j\omega L_x$$

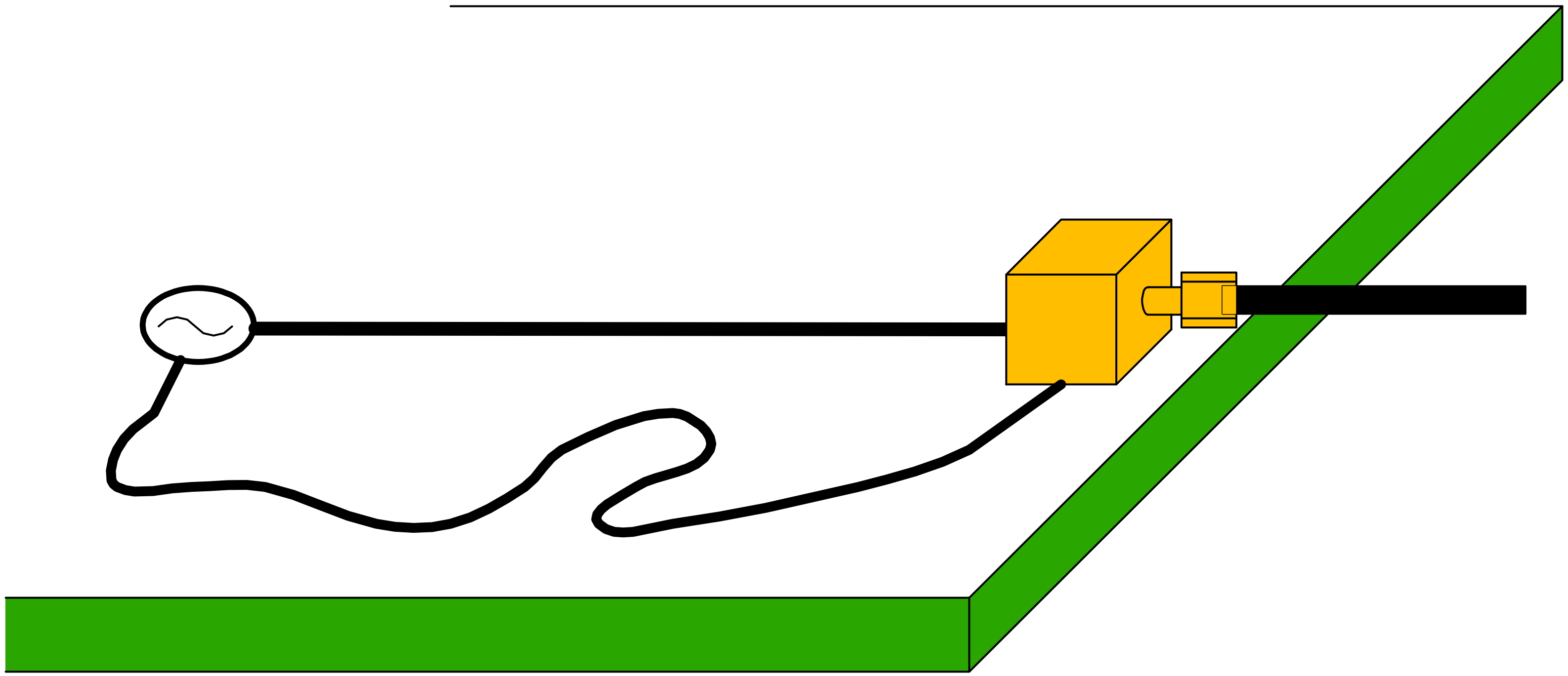
$$\frac{I_{sh}}{I_L} = \frac{j\omega L}{R_x + R_{sh} + j\omega\left(L + L_x\right)}$$

Shield Current

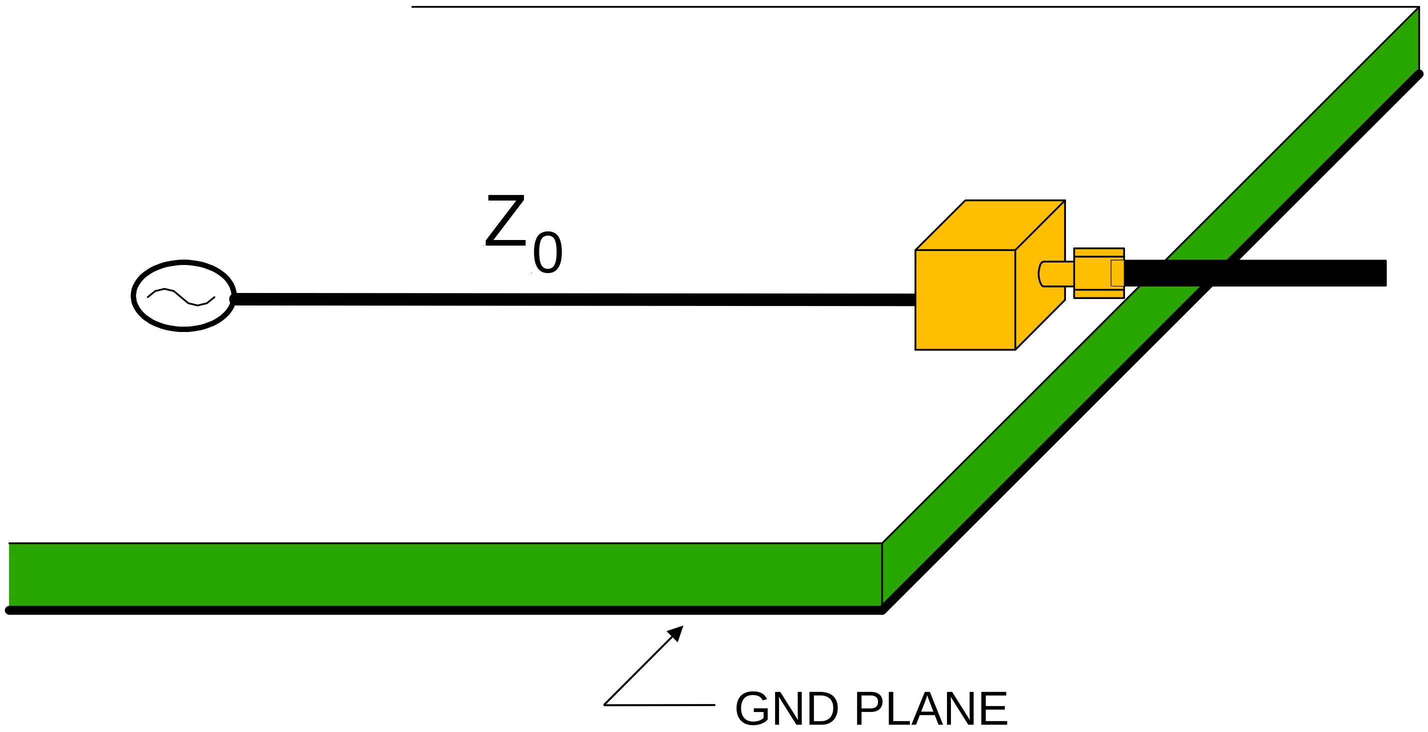


Pigtail

Z_x



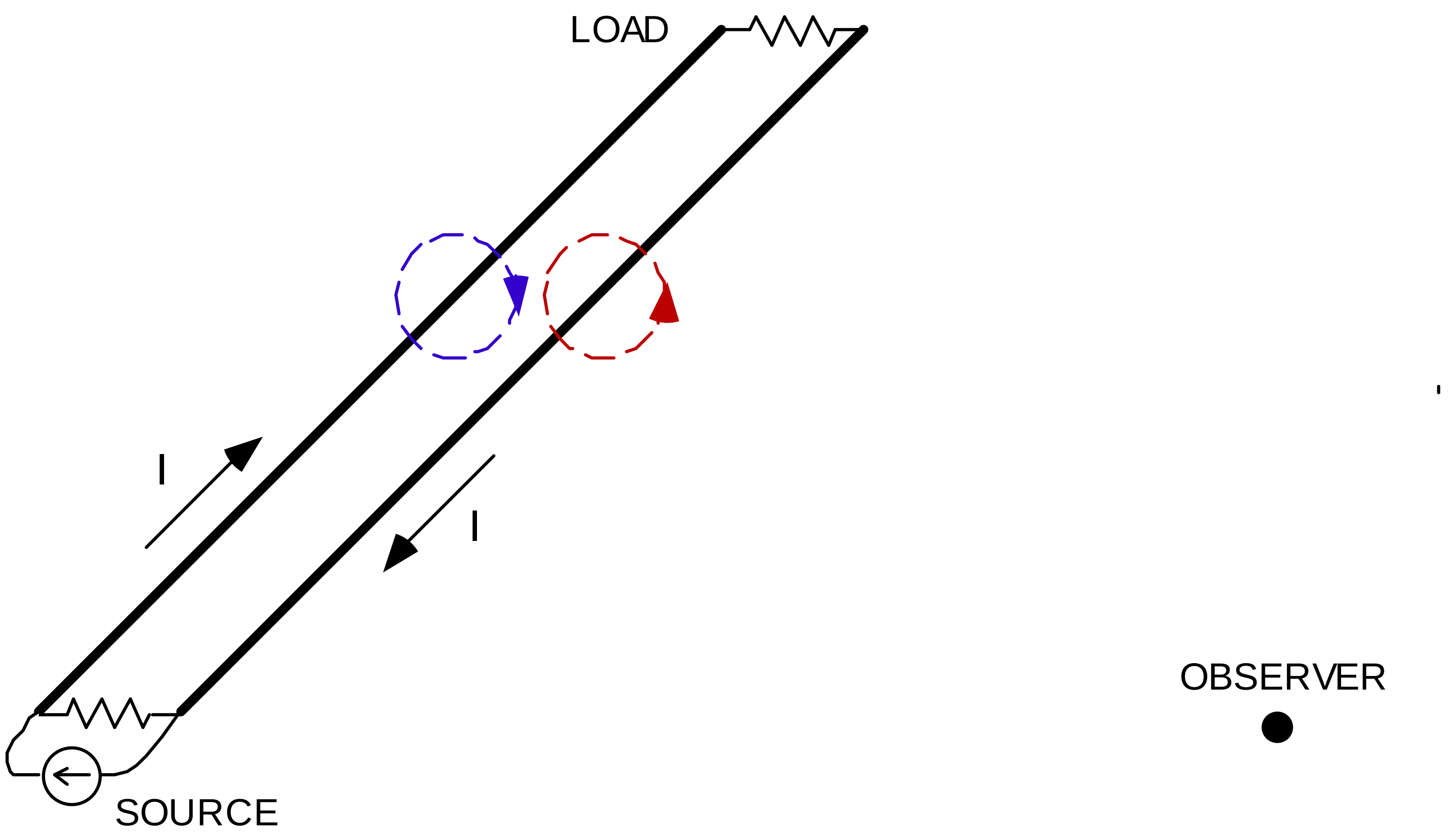
Minimum Z_x



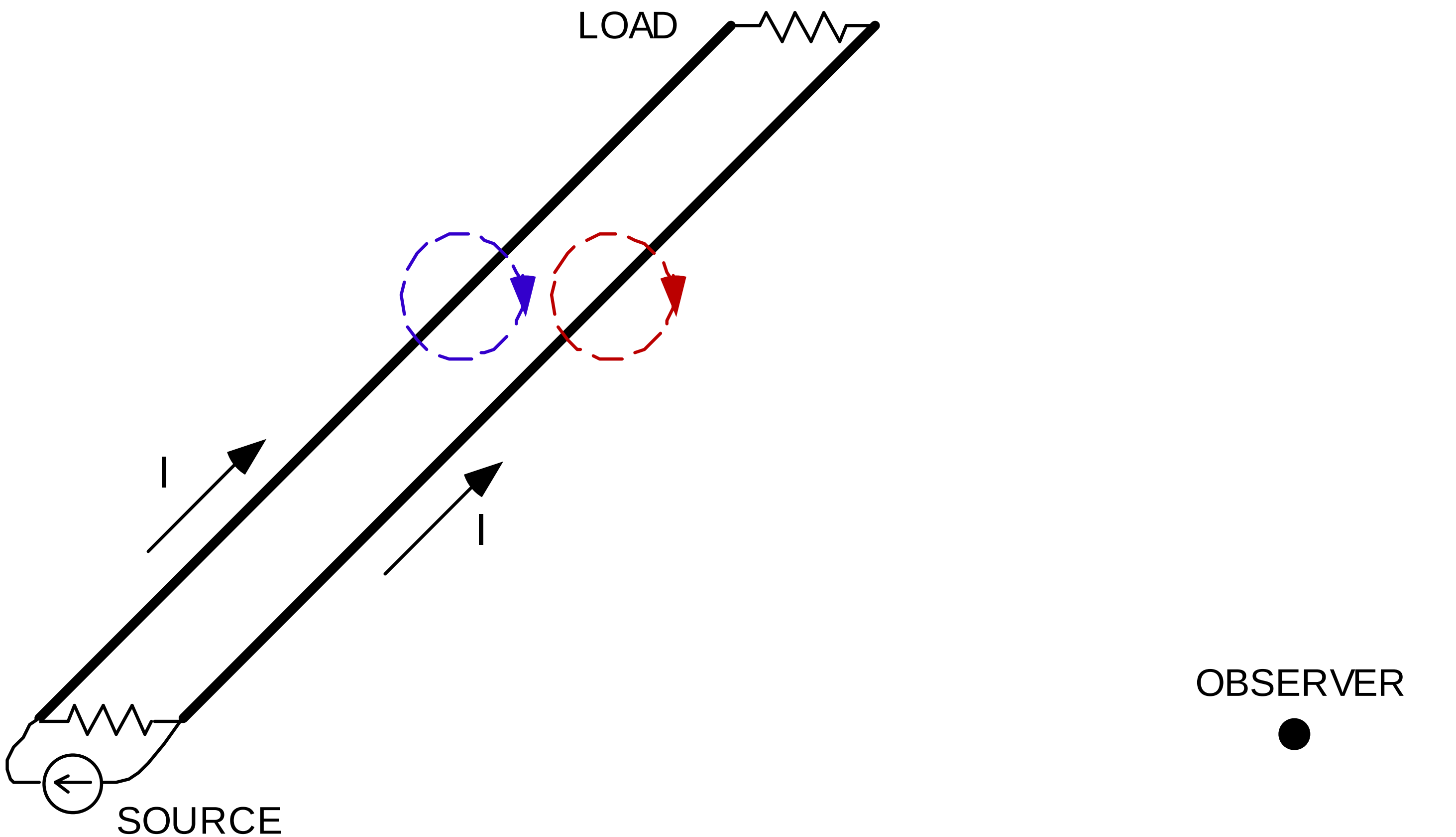
Common-Mode Radiation

- In a system, cables are often the principal radiators of CM emissions.
- Sources of CM current
  - Poor cable grounding
  - Connection to a noisy ground

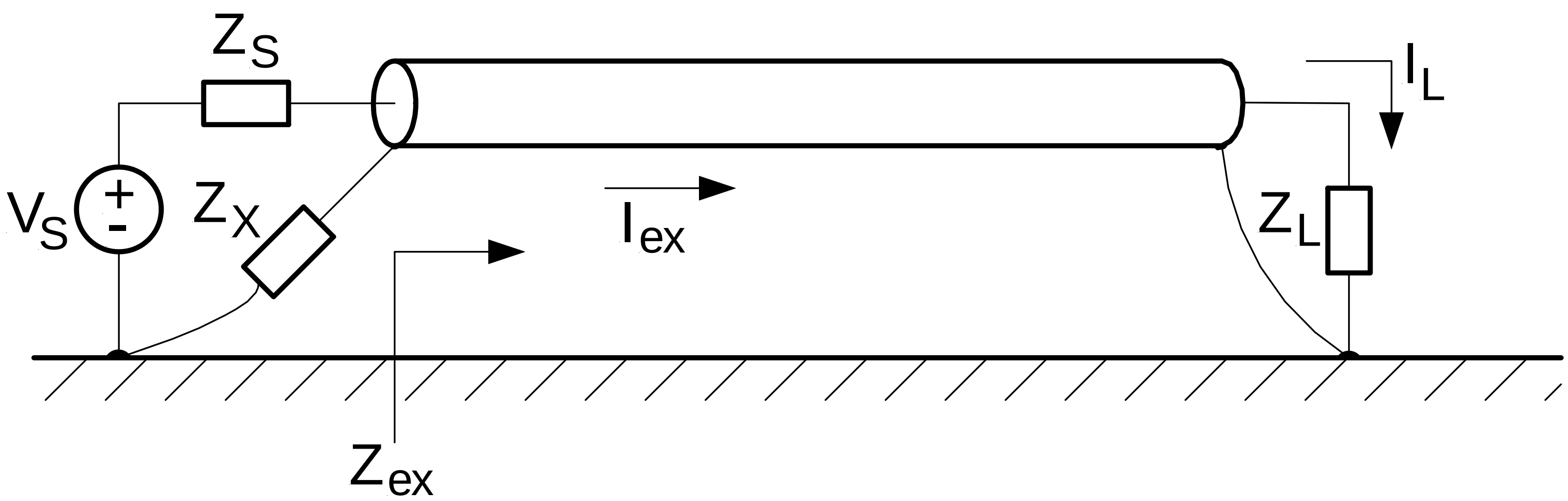
Differential Mode Radiation



Common-Mode Radiation



Poor Shield Grounding



I_{ex} IS A COMMON-MODE CURRENT.

At High Frequencies

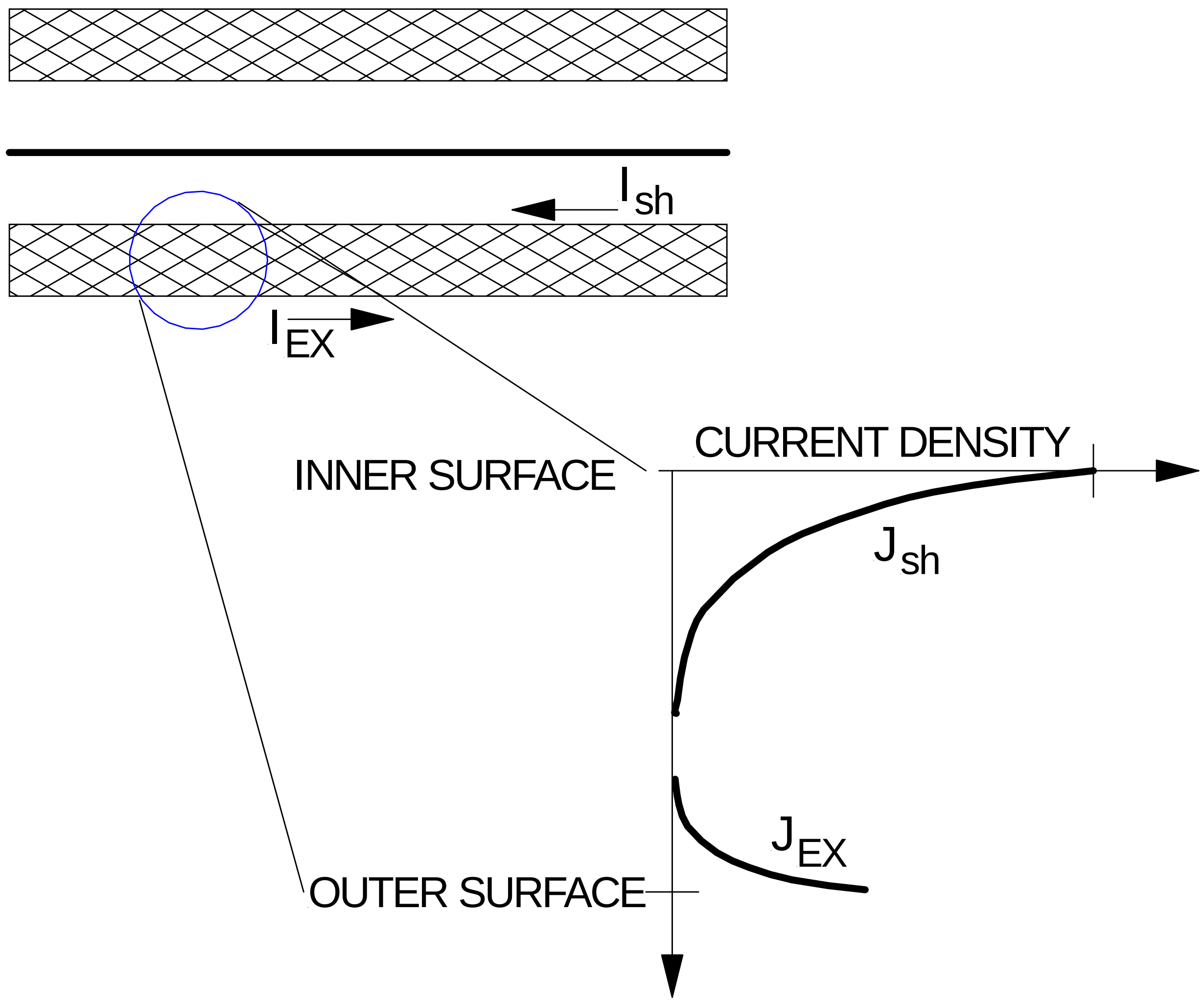
- The skin effect causes the coax to behave like a triax.
- I_{ex} will flow on the outside of the shield.

Skin Effect

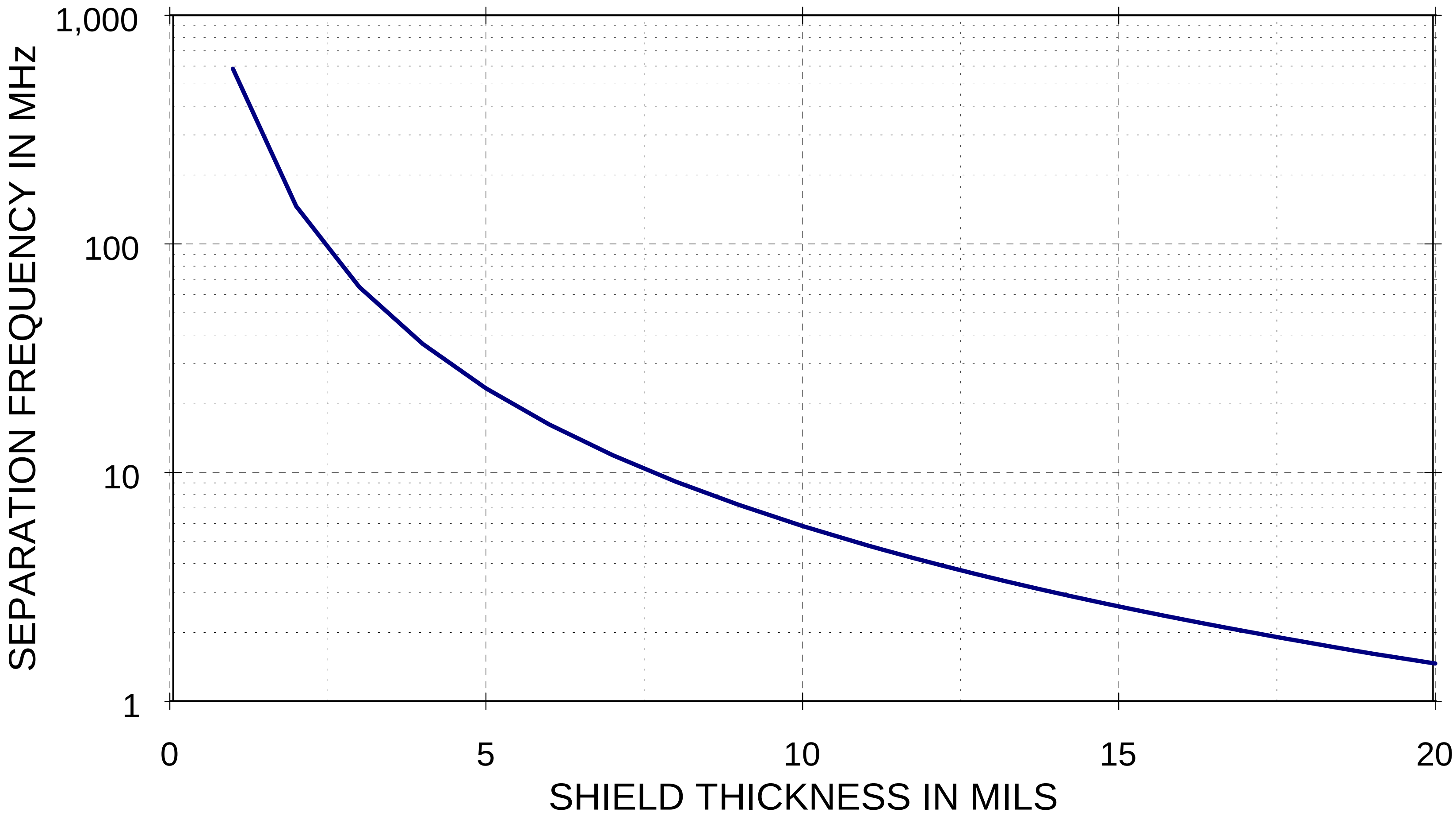
- **Describes tendency of high frequency current to ride on conductor surface**
- **Skin depth, δ, represents distance where current density is attenuated by e^{-1}.**

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu}}$$

Separation of Currents

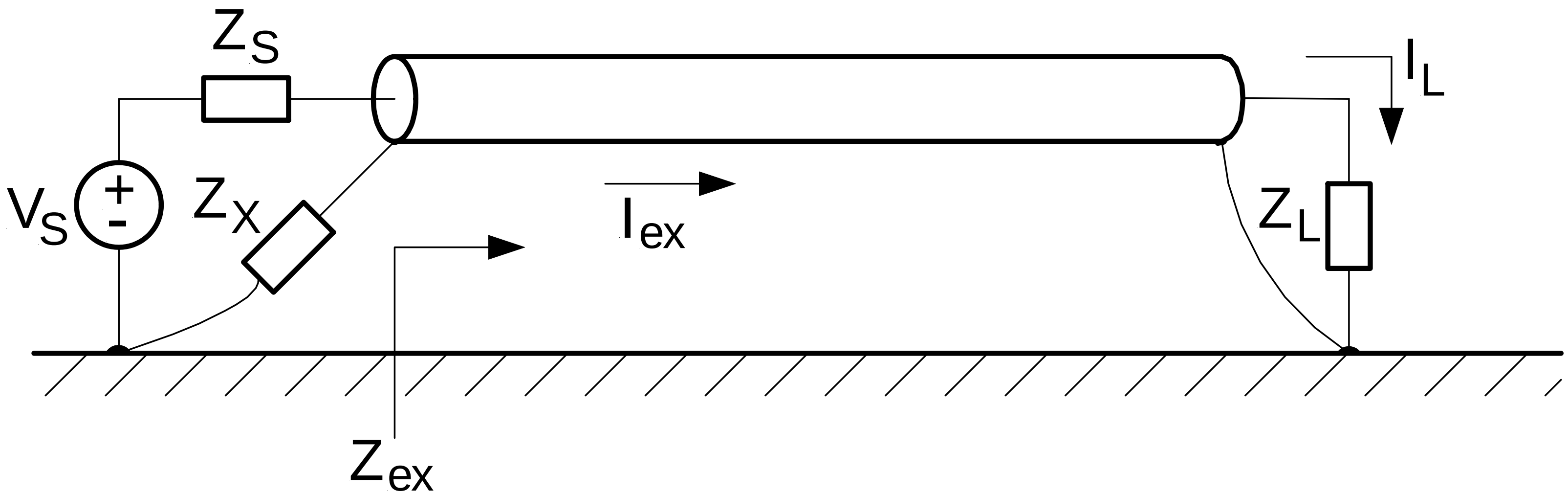


80-dB Separation Frequency



COPPER SHIELD

Poor Shield Grounding



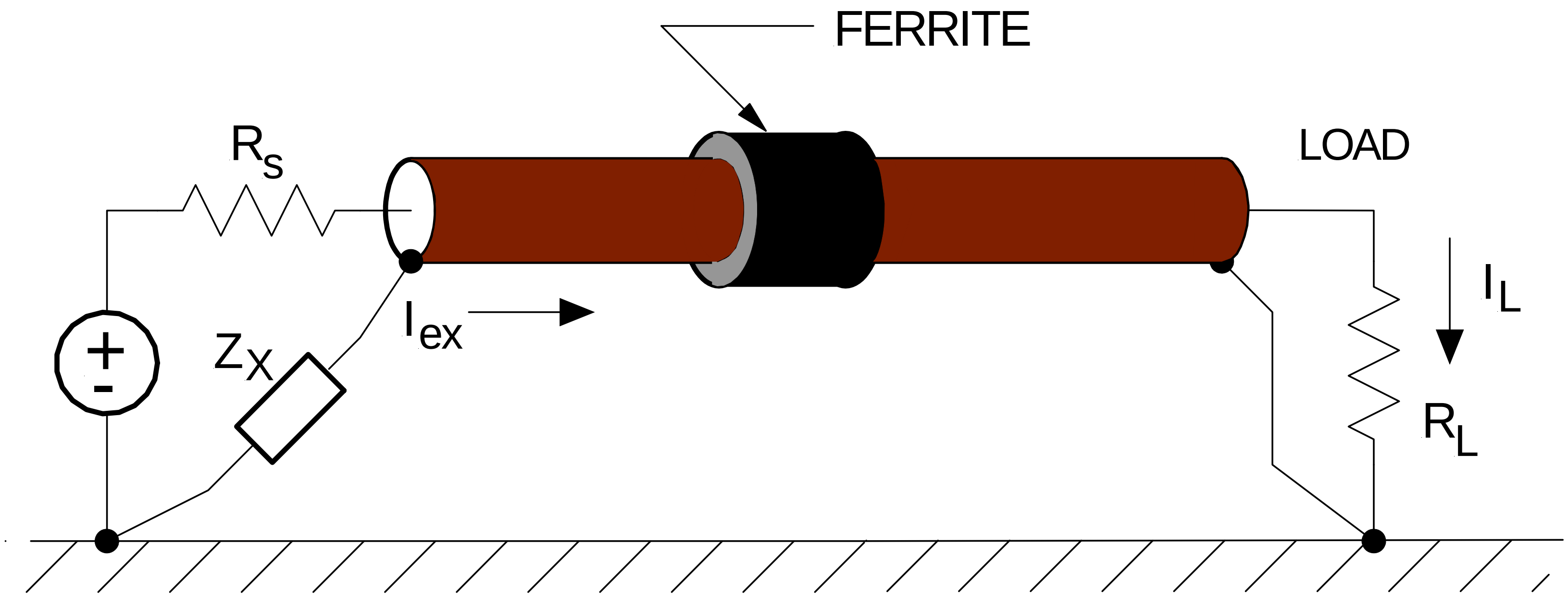
$$I_{ex} = I_L \frac{Z_x}{Z_x + Z_{ex}}$$

Z_{ex}

- **Function of frequency with numerous resonances.**
- **Depends on the cable layout, particularly its position with respect to any ground planes.**

FIX CABLES IN POSITION

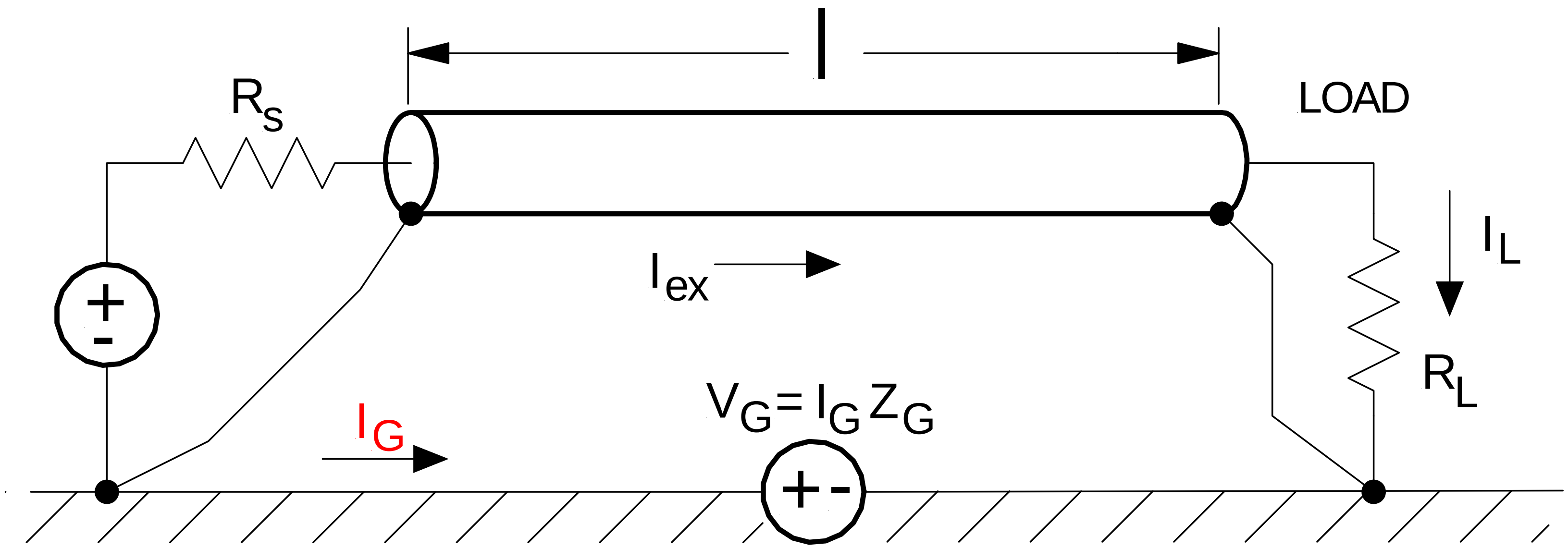
Raising Z_{ex}



Differential Ground Voltage

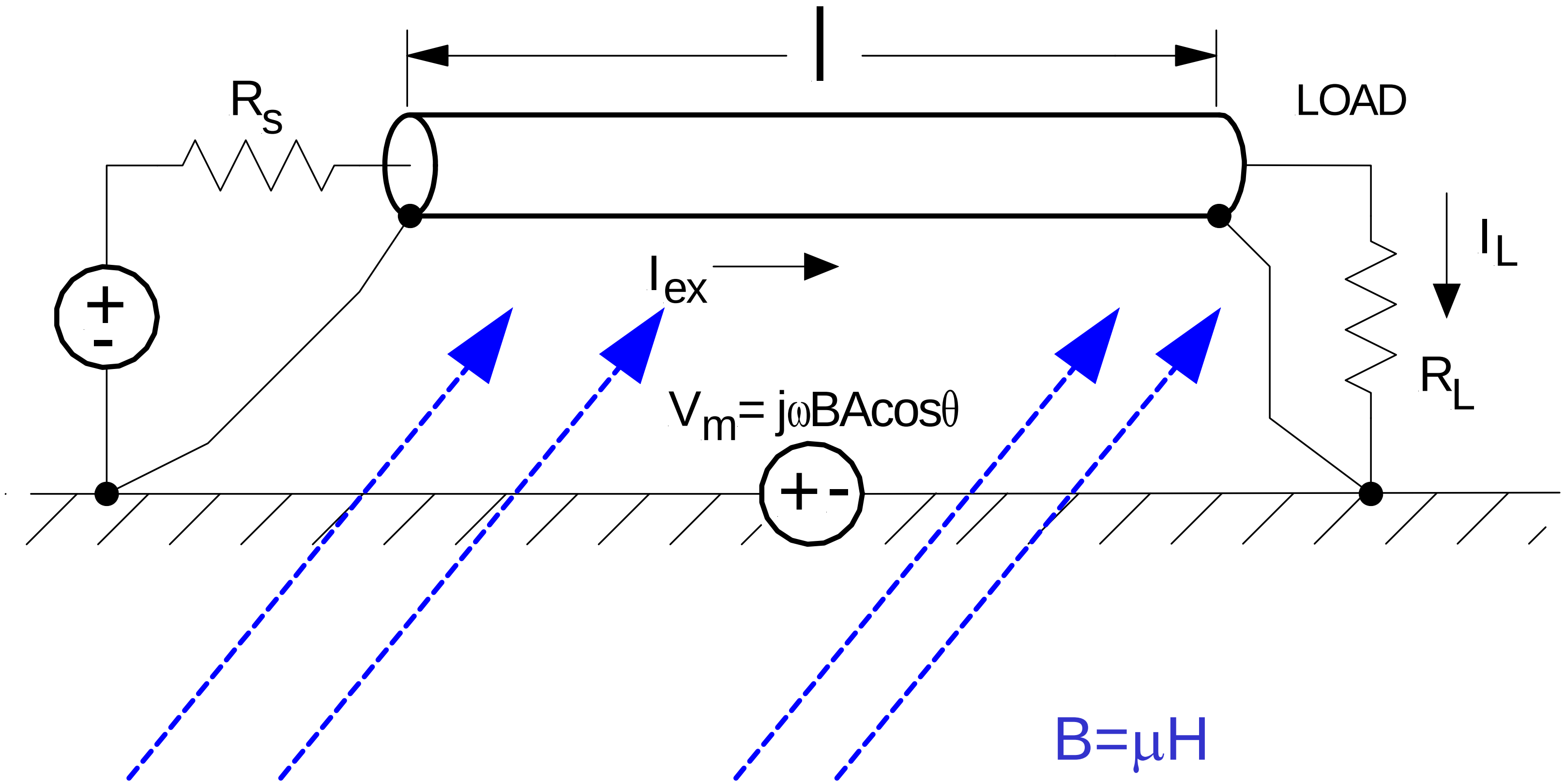
- The ground potential at the two ends of the cable may differ.
- Symptom—noise voltage coupled across load
- Causes
  - Ground loop coupling
  - Common-mode coupling

Ground-Loop Coupling

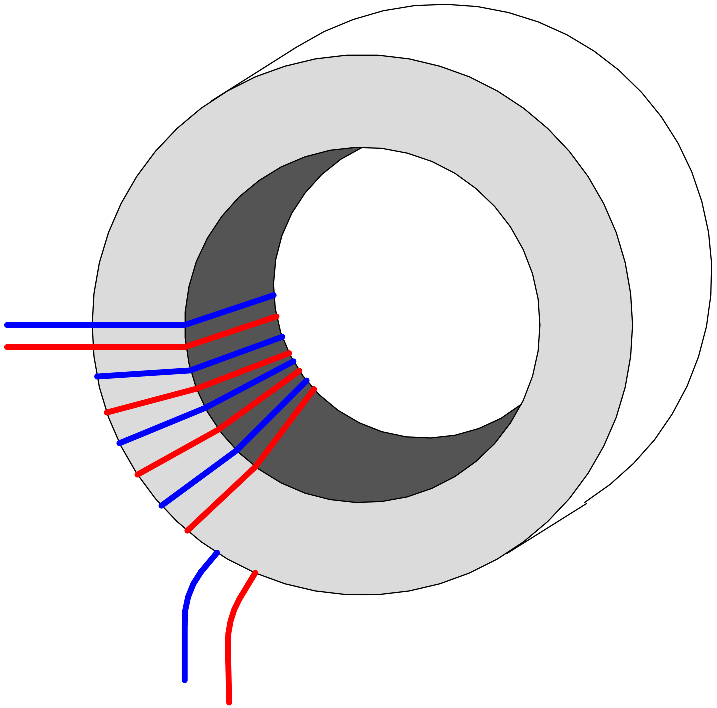


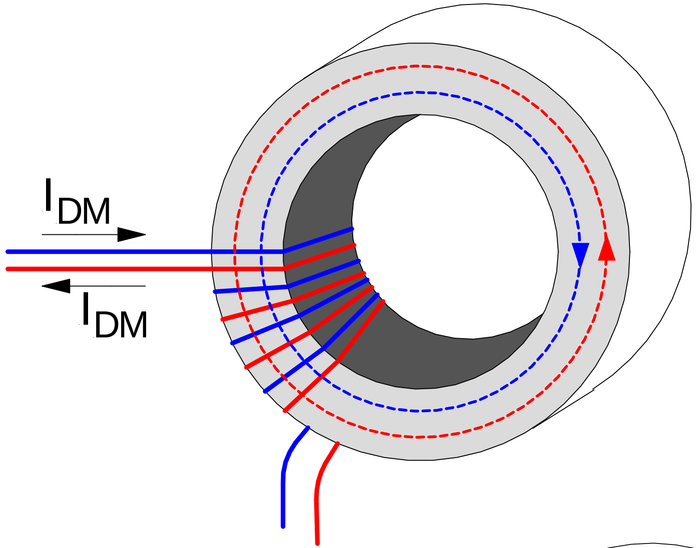
$$I_L = \frac{V_g}{(R_s + R_L)\left(1 + j\omega \frac{L}{R_{sh}}\right)}$$

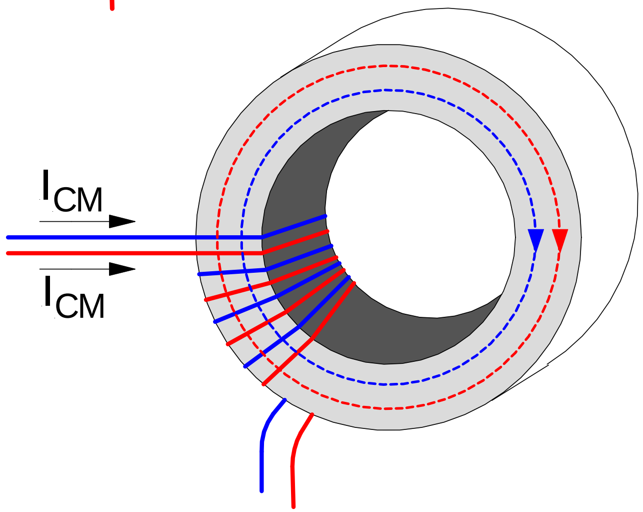
Common-Mode Coupling



Common-Mode Choke

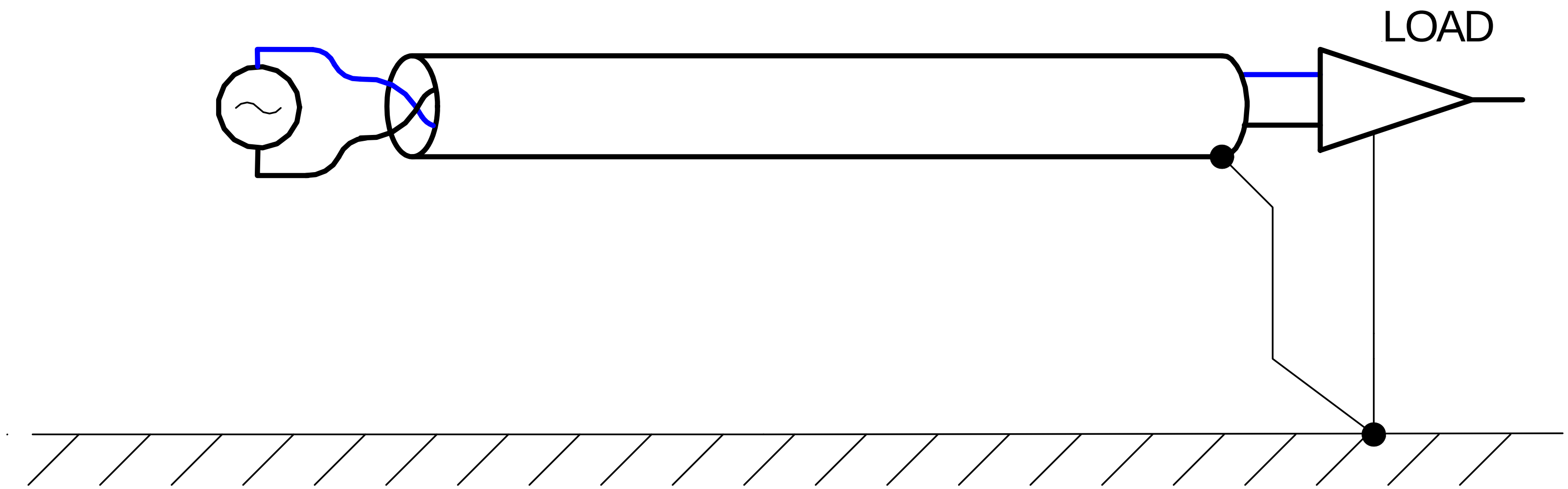




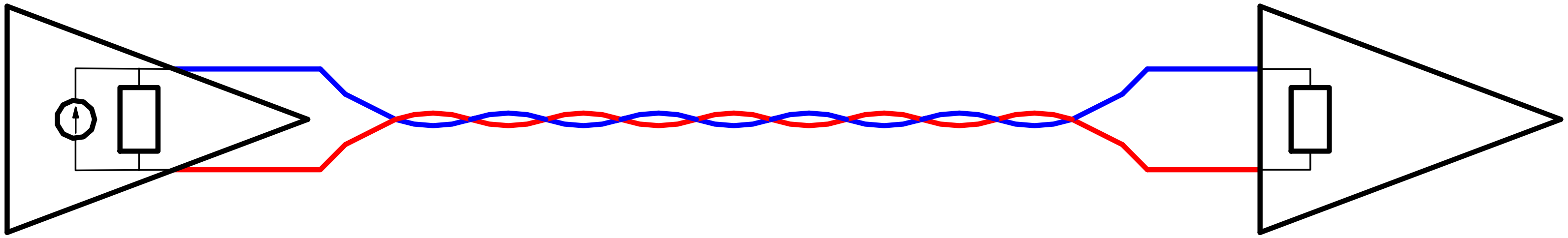


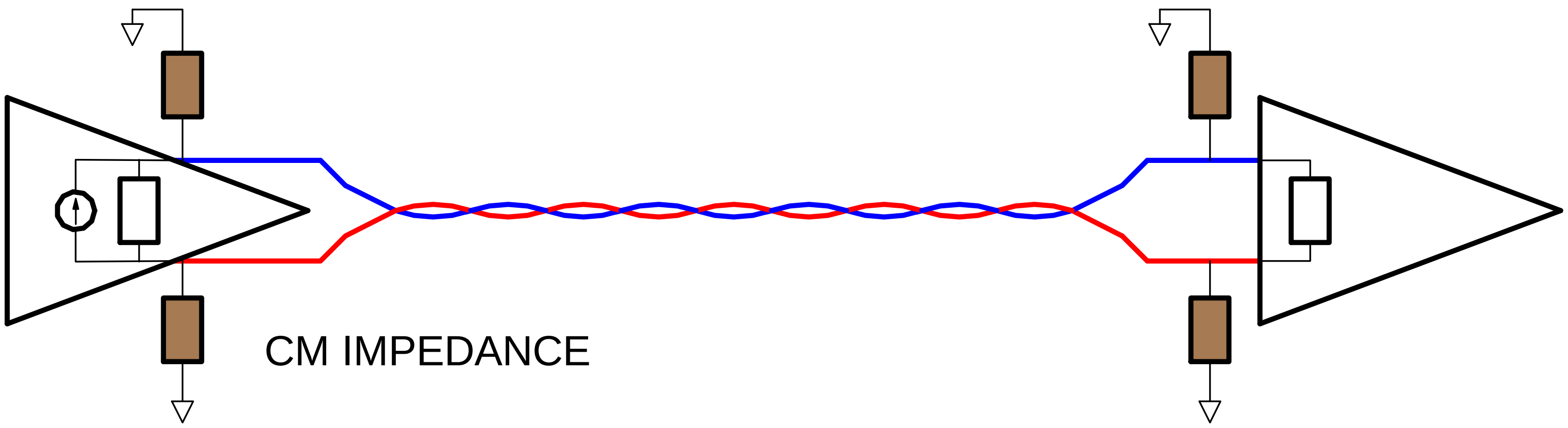
$$R_w << \omega L$$

Shielded Twisted Pair

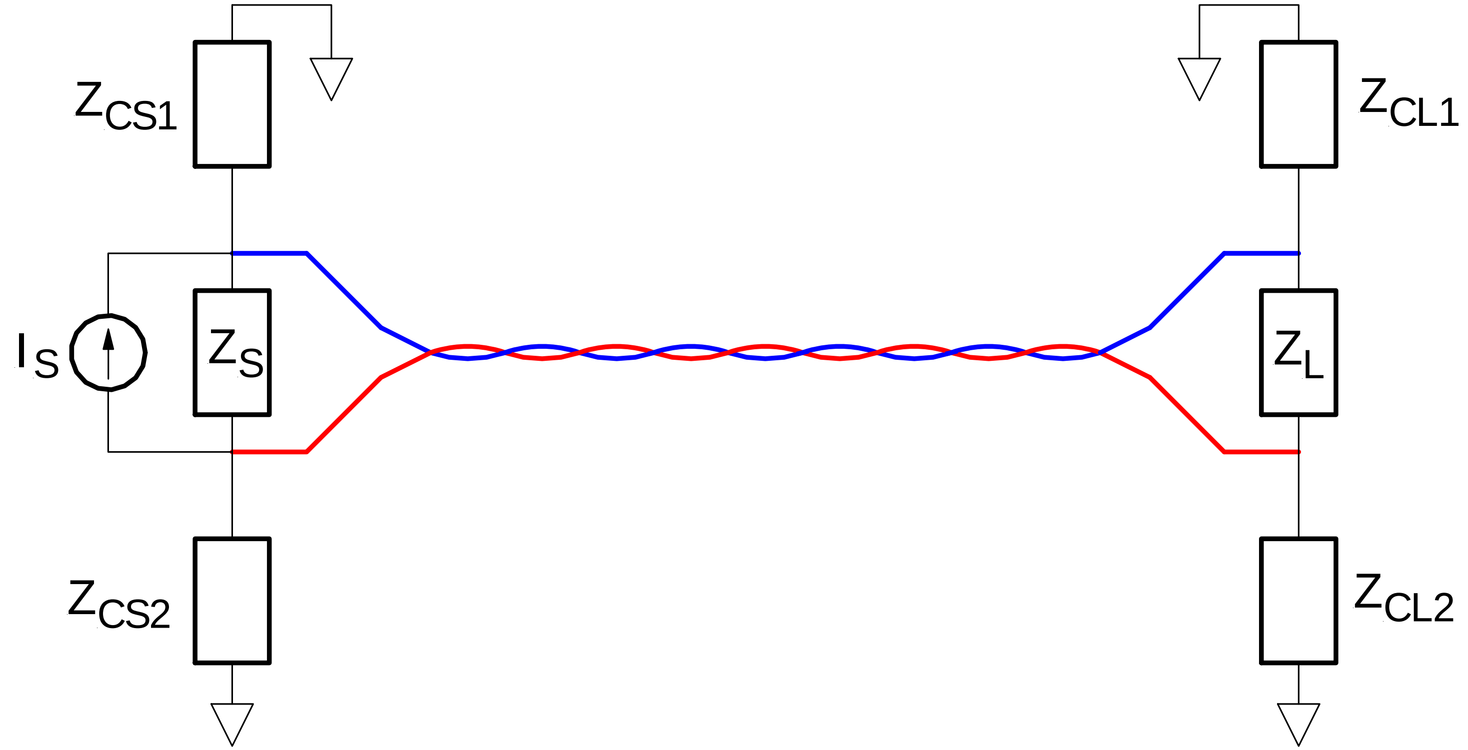


Differential to Common-Mode Conversion



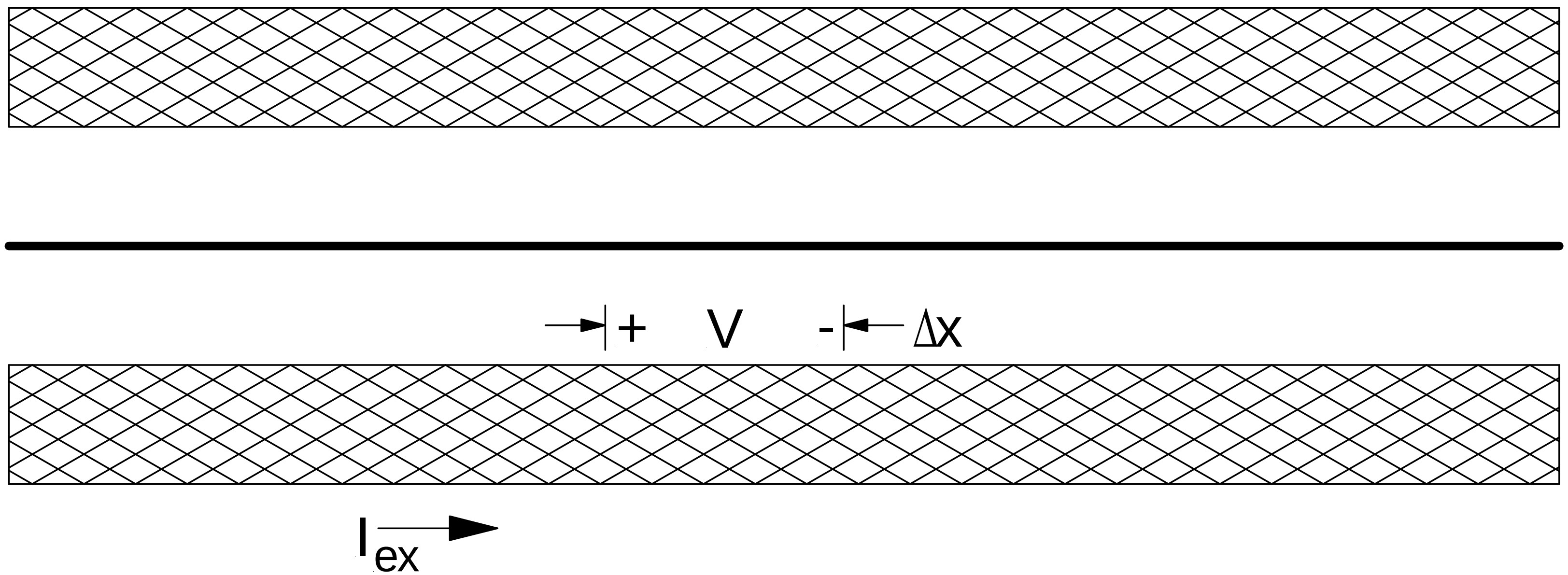


DM-to-CM Conversion



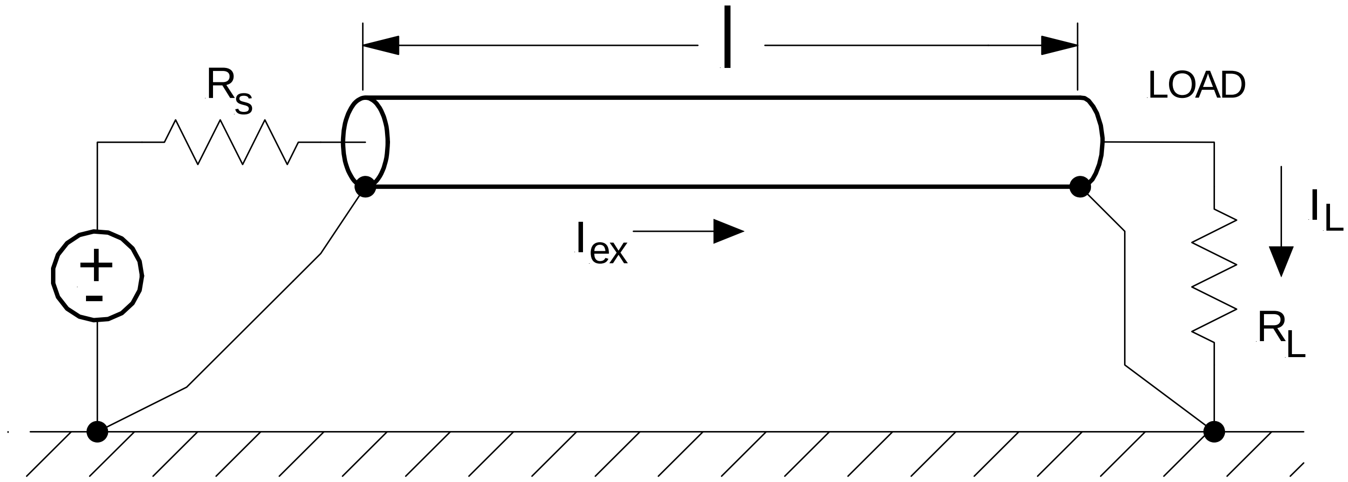
$I_{CM} = 0$ WHEN $Z_{CS1} Z_{CL2} = Z_{CS2} Z_{CL1}$

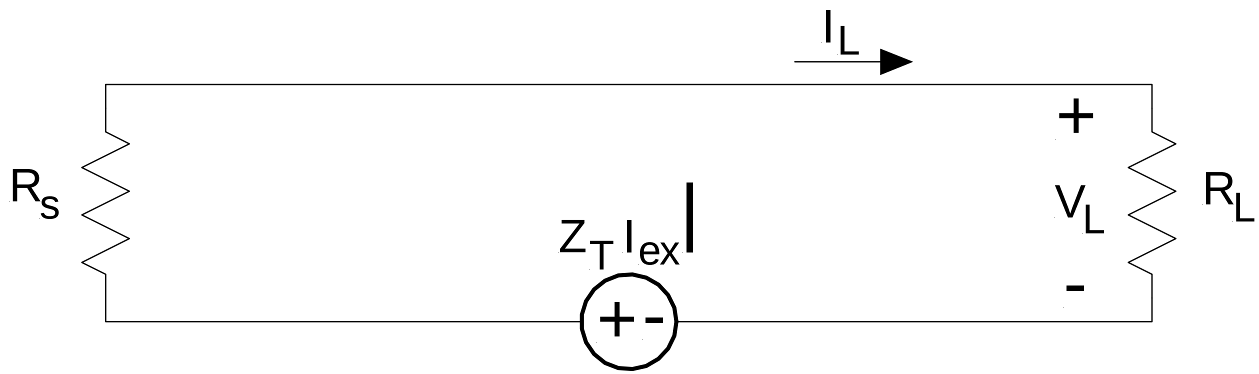
Cable Transfer Impedance



$$Z_T = \frac{V}{I_{ex}\Delta x}$$

Coupling Calculation





Shielding Effectiveness Measures

- **Traditional**

$$S = 20\log_{10}\left(\frac{I_{ex}}{I_L}\right) \quad [\mathrm{dB}]$$

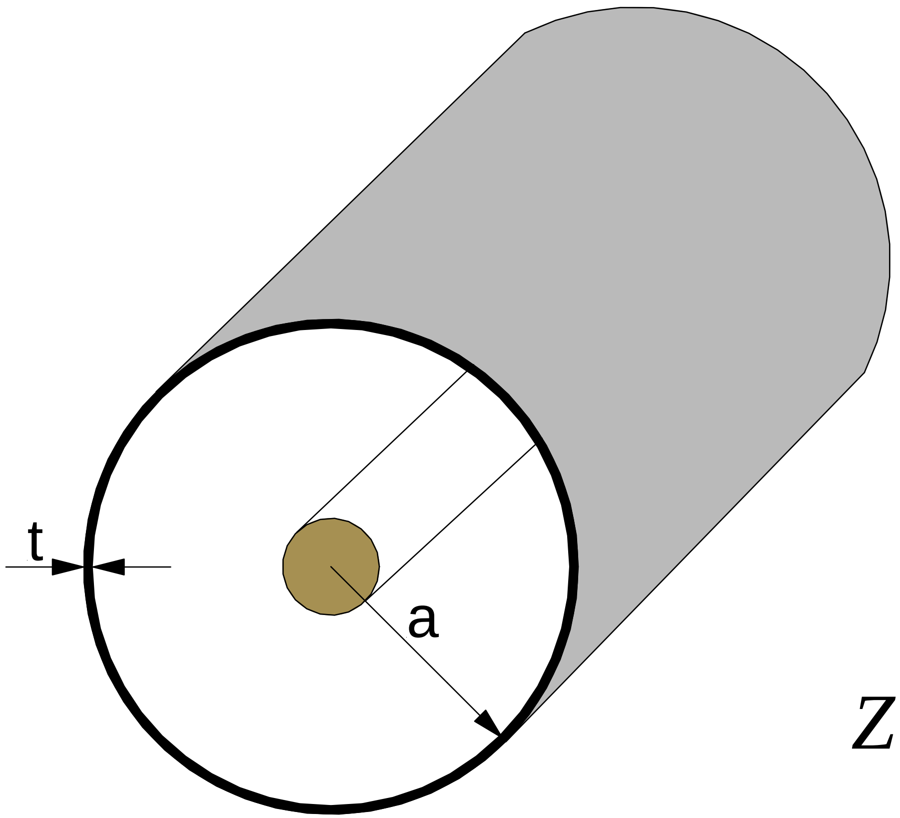
$$S = 20\log_{10}\left(\frac{Z_T \ell}{R_s + R_L}\right)$$

- **Transfer**

$$Z_{TL} = 20\log_{10}\left(\frac{V_L}{I_{ex}}\right) \quad [\mathrm{dB}\Omega]$$

$$Z_{TL} = 20\log_{10}\left(\frac{Z_T \ell R_L}{R_s + R_L}\right)$$

Z_T of a Solid Shield



DC RESISTANCE

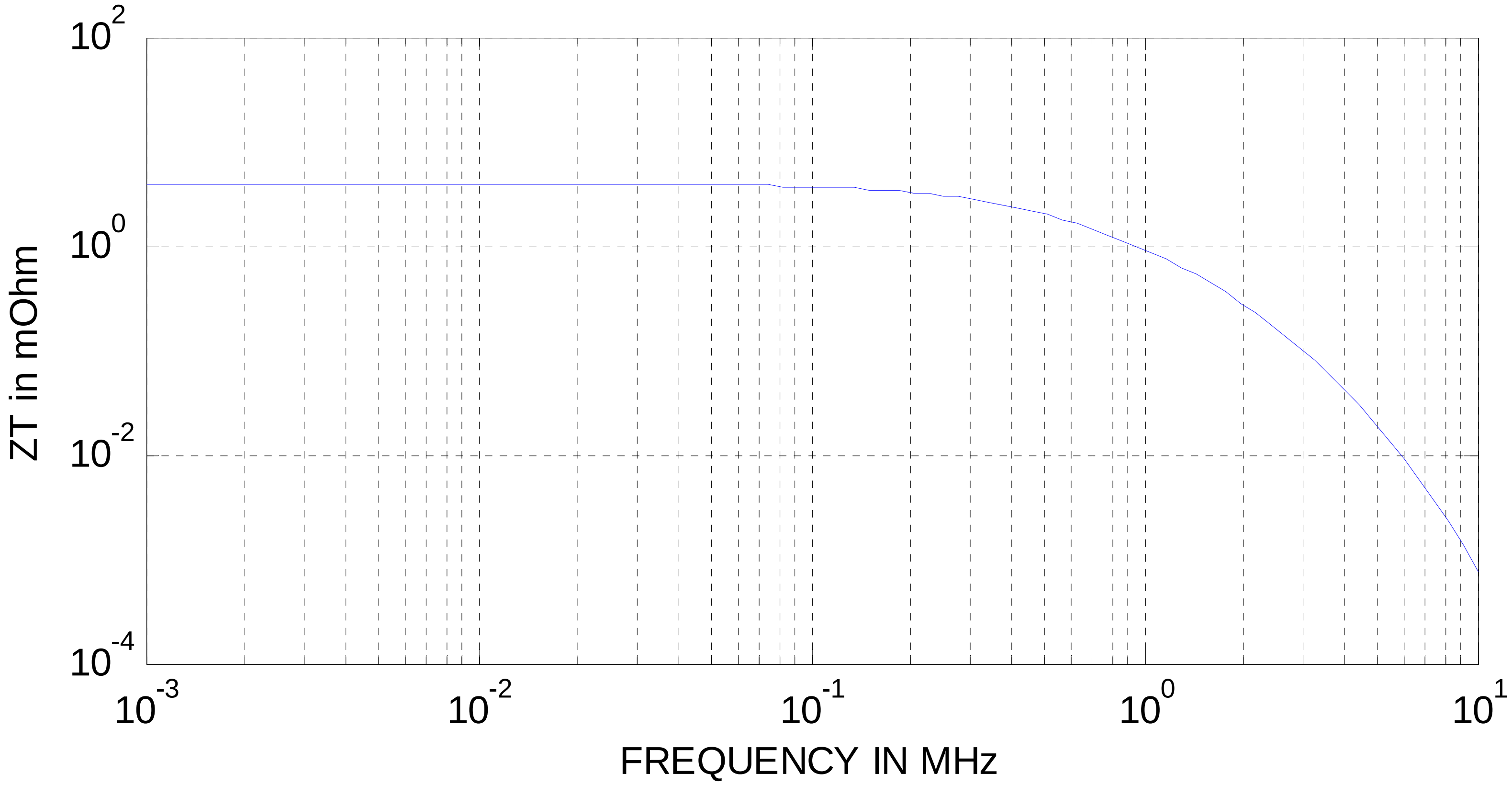
$$R_0 = \frac{1}{2\pi a t \sigma} \quad [\Omega/\mathrm{m}]$$

a = MEAN RADIUS

$$Z_T = R_0 \frac{(1+j)\frac{t}{\delta}}{\sinh\left[(1+j)\frac{t}{\delta}\right]}$$

δ = SKIN DEPTH

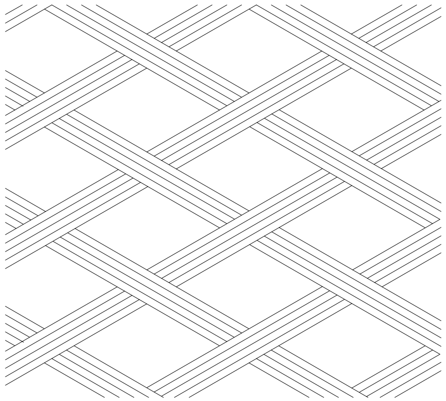
Solid Shield Example



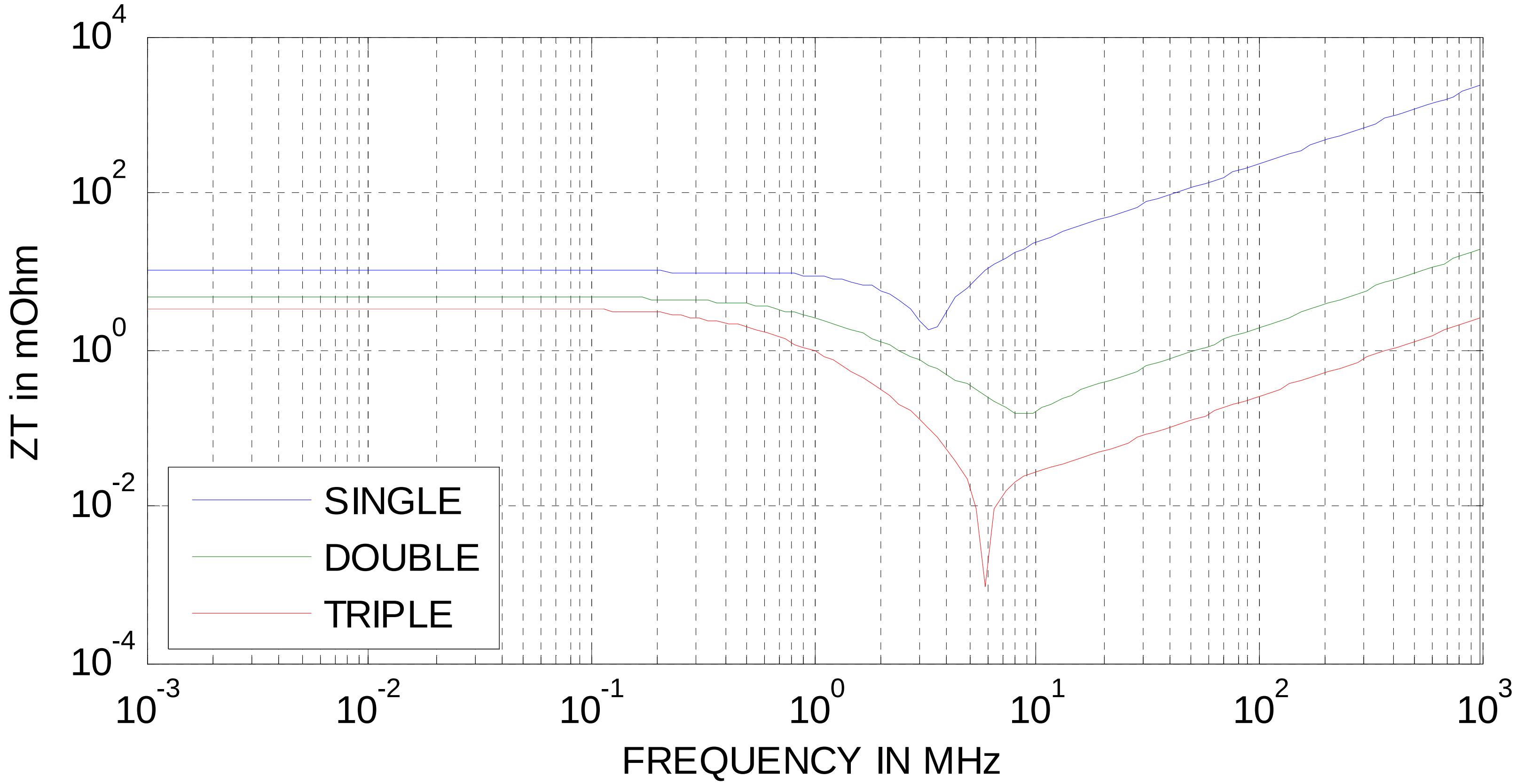
Braided Shield

- Coupling through rhombic apertures modeled by mutual inductance, M_{12}.
- More susceptible to corrosion

$$Z_T = R_0 \frac{(1+j)\frac{t}{\delta}}{\sinh\left[(1+j)\frac{t}{\delta}\right]} + j\omega M_{12}$$

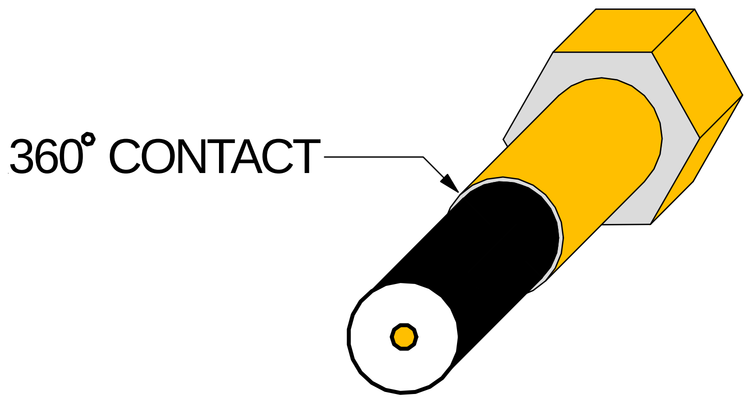


Braided Shield

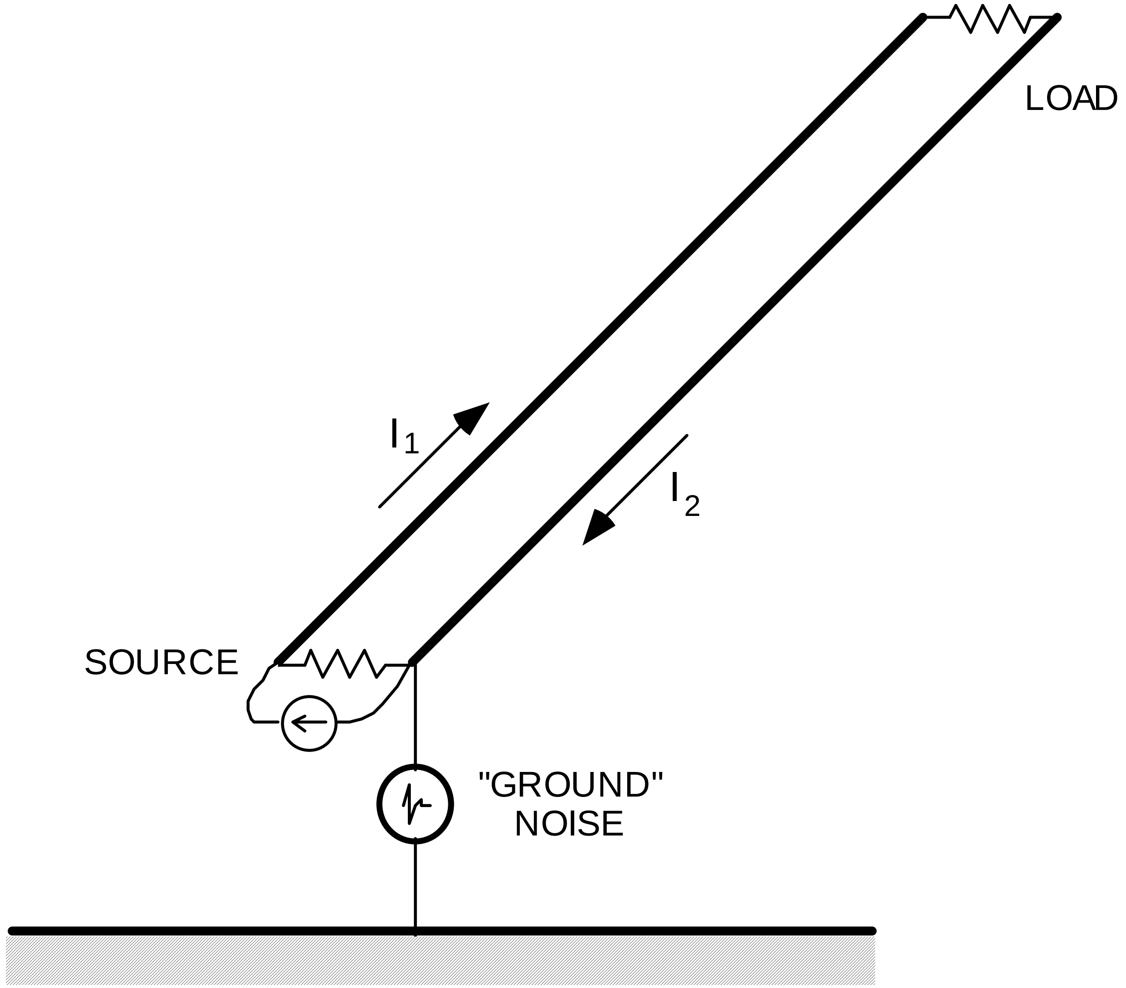


Connectors

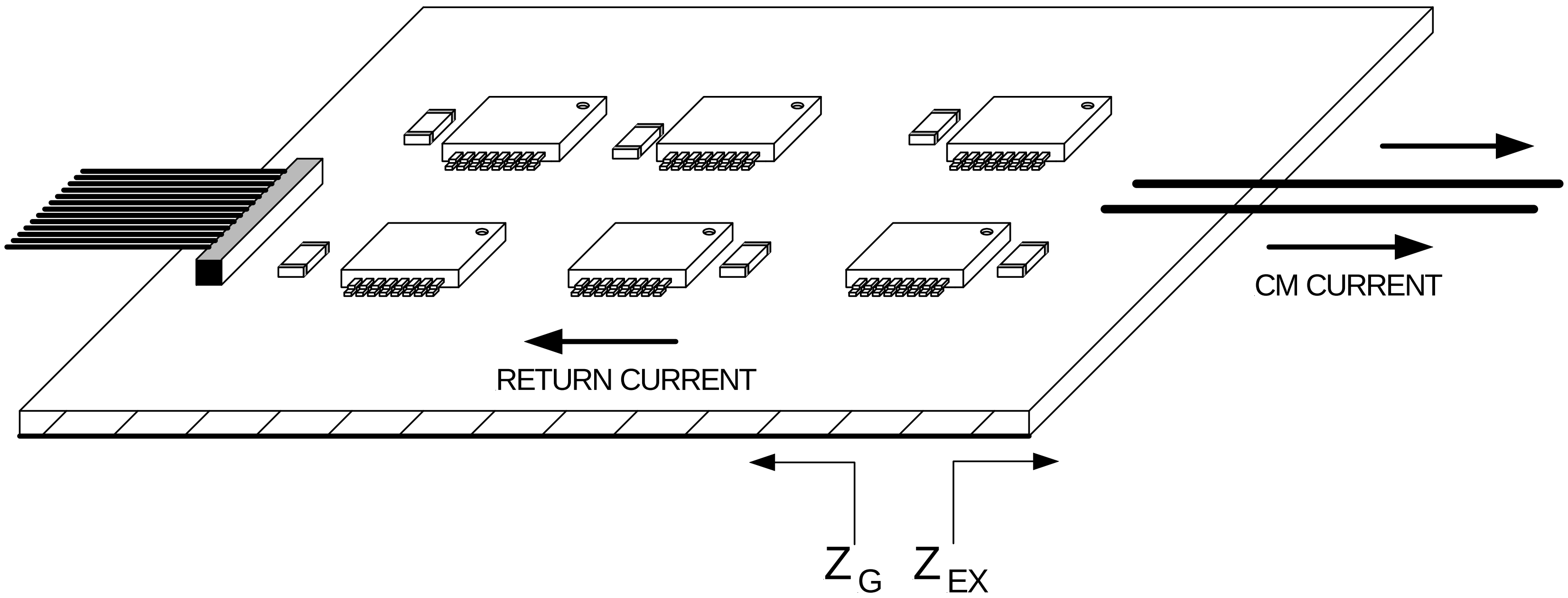
- Connectors also have transfer impedances;
  - e.g., BNC, $R_0 = 2\ m\Omega$, $M_{12} = 5\ pH$
- Cable shield must have a 360° low-resistance contact to its connectors.



“Ground” Noise



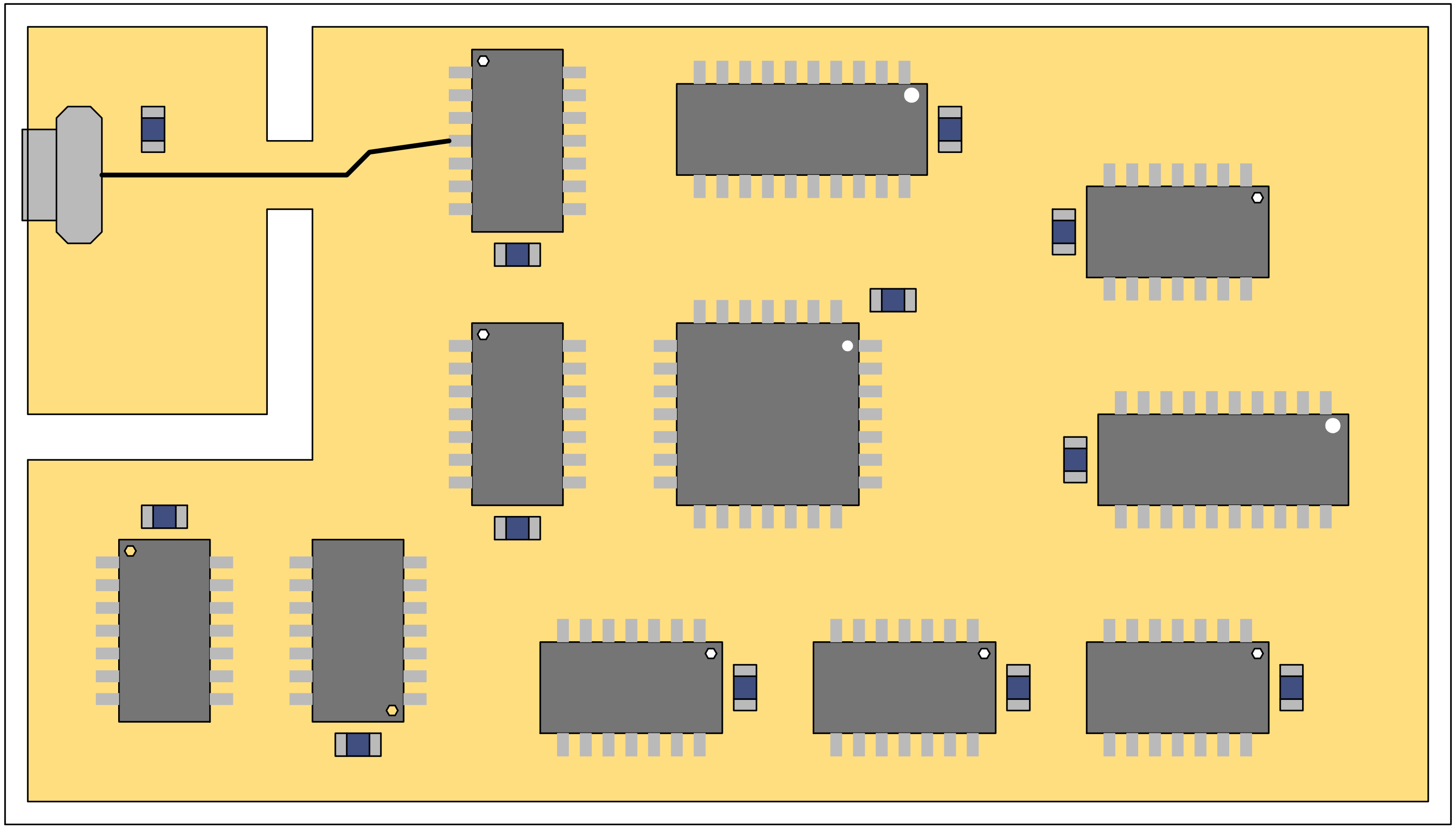
Common-Mode Excitation



ATTACH CABLE TO QUIETER GROUND REGIONS.

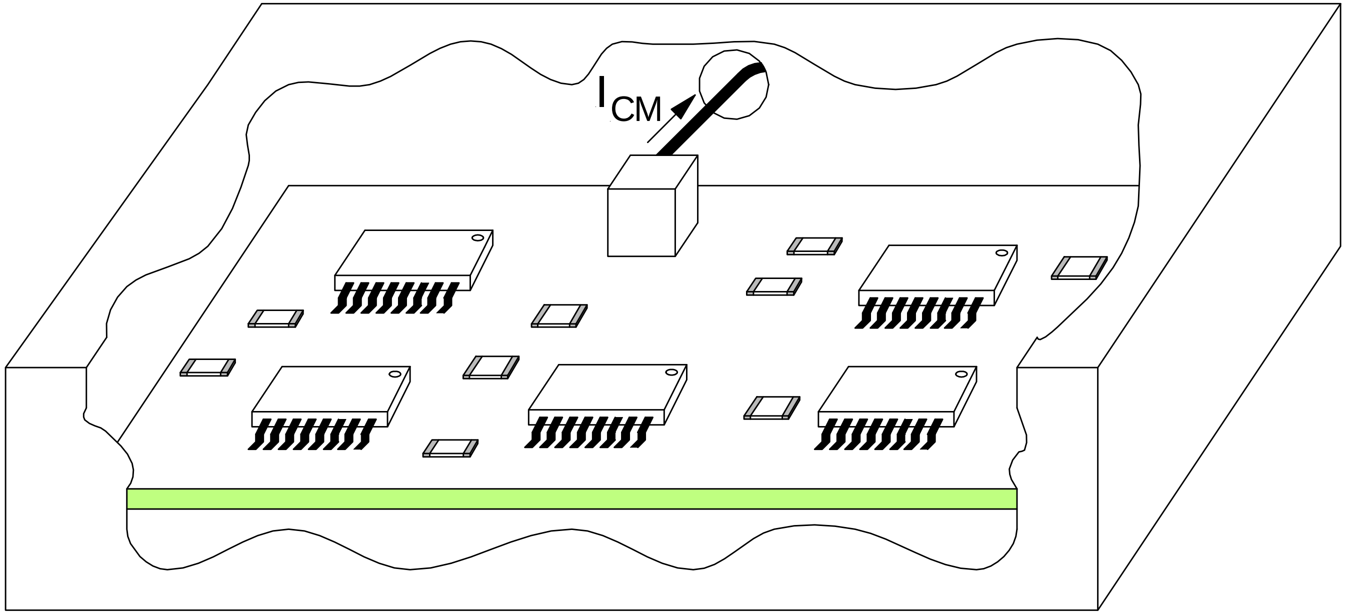
$$I_{CM} = I_{RTN}\frac{Z_G}{Z_G + Z_{EX}}$$

Cable Grounding “Island”

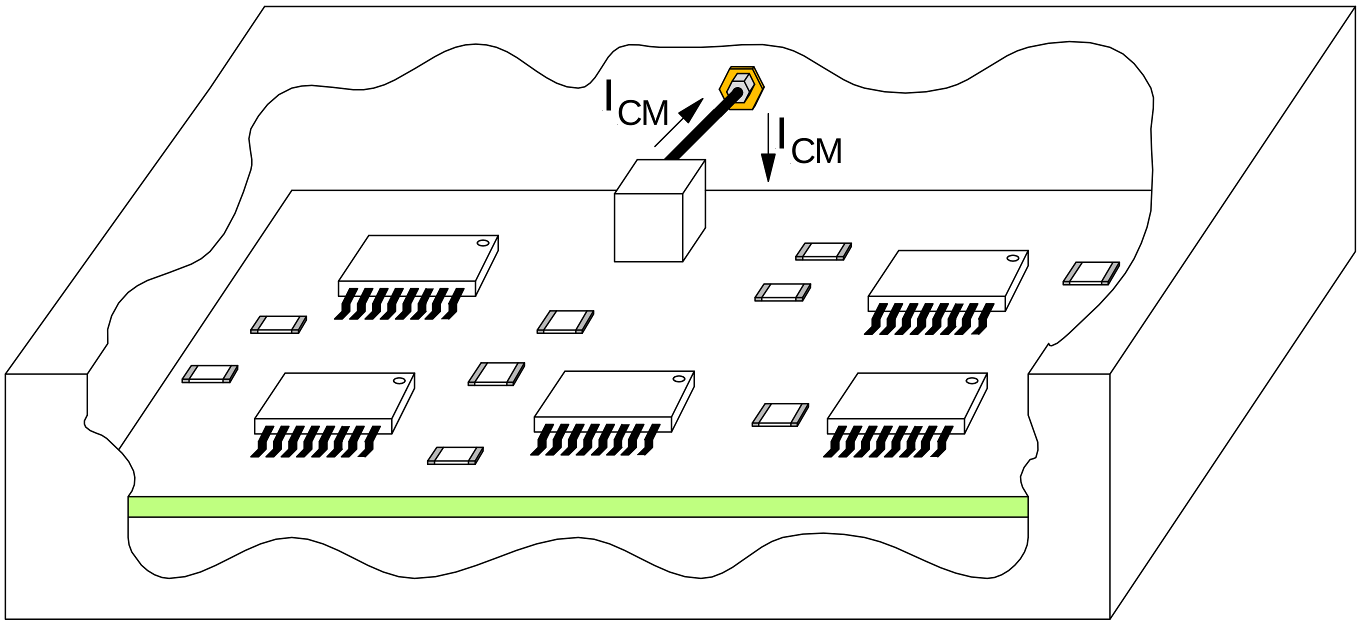


NOT AS EASY AS IT LOOKS. SIGNAL TRACES SHOULD NOT CROSS GROUND CUTOUT.

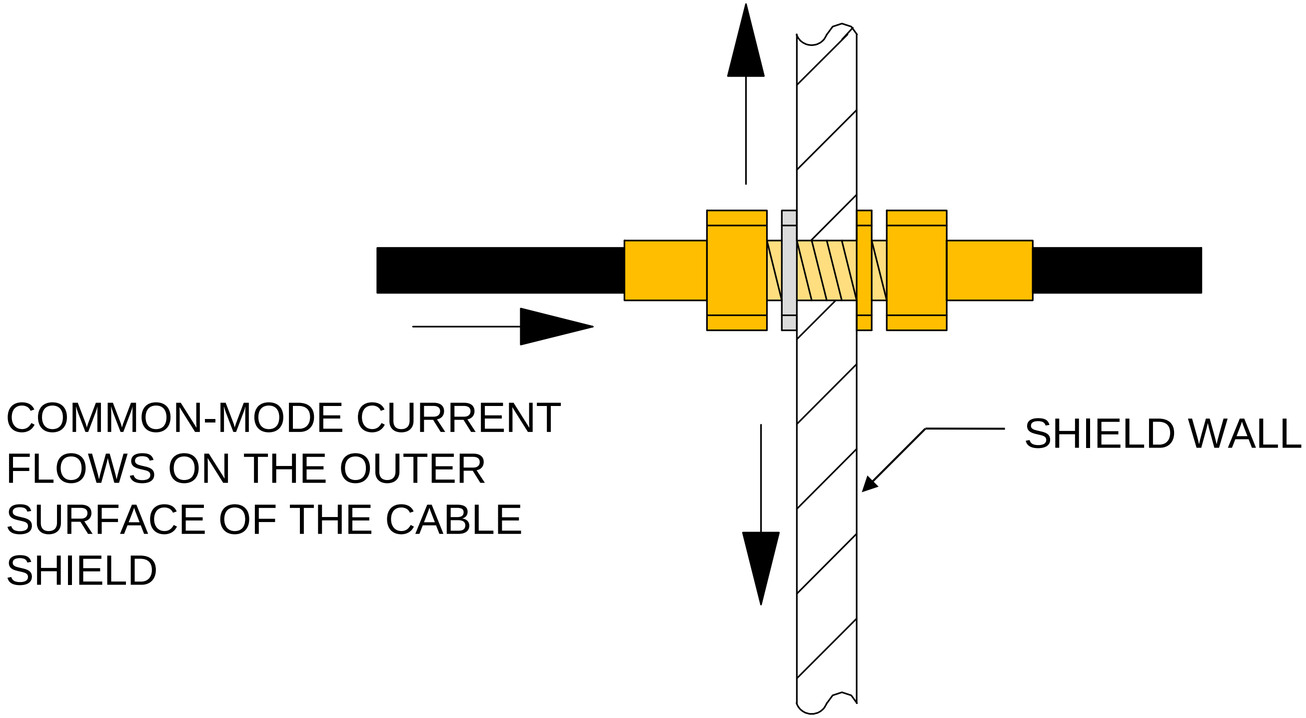
Bringing a Cable through a Shield Wall



Bulkhead Connector

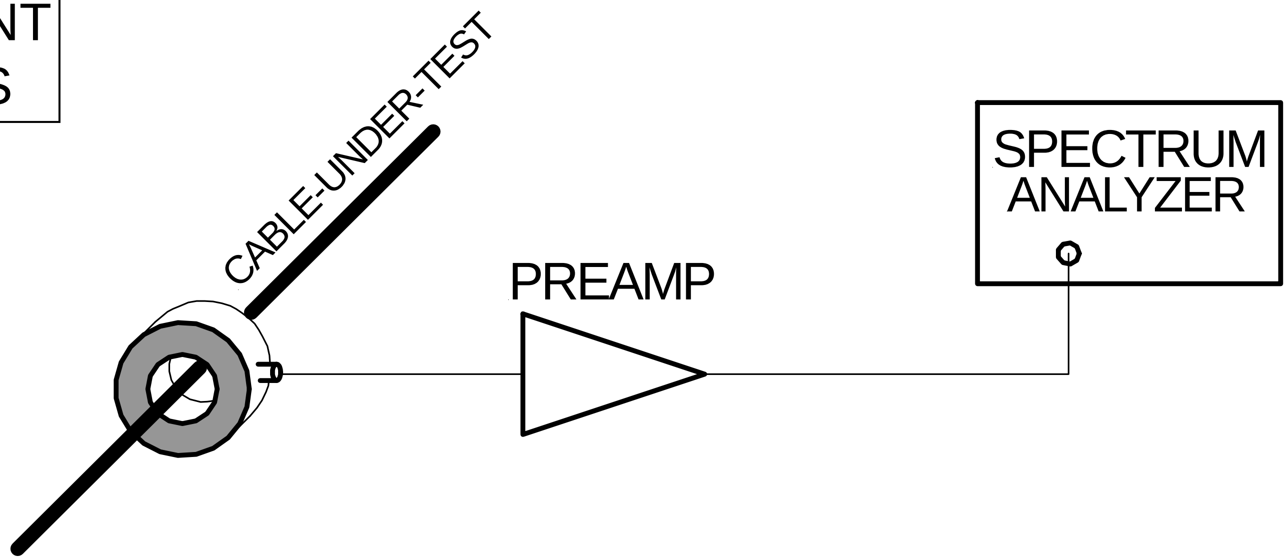


Stripping Common-Mode Current



Measuring Common-Mode Current

CURRENT
PROBES



Summary of Concepts

- Return current seeks the minimum impedance.
- Above the 5x shield cutoff frequency, nearly all the return current flows in the shield of a well grounded cable.
- Common-mode current induced by poor cable grounding flows on the outer surface of a cable shield.

Summary of Concepts

- A cable performs no better than its connectors.
- Terminate cable shields 360° to their connectors.
- Connecting a shield to a noisy ground produces CM current on the outer surface of the shield.
- Cables are best brought through a shield wall using a bulkhead connector.

Books

- **Coupling to Shielded Cables**
  E.F. Vance, John Wiley & Sons, 1978.
- **Coupling of External Electromagnetic Fields to Transmission Lines**
  A.A. Smith, Jr., John Wiley & Sons, 1977.

Checklist

- Where does the return current flow?
- Where does the return current flow?
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