Low-Frequency Magnetic Field Shielding Physics and Discovery for Fabric Enclosures Using Numerical Modeling

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2014 IEEE Symposium on Electromagnetic Compatibility

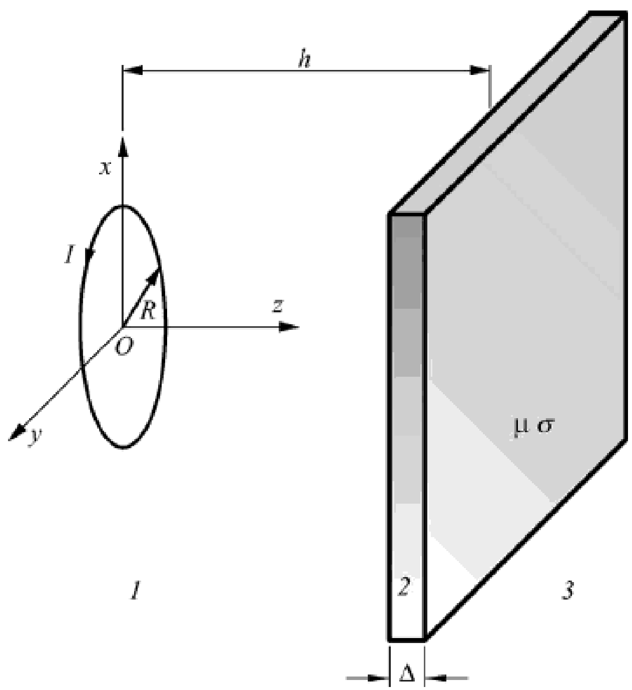
Session ID: **MO-PM-5**

Outline

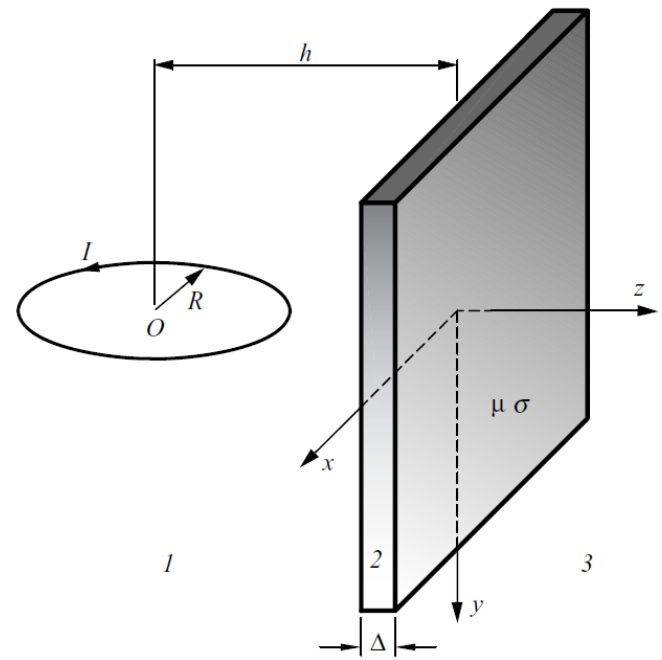
- The infinite planar shield as a canonical geometry for the design of magnetic shields
  - Superiority of various materials such as Copper, Steel and Permalloy for different thicknesses
- Comparison of simulated results with the several design approximations for infinite planar shields
- Cylindrical and Spherical magnetic conducting shield
- A simulation tool for LF magnetic field discovery and design
  - Canonical loop problems from the literature
  - MIL-STD 188-125-2 enclosure with loop antenna

Introduction

The infinite planar shield has been studied as a canonical geometry for the design of EM shields. The shield consists of an infinite planar sheet with thickness **Δ**, large value of the conductivity **σ**, and/or of the relative magnetic permeability $\boldsymbol{\mu_r}$. [1]
Following figures show geometry of the problem for excitation source current loop placed parallel or perpendicular to the shielding plane.

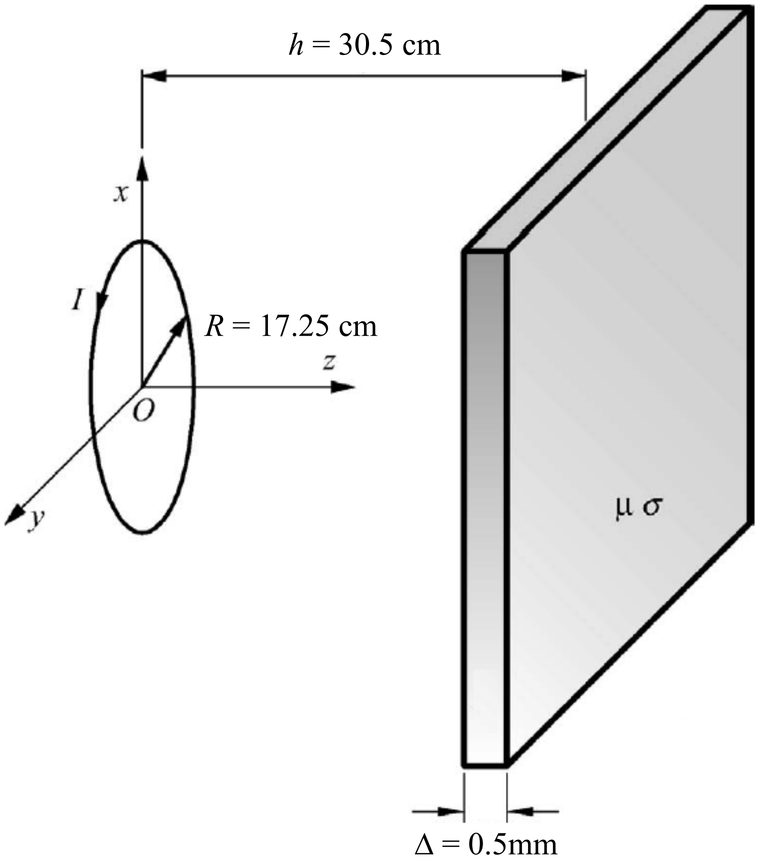


Benchmark problem 1
Circular current loop parallel to an infinite plane



Benchmark problem 2
Circular current loop perpendicular to an infinite plane

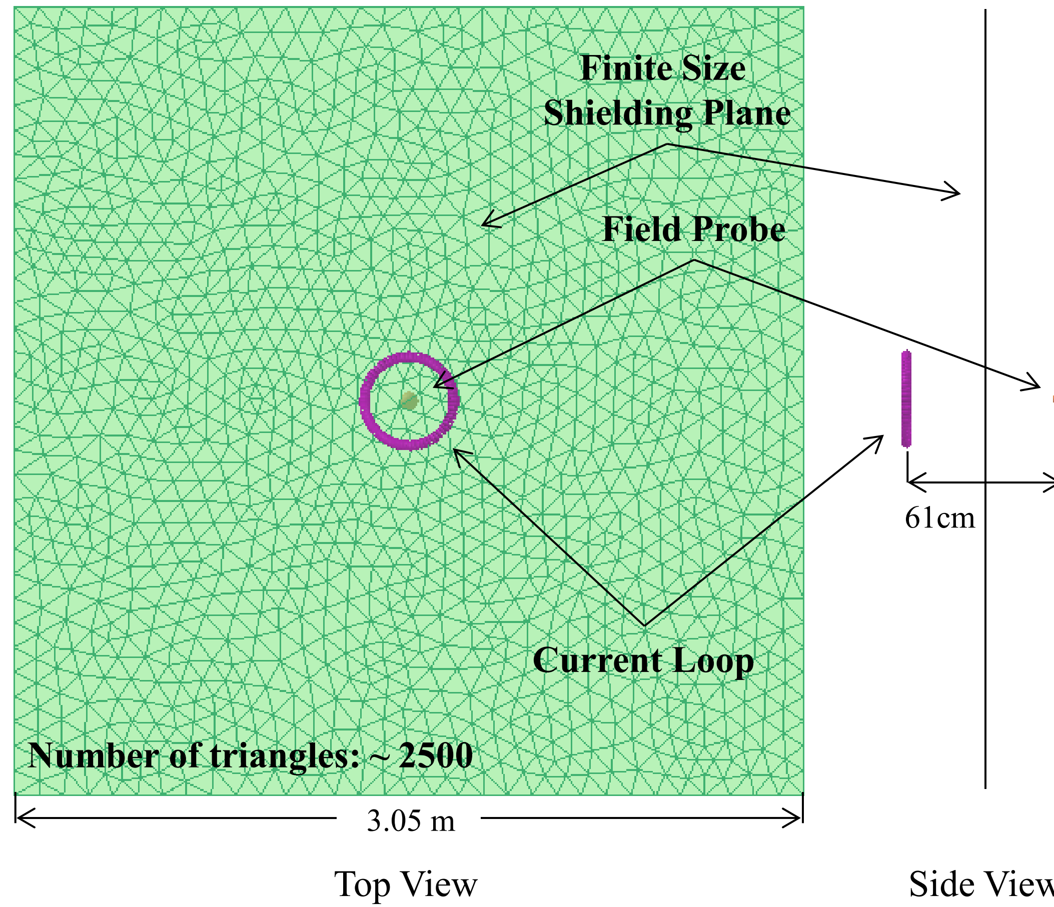
Parallel Loop Excitation - Geometry and Model



The loop center is at the XYZ origin and the loop is in XY plane.

Magnetic field is monitored at symmetric location behind the shielding plane at:

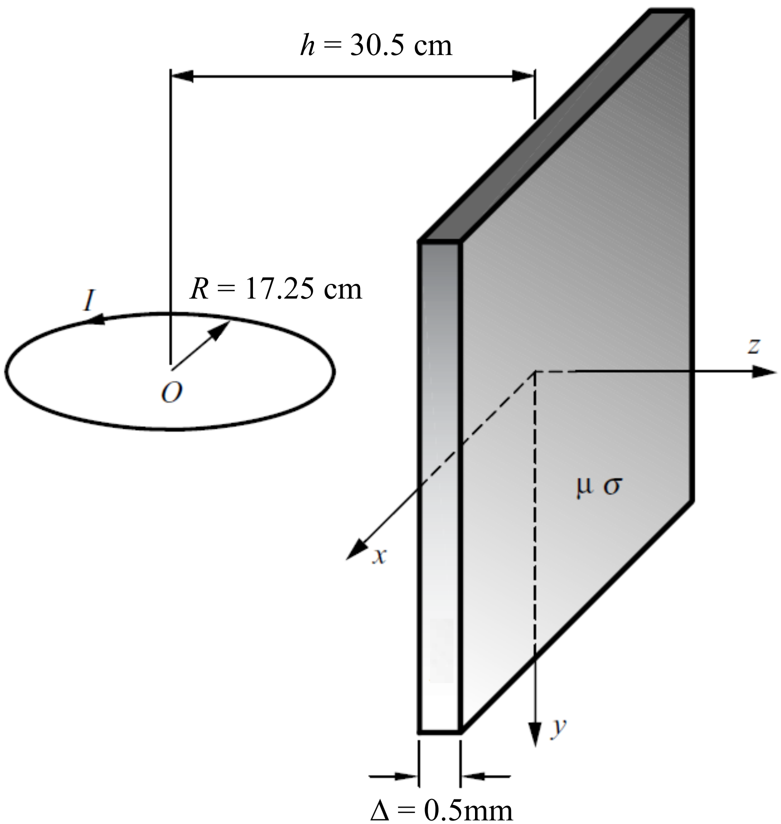
$$Z = 2h = 61 \text{ cm}$$

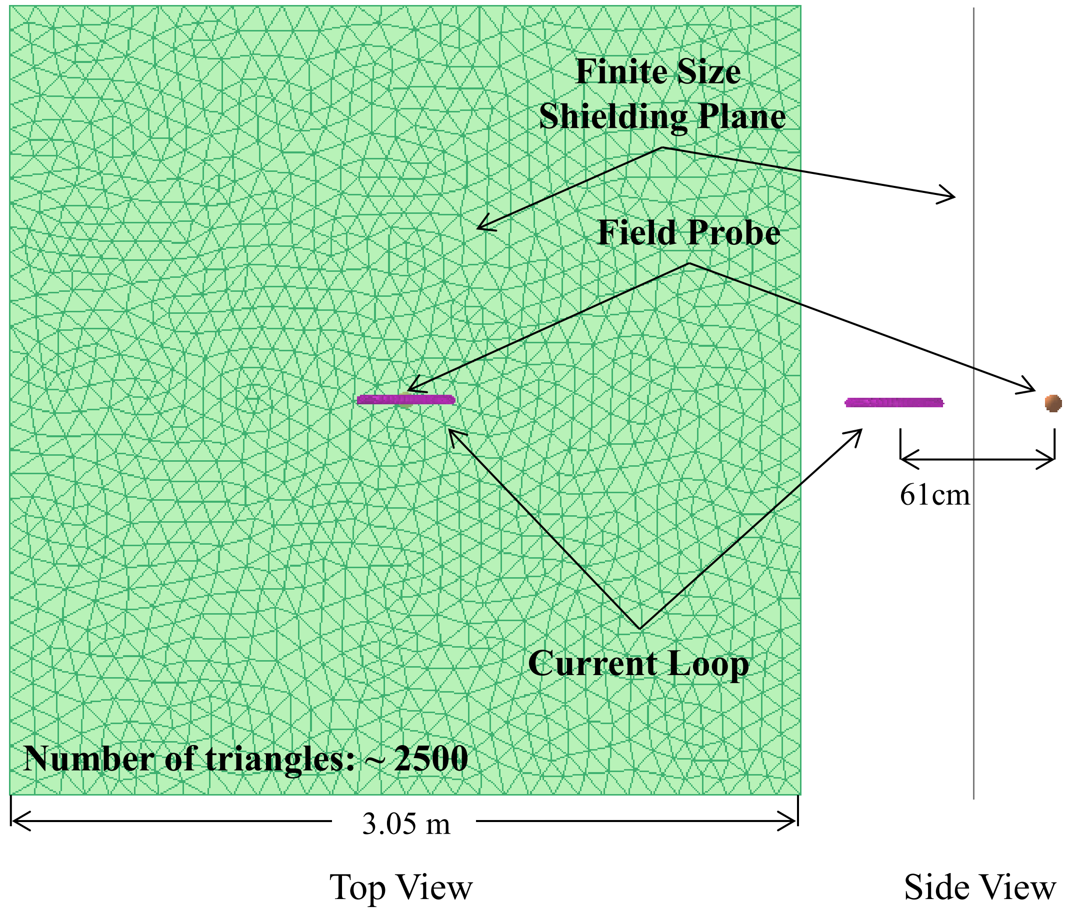


In simulation model the infinite plate was replaced by a sufficiently large plate with length and width: $a = 7h = 3.05$ m.

Modeling is performed in **EMCoS EMC Studio** [4] using Low Frequency Magnetic Field solver [5, 6].

Perpendicular Loop Excitation - Geometry and Model





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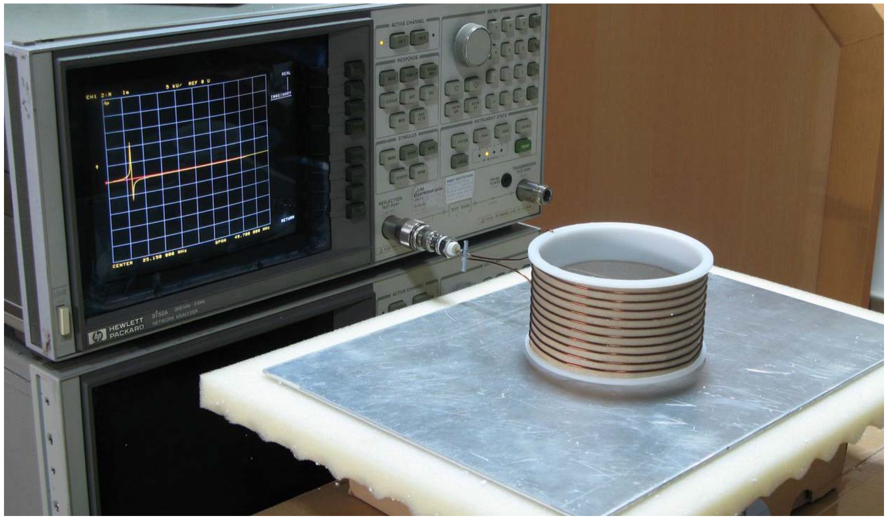
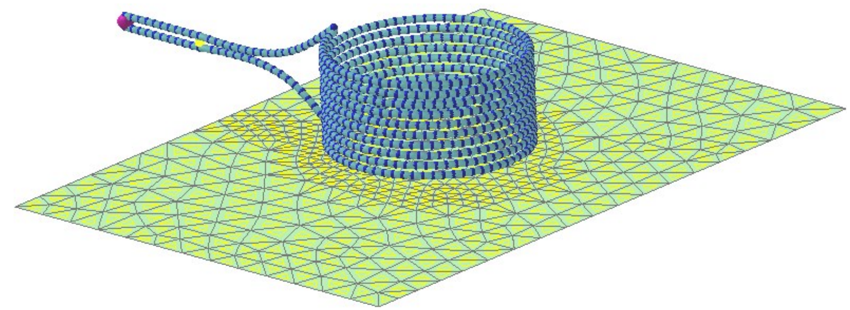
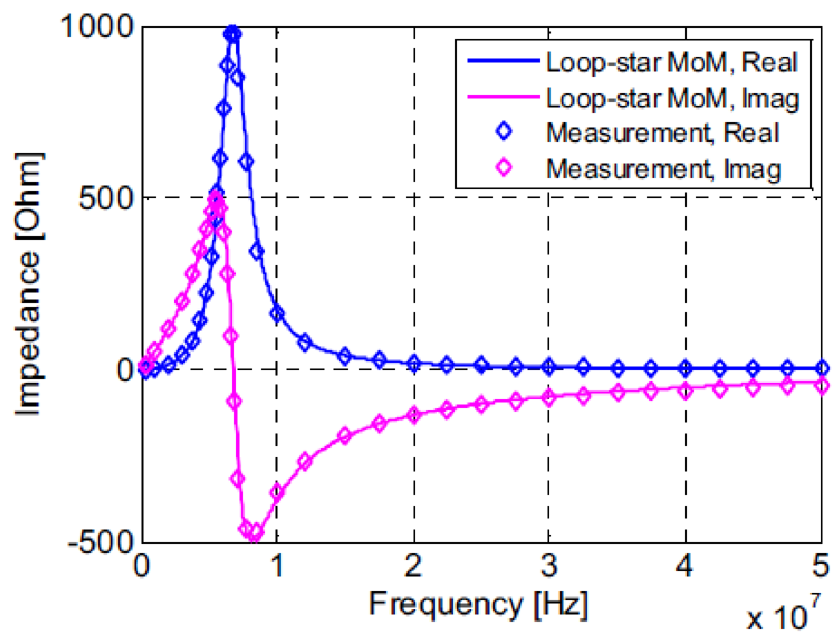
LF Modeling and Measurements: Loop over Al Plate [6]





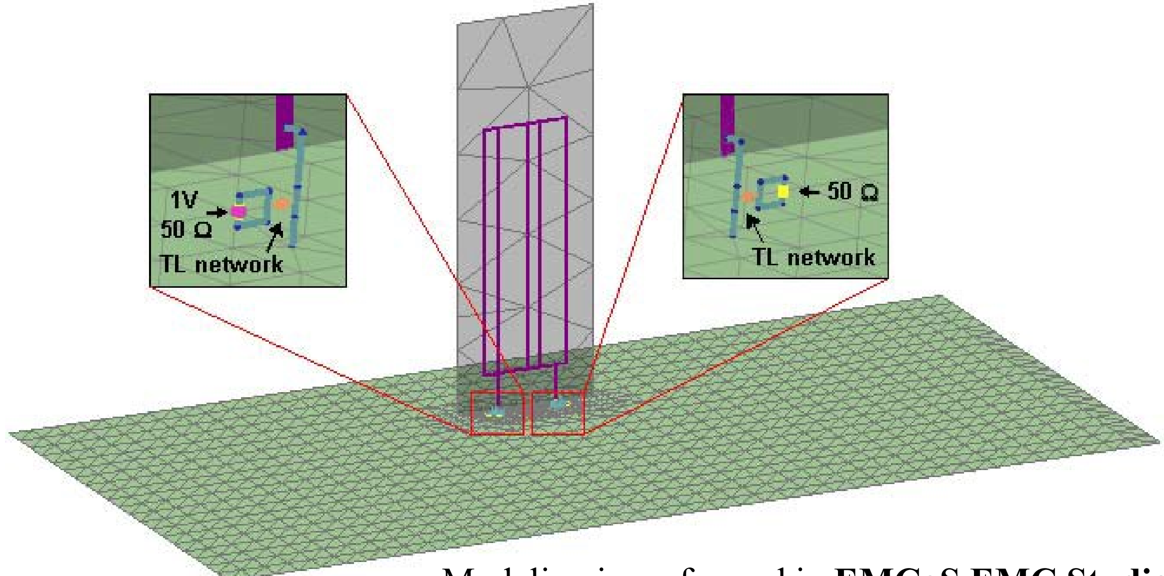
Modeling is performed in **EMCoS EMC Studio.**



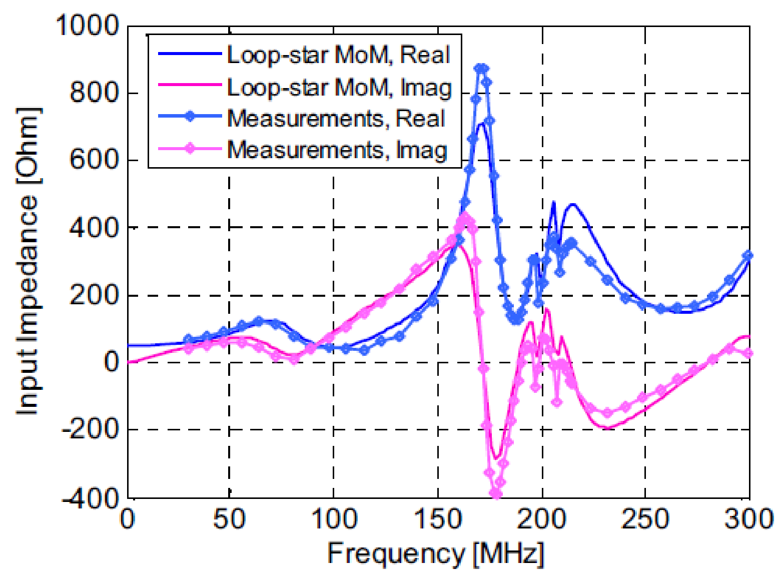
Number of coil turns: 10
Coil Radius: 51.3 mm
Height of the coil: 53 mm
Wire radius: 3.53 mm

Very good agreement between modeling and measurement for input impedance.

LF Modeling vs. Measurements: Printed Loops over Al [6]

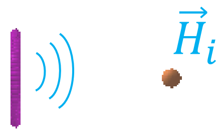


Modeling is performed in **EMCoS EMC Studio.**



Calculation of Shielding Effectiveness

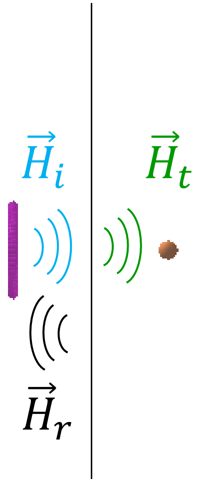
Step 1: Calculation of $\vec{H}_i$ (Incident Magnetic Field) without shield.



Step 1

Step 2: Calculation of $\vec{H}_t$ (Transmitted Magnetic Field) with shield.

Step 3: *Shielding Effectiveness* is a ratio of the magnitude of the incident magnetic (electric) field without shield, with the magnitude of the transmitted magnetic (electric) field through the shield [2].



Step 2

In terms of magnetic field, the *shielding effectiveness* could be defined as:

$$SE_{dB} = 20\log_{10}\left|\frac{\vec{H}_i}{\vec{H}_t}\right|$$

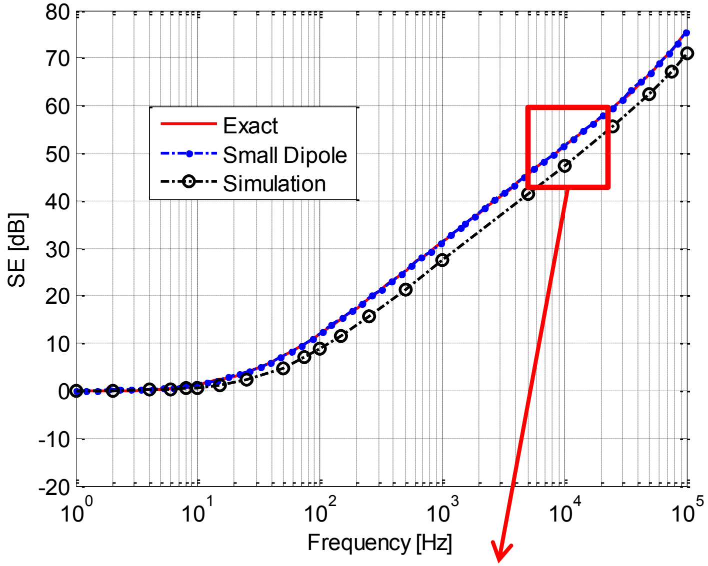
In terms of electric field, the *shielding effectiveness* could be defined as:

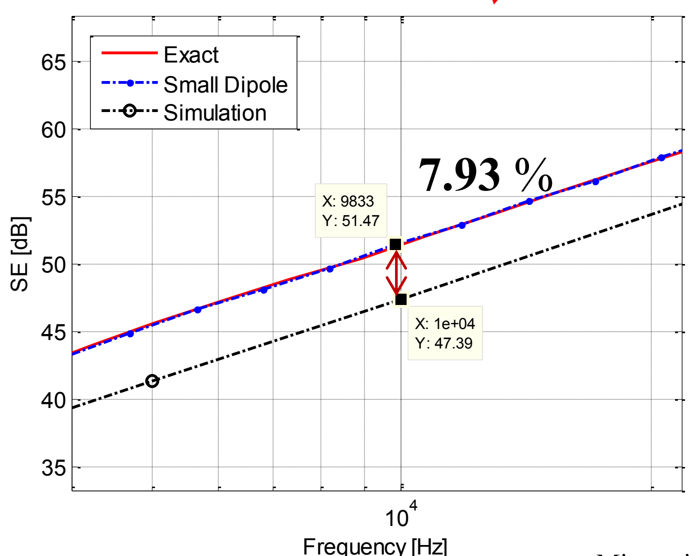
$$SE_{dB} = 20\log_{10}\left|\frac{\vec{E}_i}{\vec{E}_t}\right|$$

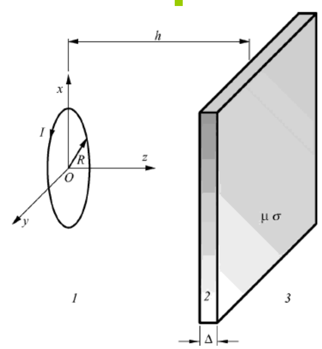
Parallel Loop – Simulation Results Validation

COPPER

$\mu = 1 \quad \sigma = 54 \times 10^6$ [S/m] $\quad \Delta = 0.5$ mm



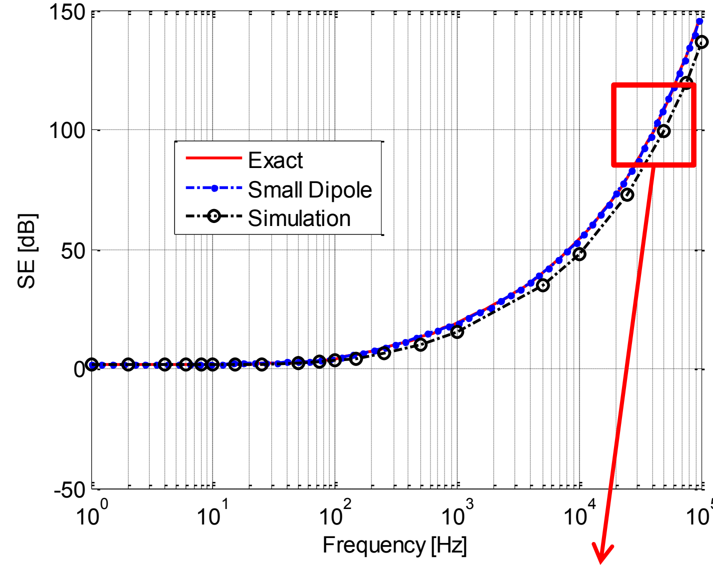


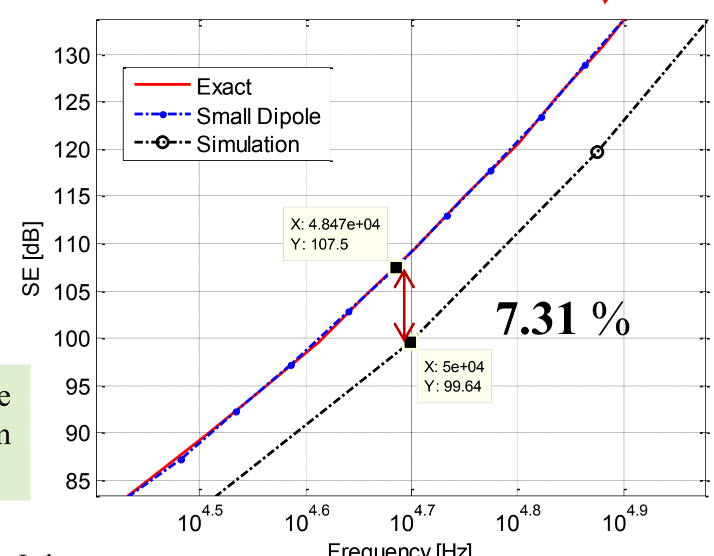


Exact and Small Dipole curves are provided from [1], Fig. B.12, pg. 306

1010 LOW CARBON STEEL

$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m] $\quad \Delta = 0.5$ mm





Parallel Loop – Simulation Results Validation

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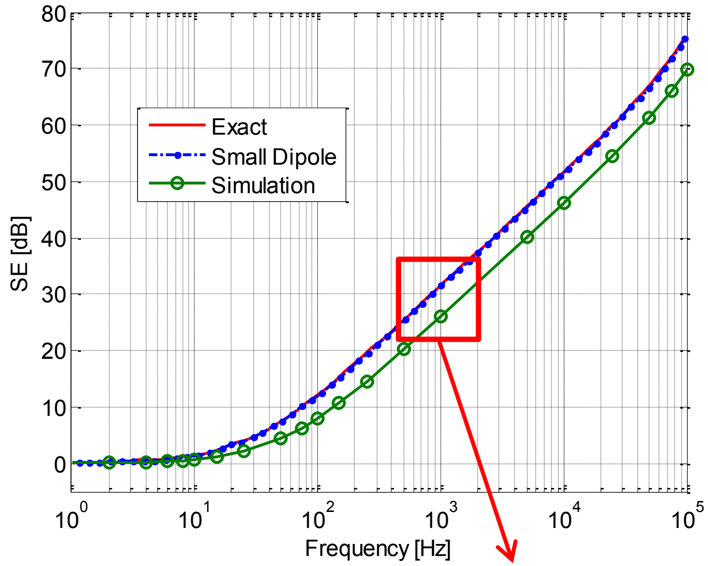
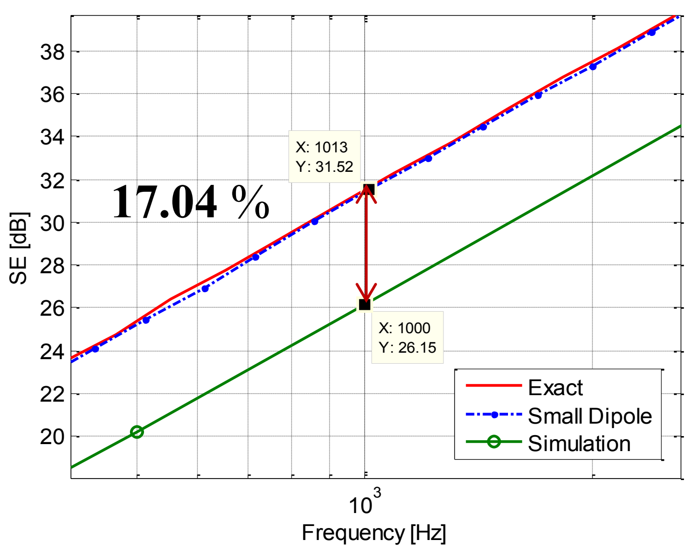
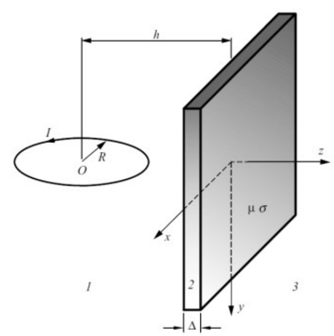


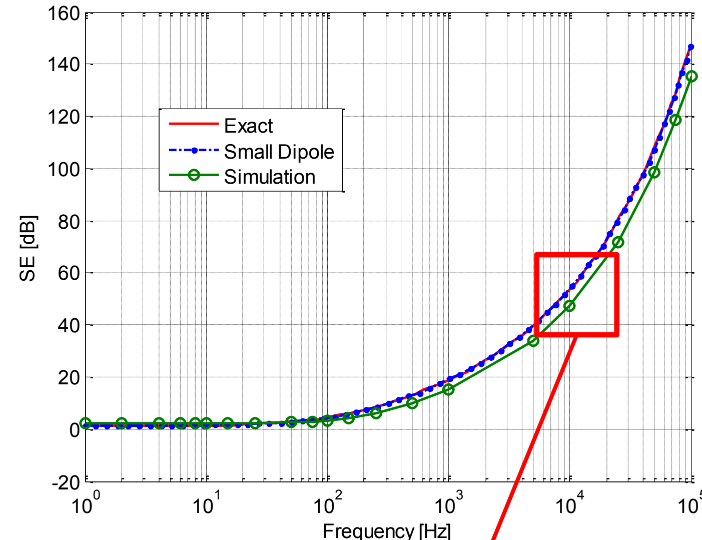


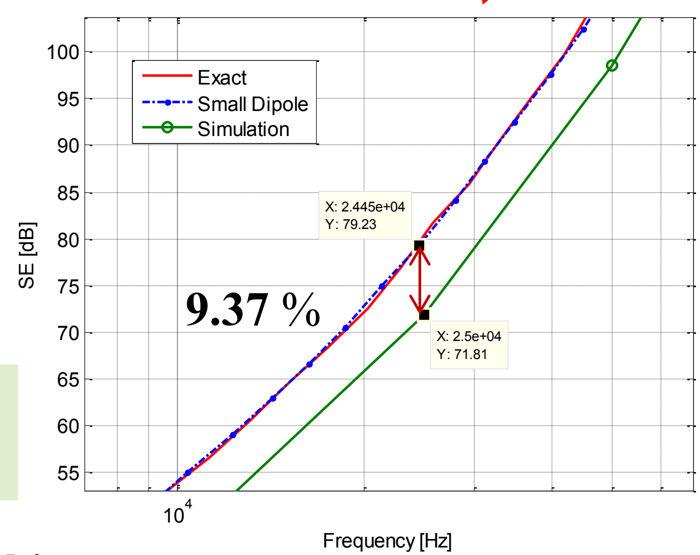


Exact and Small Dipole curves are provided from [1], Fig. B.14, pg. 309

1010 LOW CARBON STEEL

$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m] $\quad \Delta = 0.5$ mm





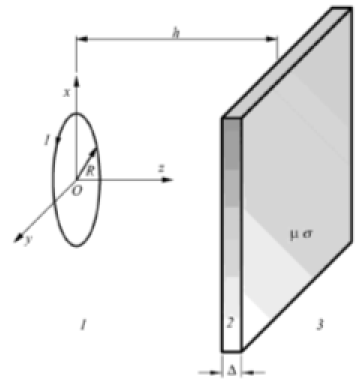
Simulation - Thickness Variation Test

COPPER

μ =1   σ = 54 x 10^6 [S/m]   Δ = 0.5 mm

At **10 KHz** frequency:

Thickness	SE
15 um	~ 17.1 dB
50 um	~27.4 dB
100 um	~33.3 dB



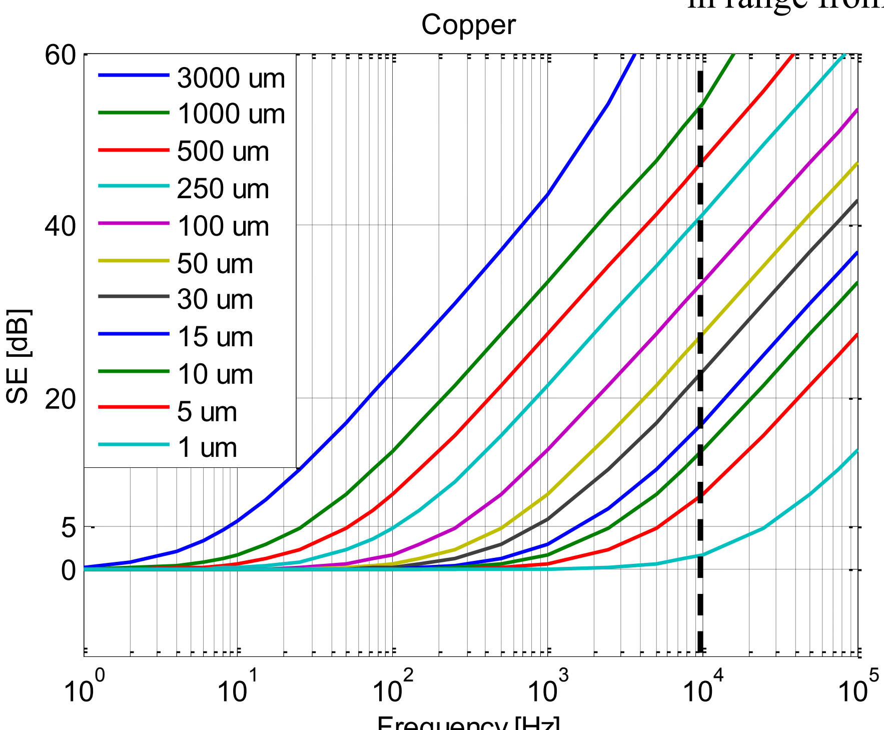
Shielding plate thickness, Δ was swept in range from 1 micron to 3 mm.

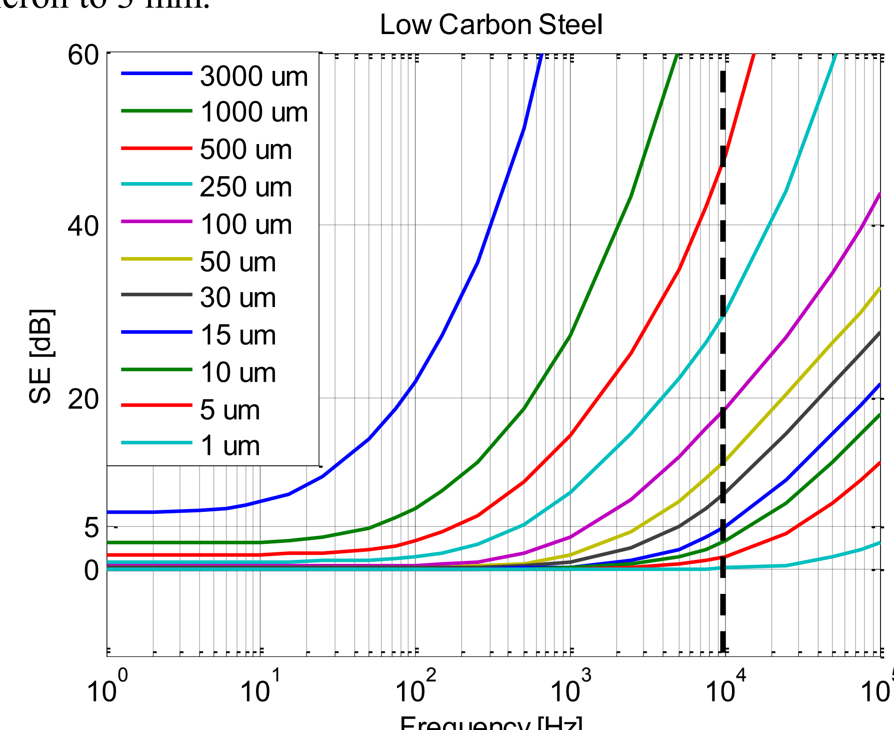
1010 LOW CARBON STEEL

μ =200 σ = 9 x 10^6 [S/m] Δ = 0.5 mm

At **10 KHz** frequency:

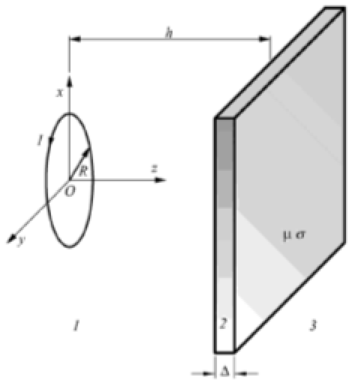
Thickness	SE
15 um	~ 5 dB
50 um	~12.7 dB
100 um	~18.7 dB

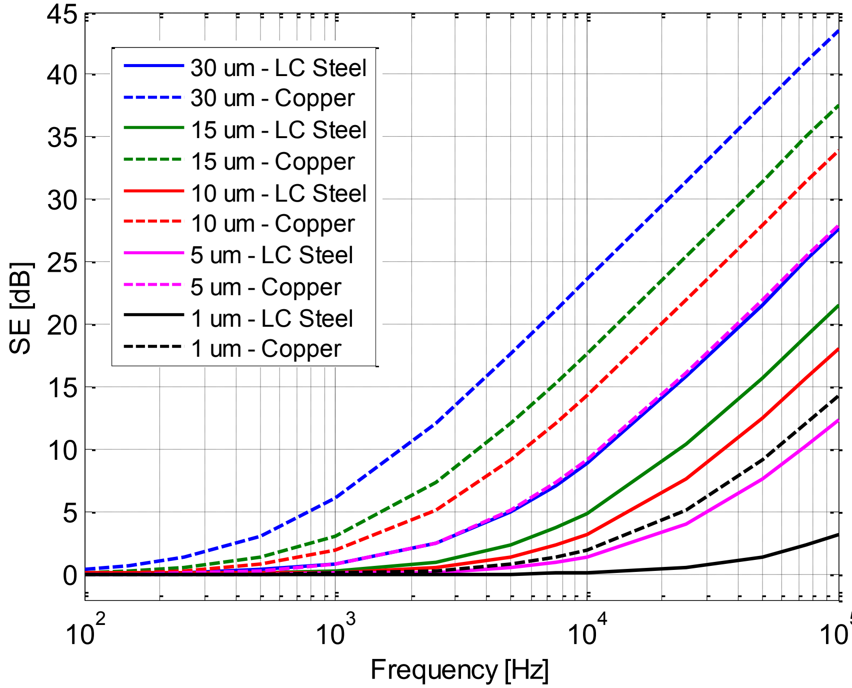


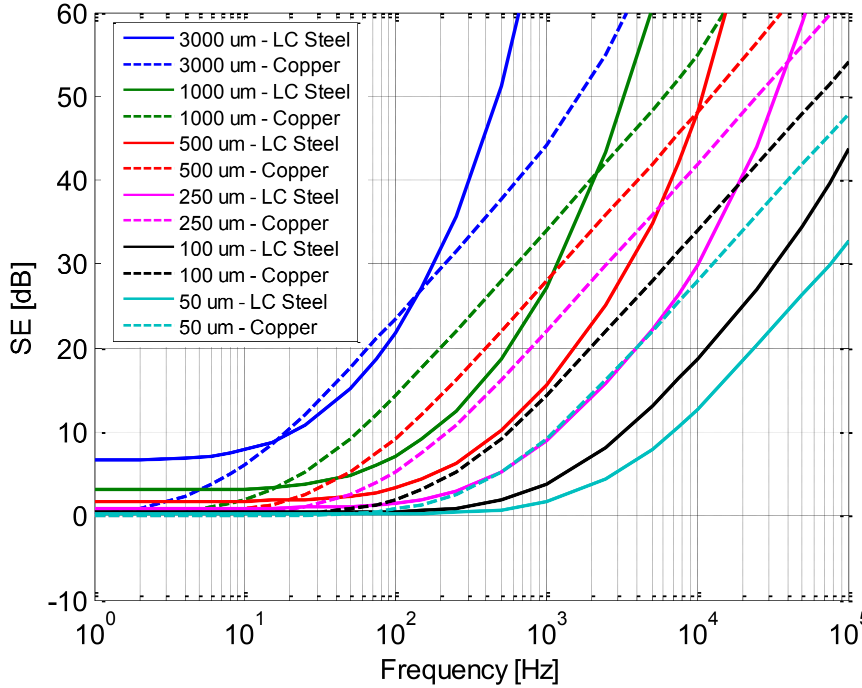


Copper and Low Carbon Steel

Comparison of SE for Copper and Low Carbon Steel for different thicknesses:







COPPER

$\mu = 1 \quad \sigma = 54 \times 10^6$ [S/m]

1010 LOW CARBON STEEL

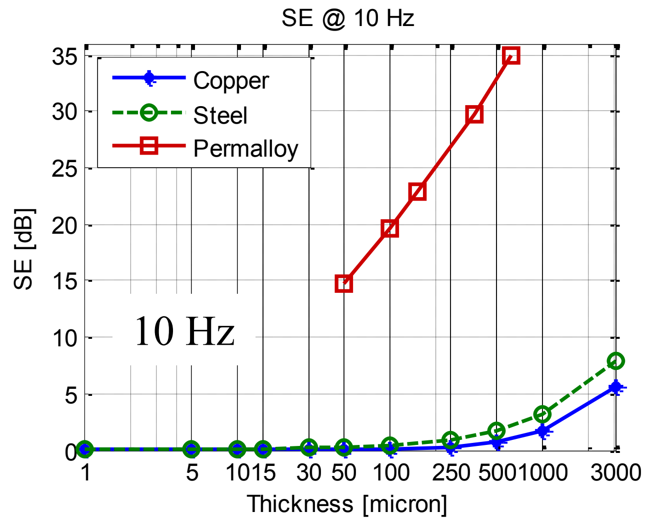
$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m]

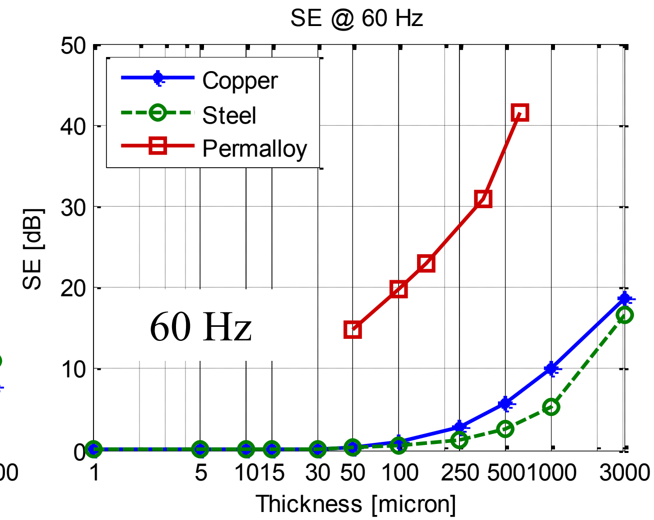
SE vs. Thickness @ 10Hz, 60Hz, 100Hz, 1KHz, 100KHz

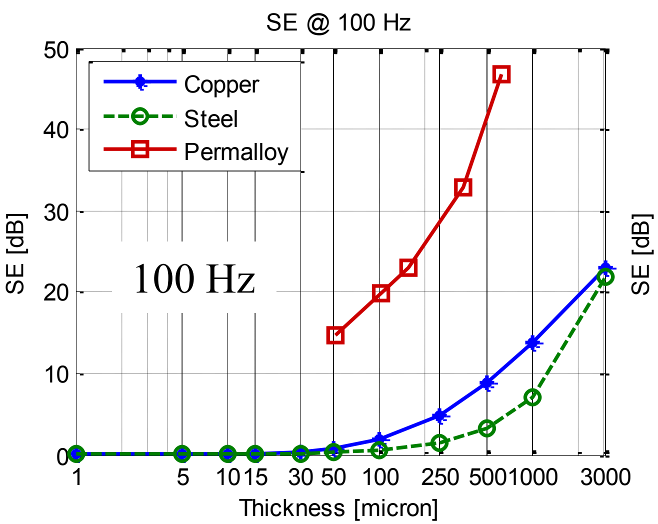
COPPER
$\mu = 1 \quad \sigma = 54 \times 10^6$ [S/m]

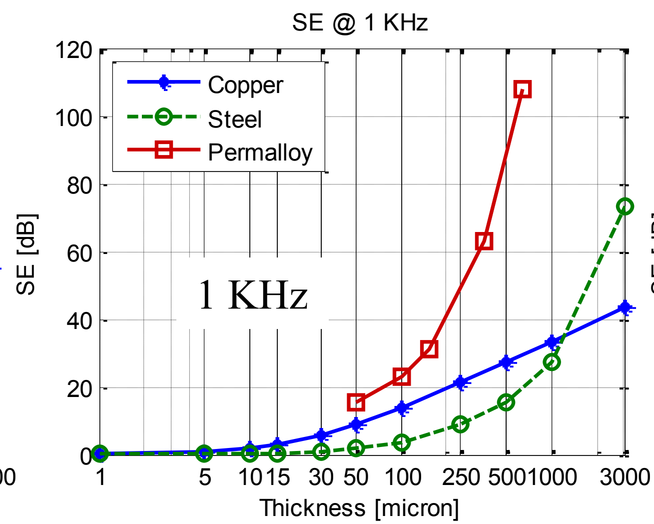
1010 LOW CARBON STEEL
$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m]

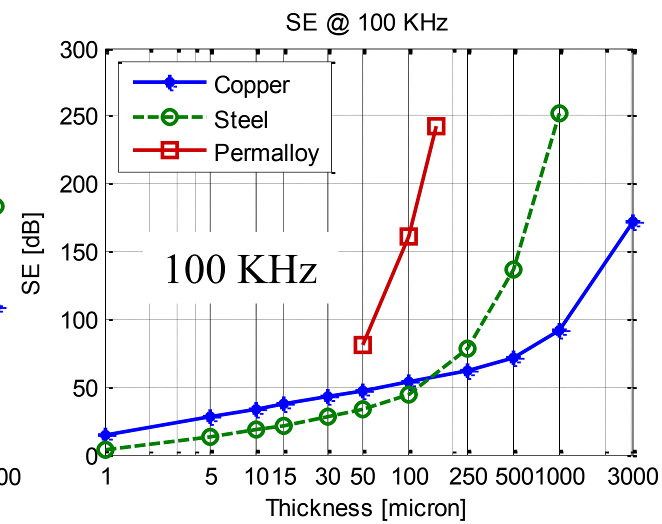
PERMALLOY
$\mu = 50000 \quad \sigma = 1.7 \times 10^6$ [S/m]



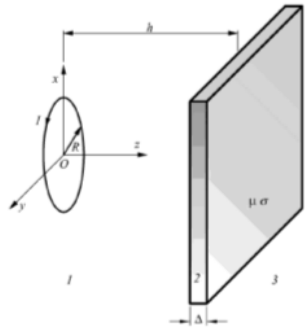








SE vs. Thickness @ 10Hz, 60Hz, 100Hz, 1KHz, 100KHz

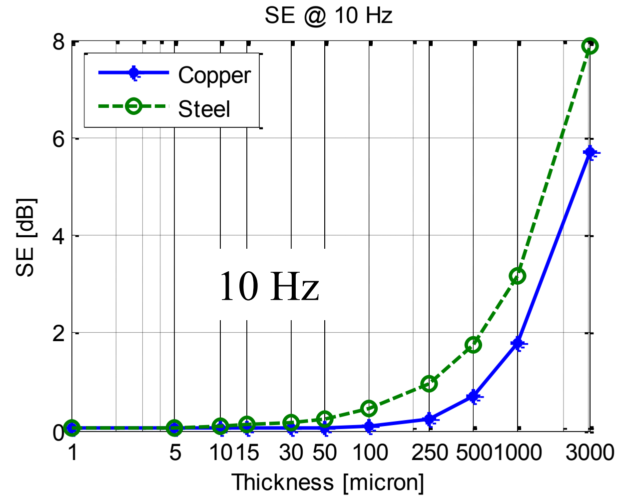


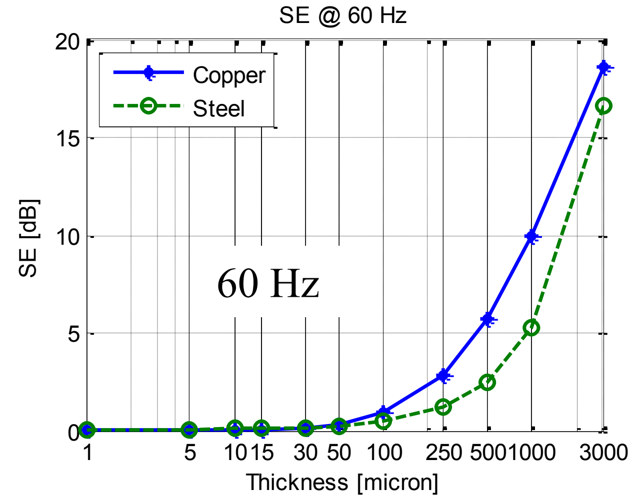
COPPER

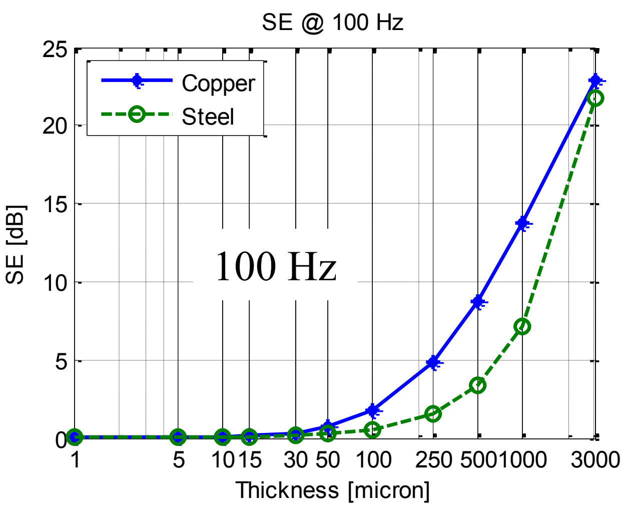
$\mu = 1 \quad \sigma = 54 \times 10^6$ [S/m]

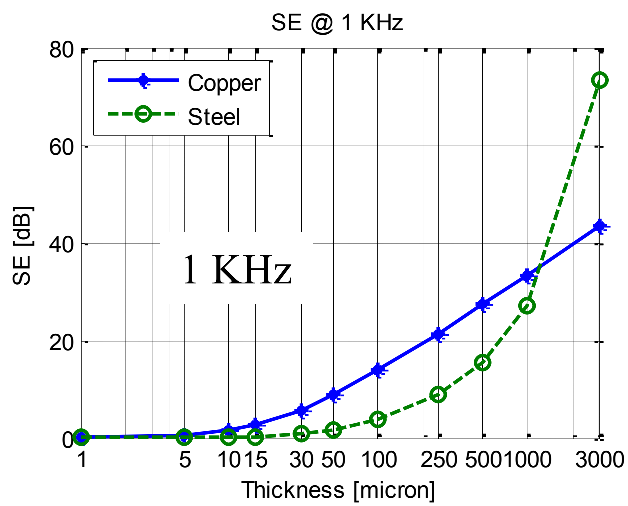
1010 LOW CARBON STEEL

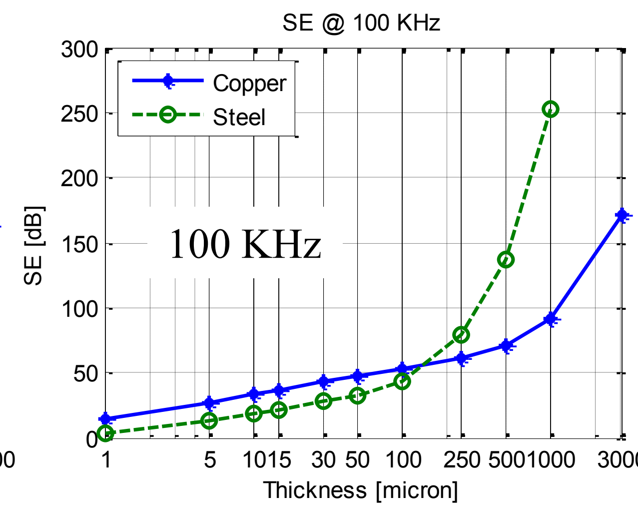
$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m]



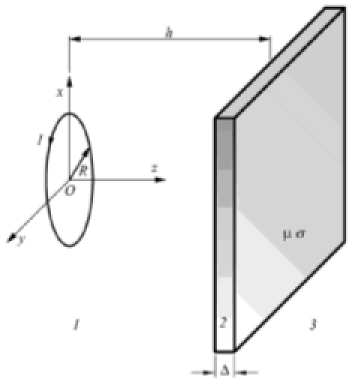




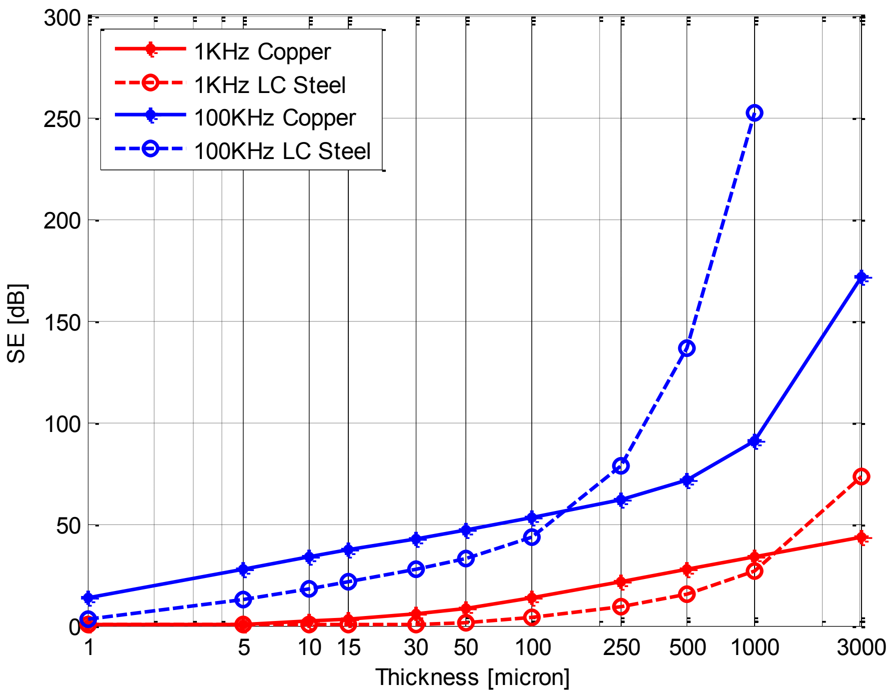


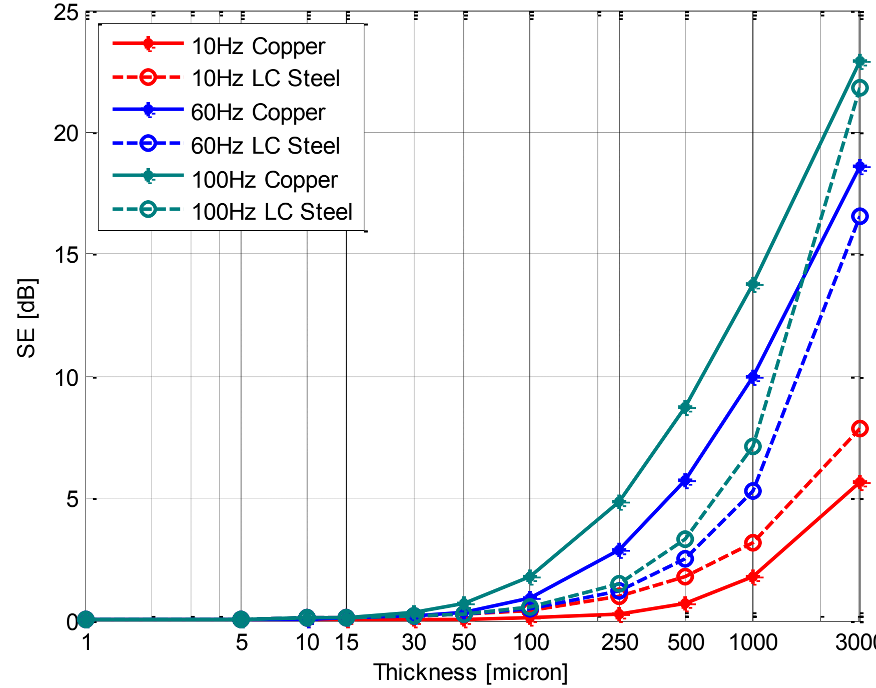


SE vs. Thickness



SE vs. Thickness @ 1KHz, 100KHz





SE vs. Thickness @ 10Hz, 60Hz, 100Hz

COPPER

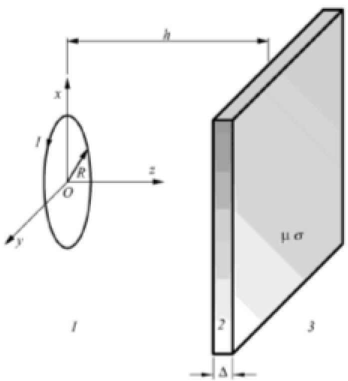
$\mu = 1 \quad \sigma = 54 \times 10^6$ [S/m]

1010 LOW CARBON STEEL

$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m]

Permeability Variation - Low Carbon Steel - 10 KHz

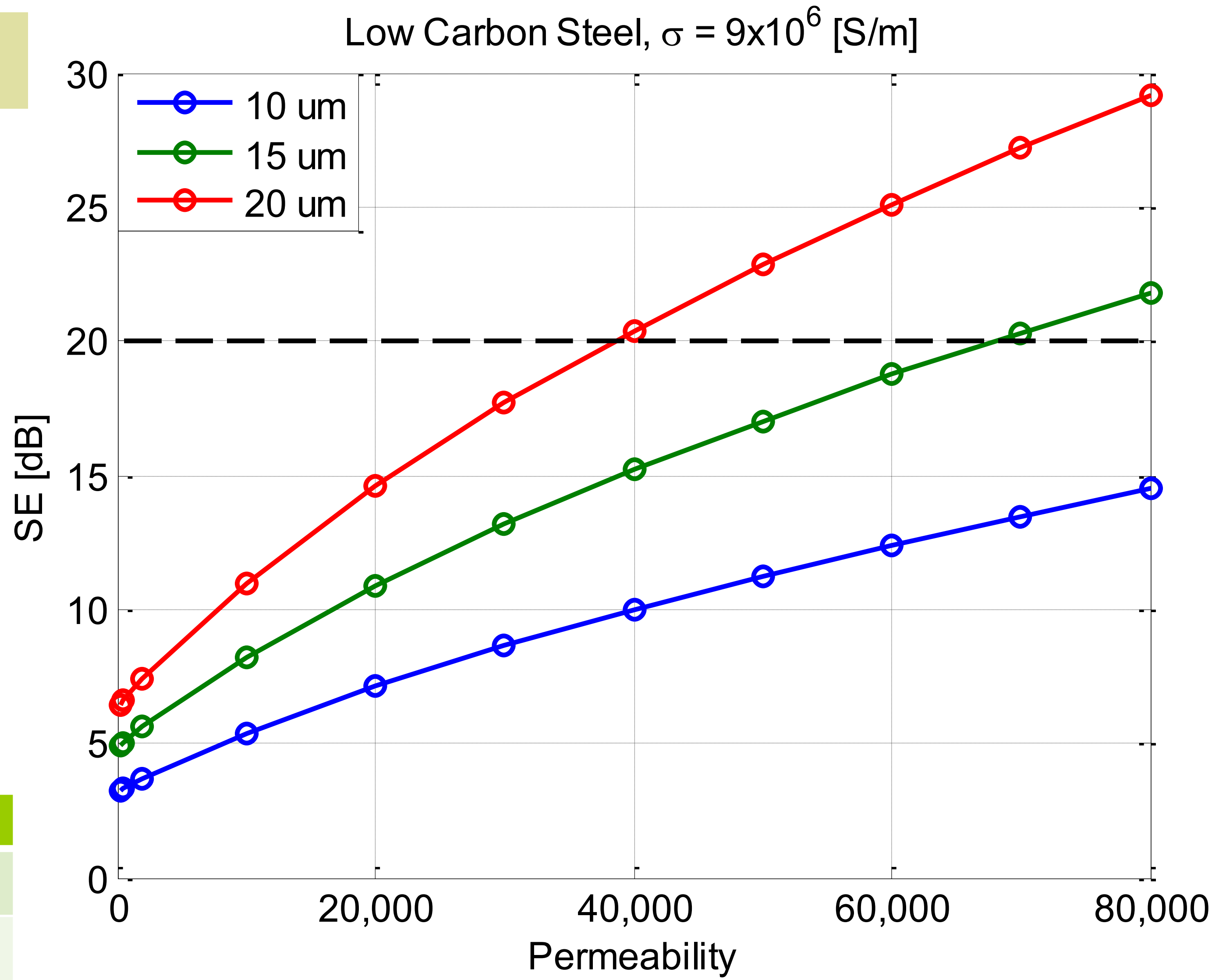
1010 LOW CARBON STEEL
$\sigma = 9 \times 10^6$ [S/m]



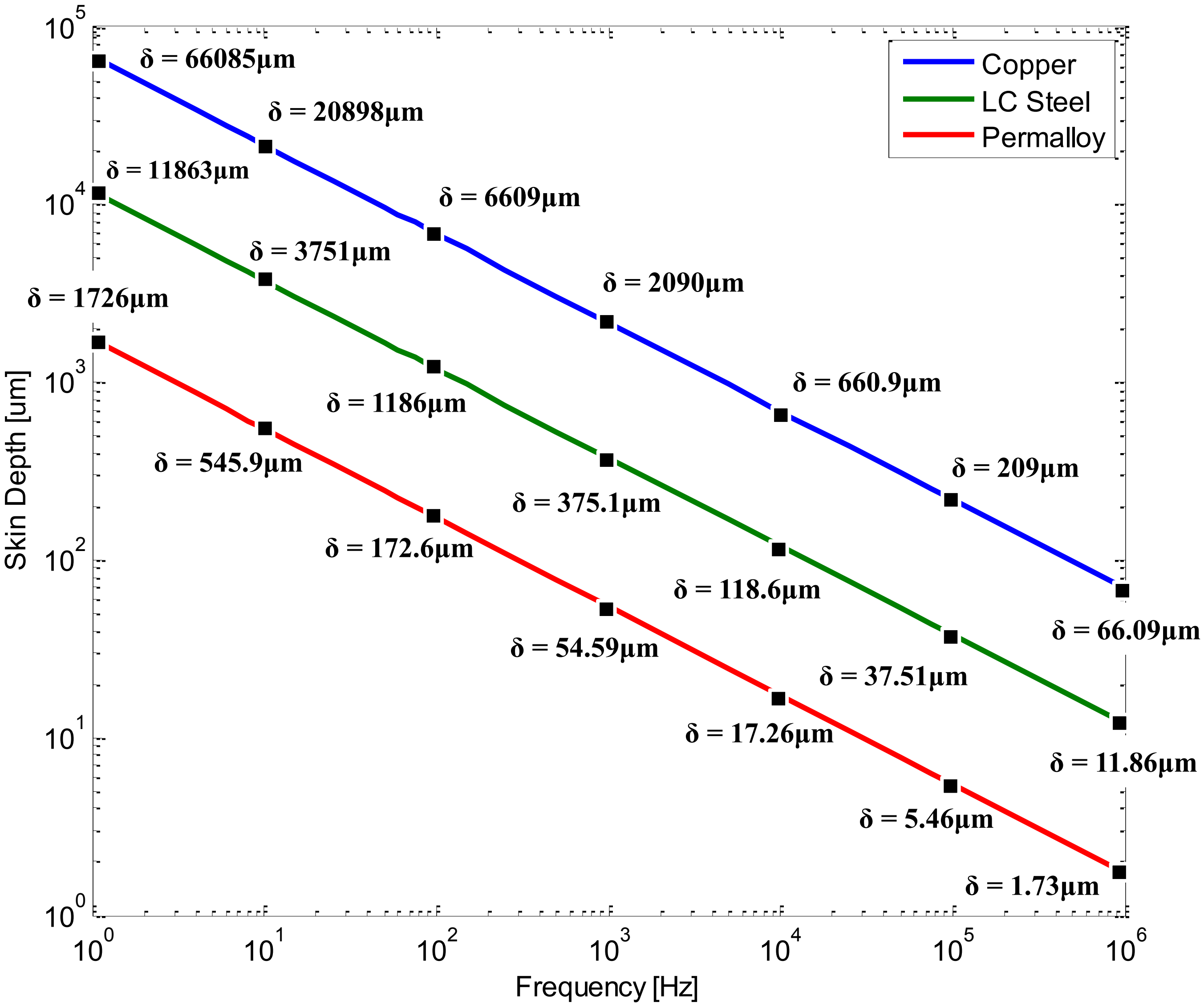
With fixed steel conductivity, permeability was tested in the range of values from $\mu = 200$ up to $\mu = 80000$ to find out required value to achieve 20 dB Shielding Effectiveness Spec.

20 dB SE **@ 10 KHz** requires:

Thickness	Permeability μ
10 um	~120,000
15 um	~70,000
20 um	~40,000



Skin Depth vs. Frequency



$$skin\ depth\ \delta = \sqrt{\frac{2}{2\pi f \mu\sigma}}$$

1010 LOW CARBON STEEL

μ =200 σ = 9 x 10^6 [S/m]

COPPER

μ =1 σ = 54 x 10^6 [S/m]

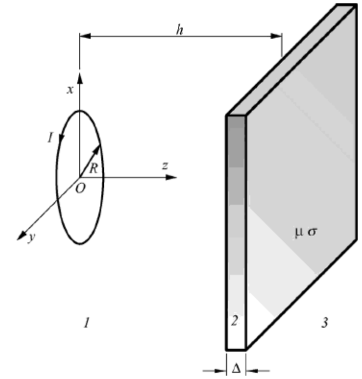
PERMALLOY

μ =50000 σ = 1.7 x 10^6 [S/m]

Parallel Loop - Bannister Approximation

Two quasi-near approximations are introduced:

1. When the measurement distance is much smaller than the operating wavelength ($L \ll \lambda_0$), the propagation constant in air can be neglected
2. When the measurement distance is much greater than the skin depth in the shield ($L \gg \delta$) and the shield is thicker than twice the skin depth, the integration variable λ can be neglected



Bannister Approximation in the low-frequency case [1]:

With the following assumptions:

- $L \ll \lambda_0$
- $L \gg \delta$
- $\Delta/\delta > 0.5$
- $L/(\delta\mu_r) > 10$

$$SE_{dB} = 8.686\frac{\Delta}{\delta} + 20log_{10}\left[\frac{L}{8.485\mu_r\delta}\frac{L}{(z-\Delta)}\left(\frac{L}{\sqrt{R^{2+}z^2}}\right)^3\right] \quad (1)$$

Absorption A term in the TL theory of planar shield

Reflection coefficient R term in the TL theory of planar shield

$$SE_{dB} = A + R$$

$\Delta = 0.5\text{mm}$ – Shield Thickness

$\delta = \sqrt{\frac{2}{2\pi f\mu\sigma}}$ – Skin Depth

$z = 1\text{m}$ – Distance from the loop center to field probe

$R = 2\text{cm}$ – Loop radius

$L = \sqrt{R^2 + (z-\Delta)^2}$ – Measurement distance

R – *reflection-loss* term, due to the mismatch between the two impedances at both interfaces.

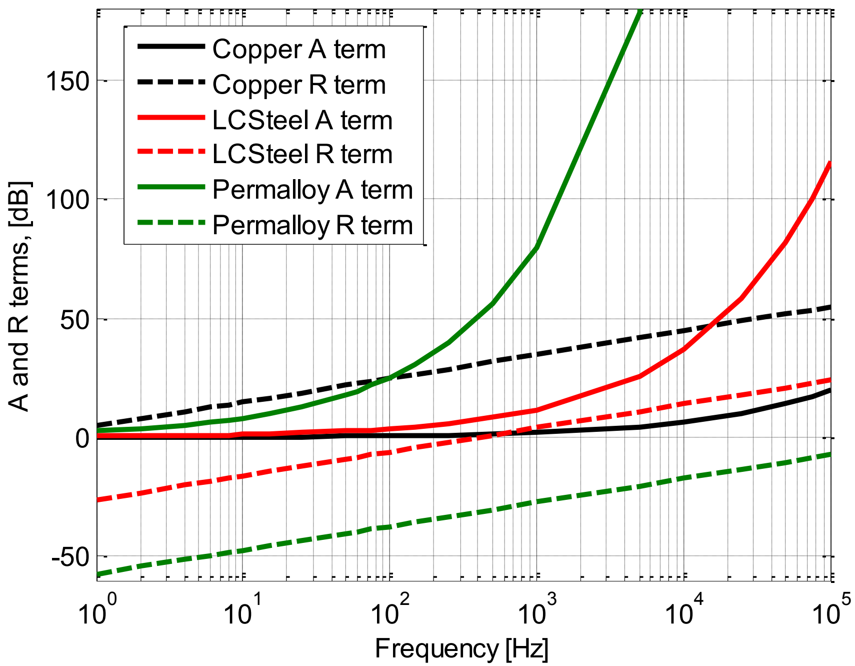
A – *absorption-loss* term, a function of shield characteristics.

Bannister Approximation - >100Hz

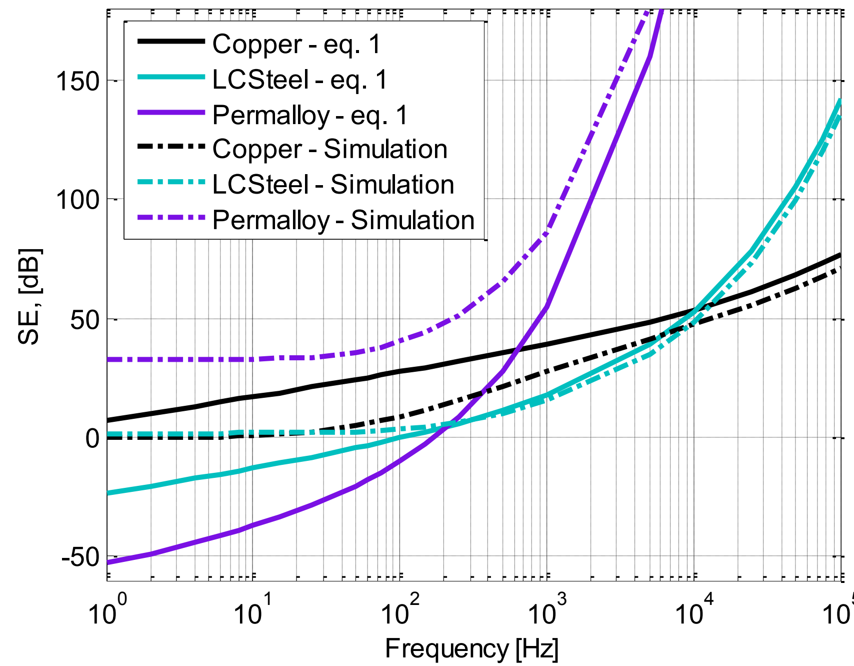
COPPER
$\mu = 1 \quad \sigma = 54 \times 10^6$ [S/m]

1010 LOW CARBON STEEL
$\mu = 200 \quad \sigma = 9 \times 10^6$ [S/m]

PERMALLOY
$\mu = 50000 \quad \sigma = 1.7 \times 10^6$ [S/m]



A and R terms according to the eq. (1)



For Copper restriction $\Delta/\delta > 0.5$ is not fulfilled.
For Permalloy restriction $L/(\delta\mu_r) > 10$ is not fulfilled.

If the shield is thinner compare to the skin depth, multiple reflections occurs between boundaries, because of the small absorption loss [**].

Bannister Approximation is good as long as the quasi-near approximation restrictions are fulfilled, for frequencies **>100Hz**.

[*] S. Celozzi, R. Araneo, G. Lovat, "Electromagnetic Shielding", *John Wiley & Sons, Inc., 2008,* Fig. B.12, page 306
[**] H. W. Ott, "Electromagnetic Compatibility Engineering", *John Wiley & Sons, Inc., 2009, Chapter 6*, page 251

TL theory Approximation [7] – Steel, Permalloy

With the additional assumptions: $K > 10$ and $\mu_r \not\cong 1$

$$SE_{dB} \cong 8.686\frac{\Delta}{\delta} + 20log_{10}[0.354K^{-1} + 0.118K + 0.408] \quad (2)$$

Absorption A term

$$SE_{dB} = A + R$$

Reflection coefficient R term

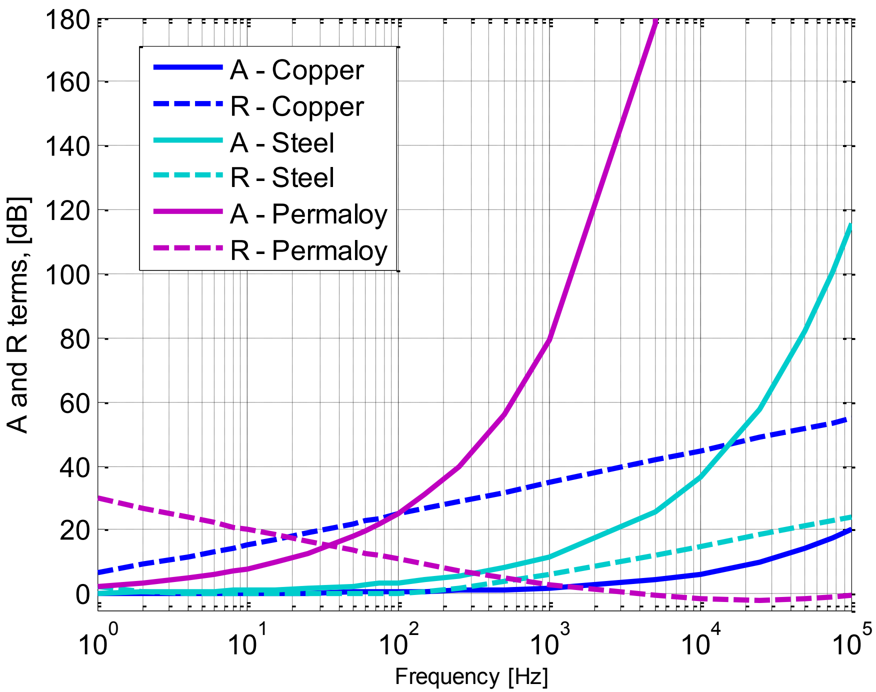
COPPER
μ =1   σ = 54 x 106 [S/m]

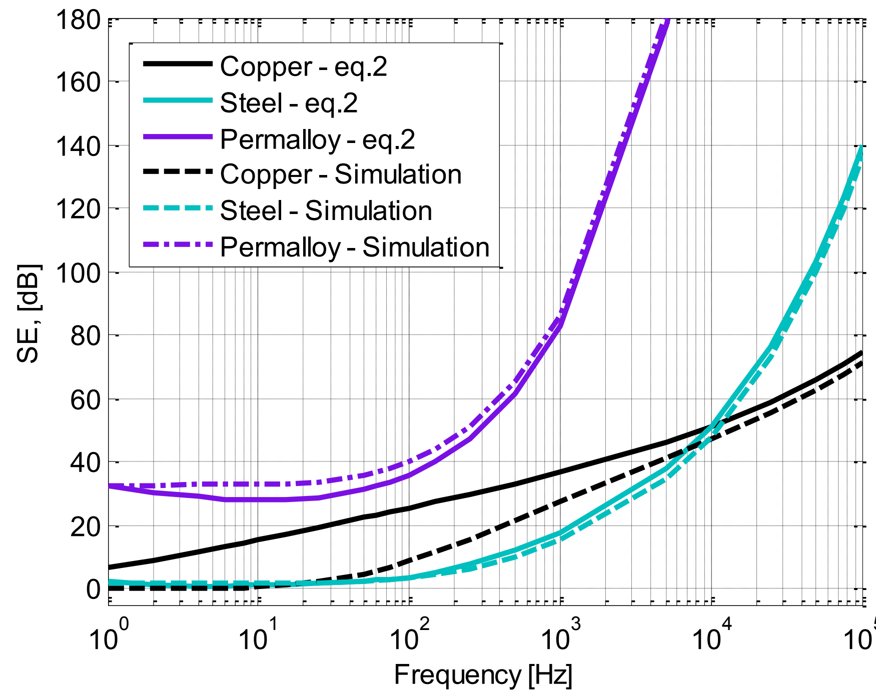
1010 LOW CARBON STEEL
μ =200   σ = 9 x 106 [S/m]

PERMALLOY
μ =50000   σ = 1.7 x 106 [S/m]

$$K = \frac{z}{\delta \mu_r}$$

For materials with $\mu_r \approx 1$, expression (2) is not valid [7].





TL theory Approximation [7] – Copper, Steel

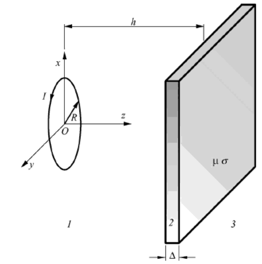
With the following assumptions: $L \gg \lambda_0,\ L > 10\delta,\ \Delta > 2\delta,\ z \gg \Delta$

$$SE_{dB} \cong 8.686\frac{\Delta}{\delta} + 20log_{10}\left[\frac{1}{8.485\delta\mu_r}\frac{R^2+z^2}{z}\right] \quad (3)$$

Absorption A term

$$SE_{dB} = A + R$$

Reflection loss R term

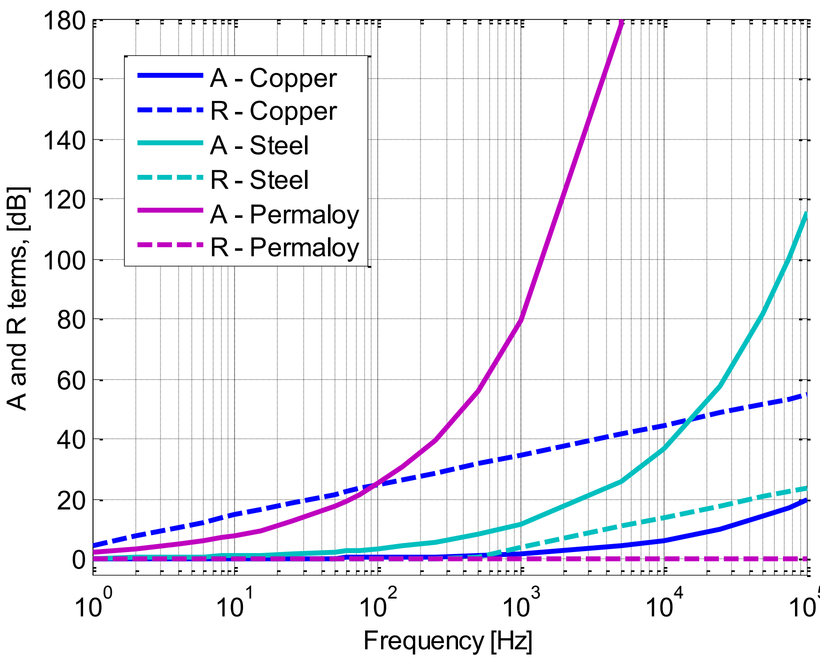


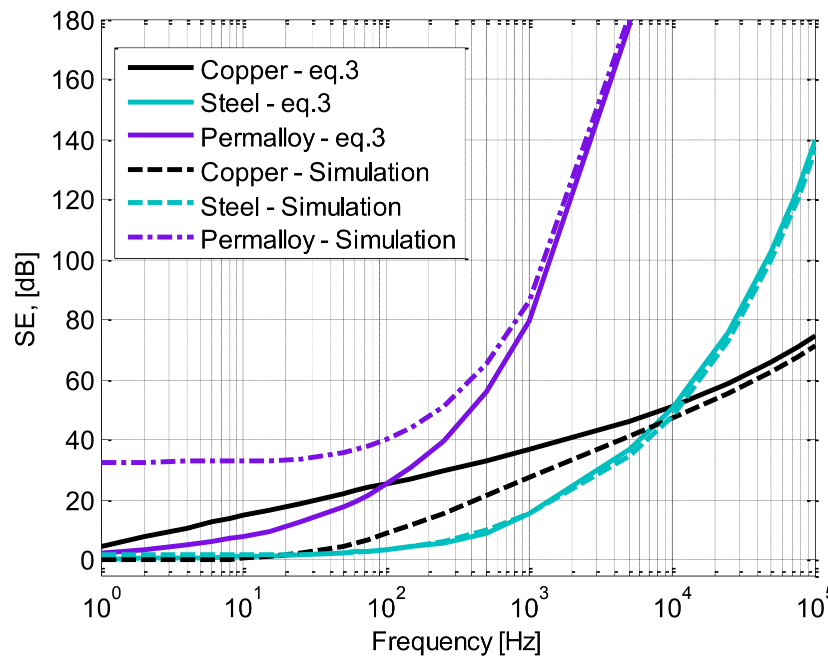
1010 LOW CARBON STEEL
μ =200 σ = 9 x 10^6 [S/m]

COPPER
μ =1 σ = 54 x 10^6 [S/m]

PERMALLOY
μ =50000 σ = 1.7 x 10^6 [S/m]

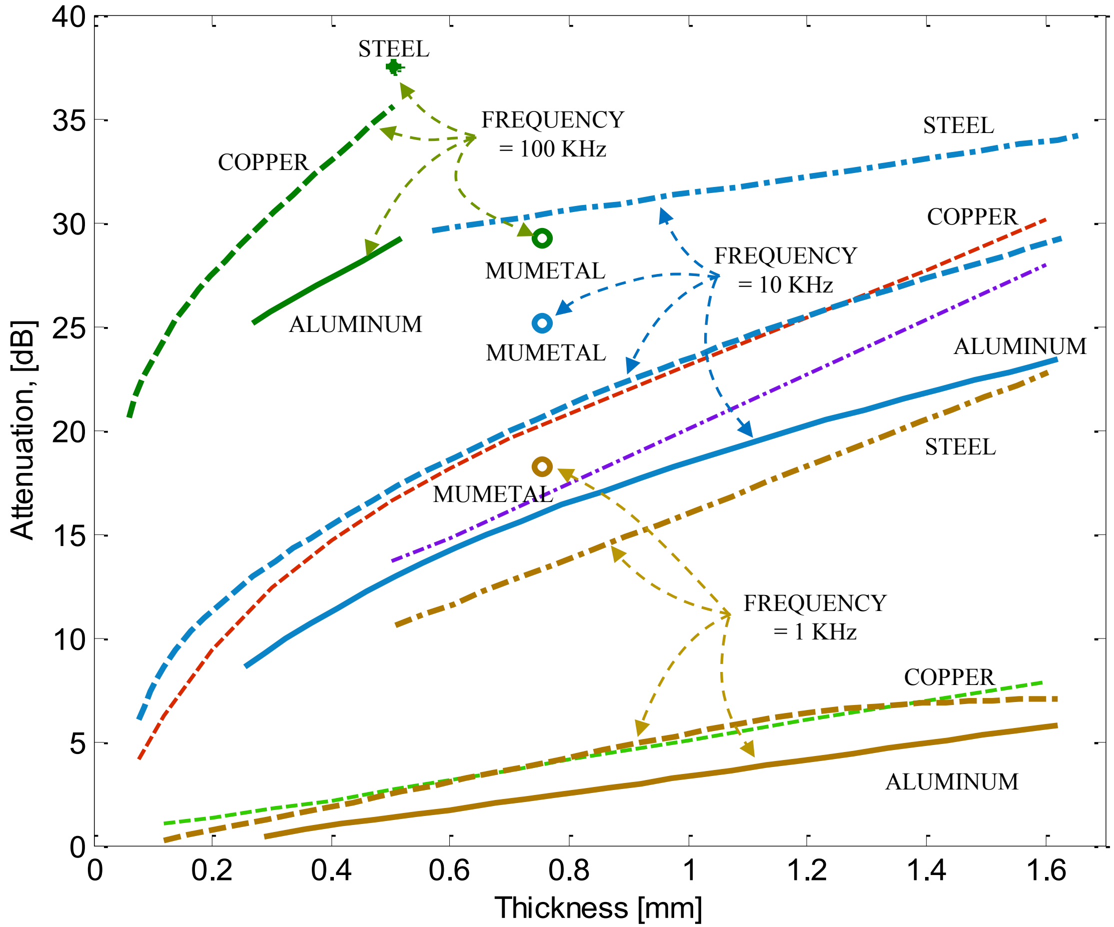
In case of a negative value of reflection loss, *R*=0 is manually defined [3].



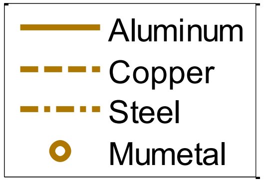


Measurement vs. Simulation

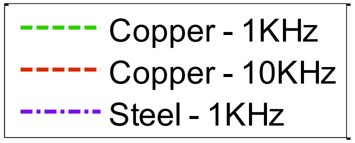
Graph represents the measured low-frequency magnetic field shielding effectiveness of various type of metallic sheets [3]. The measurements were made in the near field with the source and receptor 0.1in apart.



Measured data
At 1KHz, 10KHz, 100KHz



Dash lines
Simulation results



Material	Relative Conductivity σ_r	Relative permeability μ_r
Copper	1	1
Steel	0.02	500
Aluminum	0.61	1
Mumetal	0.03	25000

With respect to Copper.
Data is acquired from [3]

H. W. Ott, "Electromagnetic Compatibility Engineering", *John Wiley & Sons, Inc., 2009, ISBN 978-0-470-18930-6, Chapter 6.*

Absorption Loss Term

Skin depth of copper, [m]:

$$\delta_c = \frac{1}{\sqrt{\pi f \mu_0 \mu_c \sigma_{Cu}}}$$

$\mu_0 = 4\pi \cdot 10^{-7}$ – Permeability of free space
$\mu_c = 1$ – Relative permeability of copper
$\sigma_{Cu} = 5.82 \cdot 10^{7}$ – Conductivity of copper

COPPER
$\mu_r = 1$ $\sigma_{Cu} = 54 \times 10^6$ [S/m]

1010 LOW CARBON STEEL
$\mu_r = 200$ $\sigma_{rel,Cu} = 0.17$

Skin depth of arbitrary material, [m]:

$$\delta_m = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \frac{\sigma_m}{\sigma_{Cu}} \sigma_{Cu}}}$$

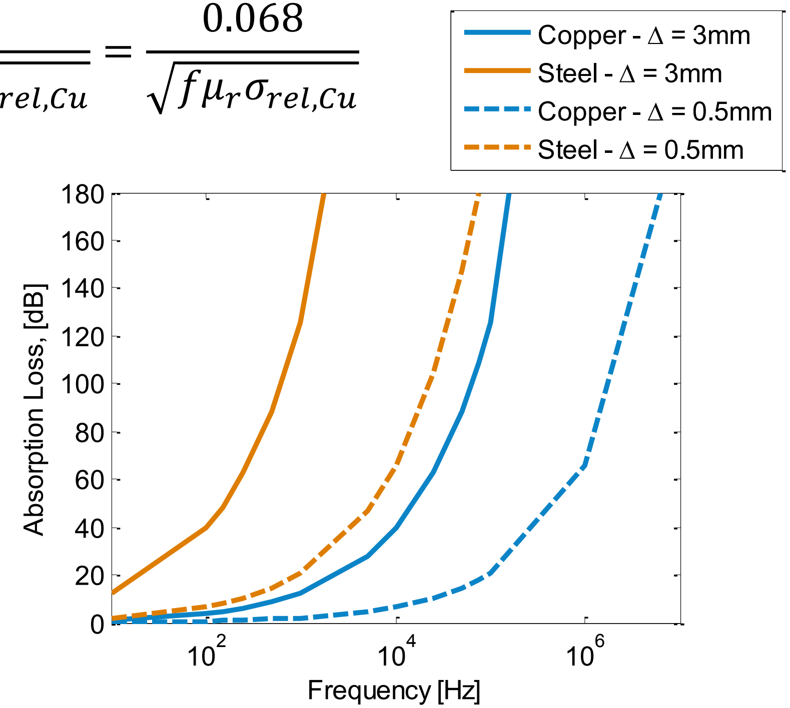
μ_r – Relative permeability of material with respect to copper
$\frac{\sigma_m}{\sigma_{Cu}} = \sigma_{rel,Cu}$ – Relative conductivity of material with respect to copper

$$\delta_m = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma_{rel,Cu}}} = \frac{1}{\sqrt{\pi \mu_0 \sigma_{Cu}}\sqrt{f \mu_r \sigma_{rel,Cu}}} = \frac{0.068}{\sqrt{f \mu_r \sigma_{rel,Cu}}}$$

$$A = 8.686 \frac{\Delta}{\delta}$$

$$A_m = 128\Delta\sqrt{f \mu_r \sigma_{rel,\,Cu}}$$

$$A_c = 128\Delta\sqrt{f}$$



Provided figure shows the advantage of steel over copper in providing absorption loss. Also thin sheet of copper has no significant loss below 1KHz.

Magnetic Field Reflection Loss

The reflection loss, R term, for magnetic field (according to eq. 3 – copper and steel):

$$R = 20log_{10}\left[\frac{1}{8.485\delta\mu_r}\frac{R^2+z^2}{z}\right] \qquad \delta_m = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma_{rel,Cu}\sigma_{Cu}}}$$

COPPER

$\mu_r = 1 \quad \sigma_{Cu} = 54 \times 10^6$ [S/m]

1010 LOW CARBON STEEL

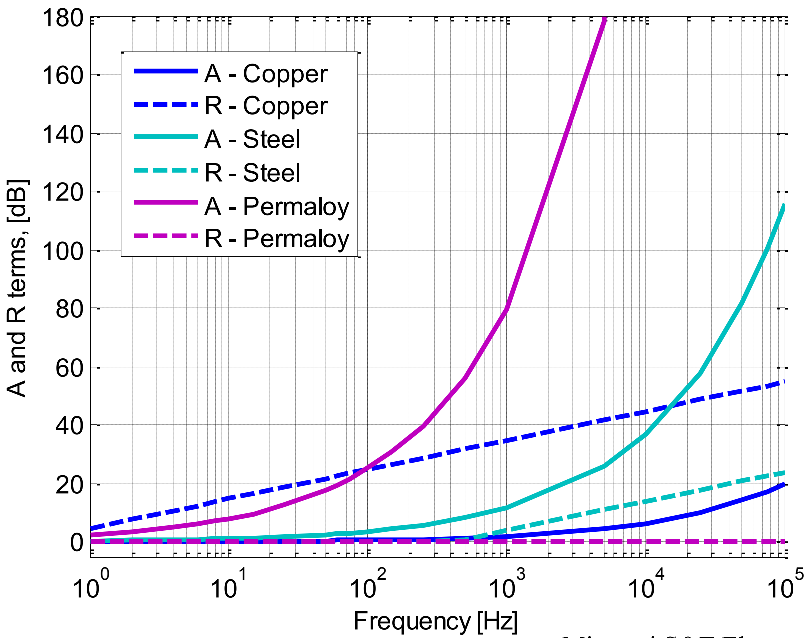
$\mu_r = 200 \quad \sigma_{rel,Cu} = 0.17$

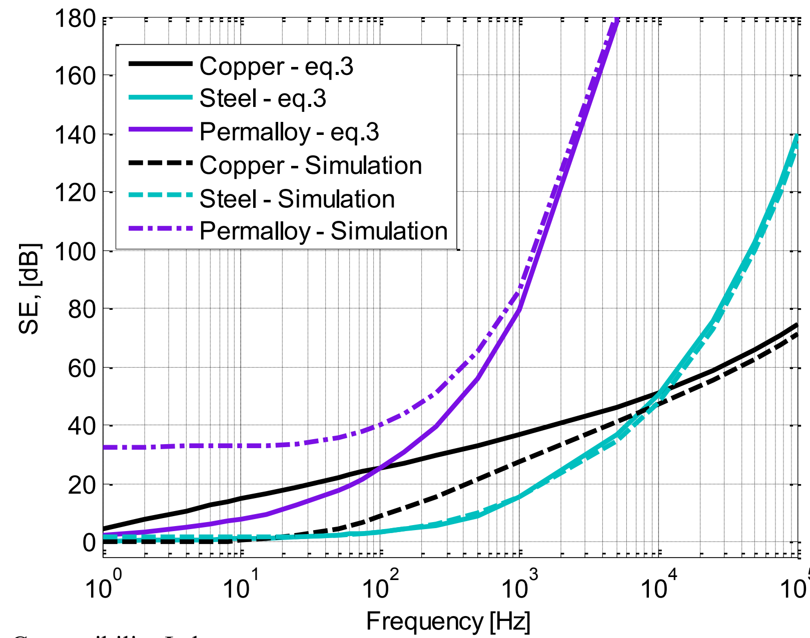
PERMALLOY

$\mu_r = 50000 \quad \sigma_{rel,Cu} = 0.03$

$$R_m = 20log_{10}\left[\frac{\sqrt{\pi\mu_0\sigma_{Cu}}}{8.485}\right] + 20log_{10}\left[\frac{\sqrt{f\mu_r\sigma_{rel,Cu}}}{\mu_r}\frac{R^2+z^2}{z}\right] = 4.7 + 20log_{10}\left[\sqrt{f}\sqrt{\frac{\sigma_{rel,Cu}}{\mu_r}}\frac{R^2+z^2}{z}\right]$$

$$SE = A_m + R_m = 132\Delta\sqrt{f\mu_r\sigma_{rel,Cu}} + 4.7 + 20log_{10}\left[\sqrt{f}\sqrt{\frac{\sigma_{rel,Cu}}{\mu_r}}\frac{R^2+z^2}{z}\right]$$





Magnetic Field Reflection Loss

The reflection loss, R term, for magnetic field (according to eq. 2 – steel, permalloy):

$$R = 20log_{10}\left[0.354\frac{\delta\mu_r}{z} + 0.118\frac{z}{\delta\mu_r} + 0.408\right] \qquad \delta_m = \frac{1}{\sqrt{\pi f \mu_0 \mu_r \sigma_{rel,Cu}\sigma_{Cu}}}$$

$$R_m = 20log_{10}\left[0.0242\frac{1}{z\sqrt{f}}\sqrt{\frac{\mu_r}{\sigma_{rel,Cu}}} + 1.72z\sqrt{f}\sqrt{\frac{\sigma_{rel,Cu}}{\mu_r}} + 0.408\right]$$

COPPER

$\mu_r = 1 \quad \sigma_{Cu} = 54 \times 10^6$ [S/m]

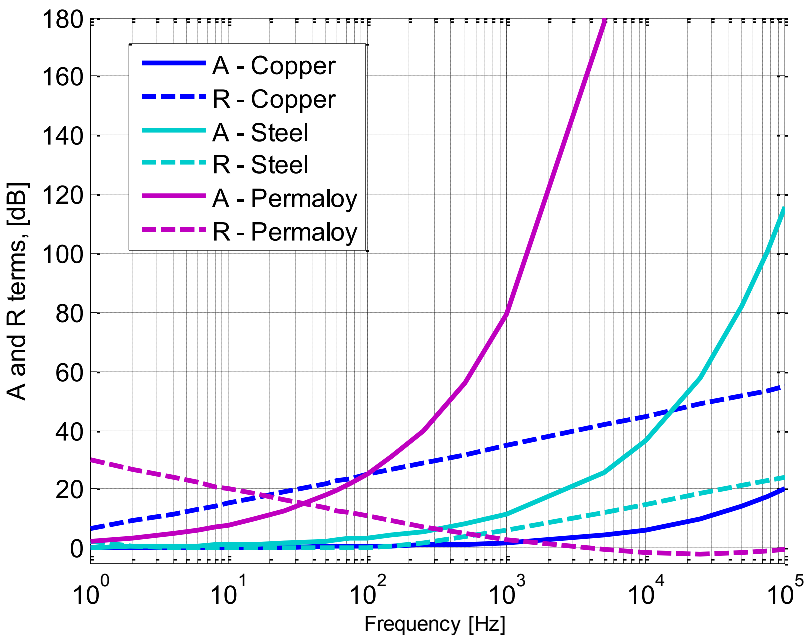
1010 LOW CARBON STEEL

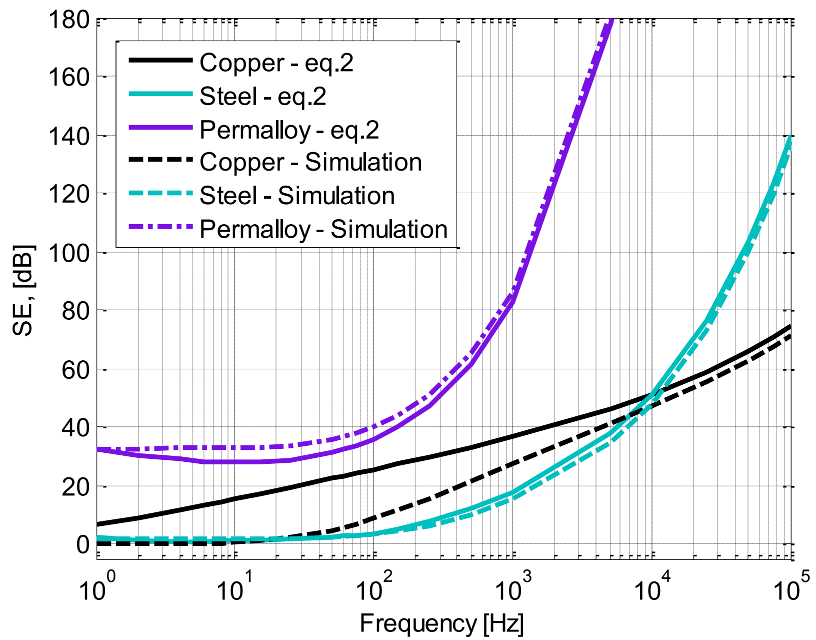
$\mu_r = 200 \quad \sigma_{rel,Cu} = 0.17$

PERMALLOY

$\mu_r = 50000 \quad \sigma_{rel,Cu} = 0.03$

$$SE = A_m + R_m = 132\Delta\sqrt{f\mu_r\sigma_{rel,Cu}} + 20log_{10}\left[0.0242\frac{1}{z\sqrt{f}}\sqrt{\frac{\mu_r}{\sigma_{rel,Cu}}} + 1.72z\sqrt{f}\sqrt{\frac{\sigma_{rel,Cu}}{\mu_r}} + 0.408\right]$$



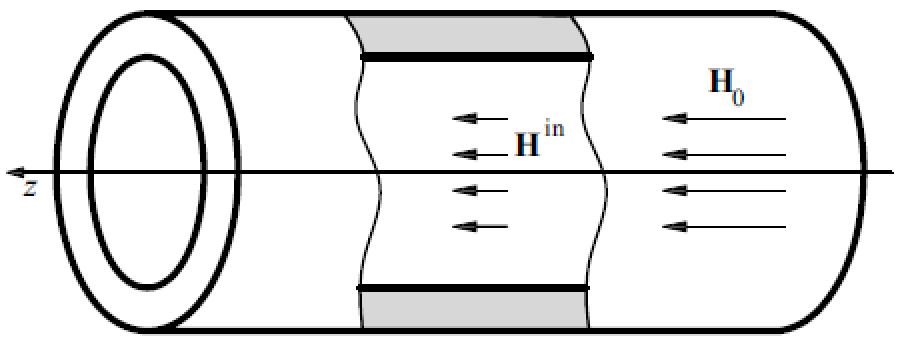


Introduction

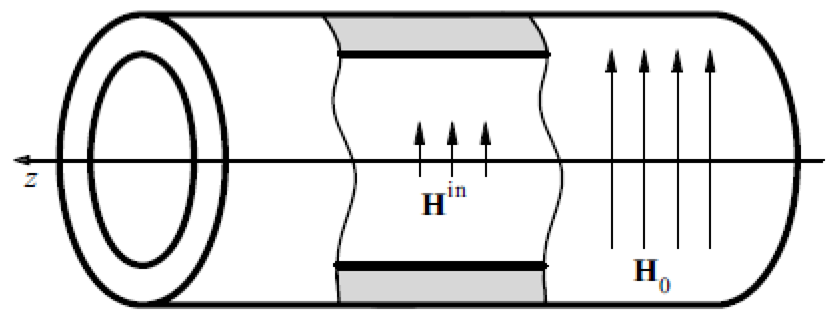
Consider an infinitely long cylindrical shell with inner radius α, outer radius b and wall thickness Δ(i.e., $\Delta = b - \alpha$). The shell is placed in uniform ac magnetic field of amplitude H_0.

The infinitely long cylindrical magnetic conducting shield has been studied as a canonical geometry for the design of EM shields. The shield consists of an infinitely long cylindrical shell with radius ρ_0 = **30cm** and thickness Δ = **0.15mm**, with large value of the conductivity $\boldsymbol{\sigma}$, and/or of the relative magnetic permeability $\boldsymbol{\mu_r}$ [*].

Following figures show geometry of the problem for cylindrical shell placed in an uniform external "transverse" or "parallel" magnetic field.



Benchmark problem 1
Cylindrical shell placed in an uniform external **parallel** magnetic field



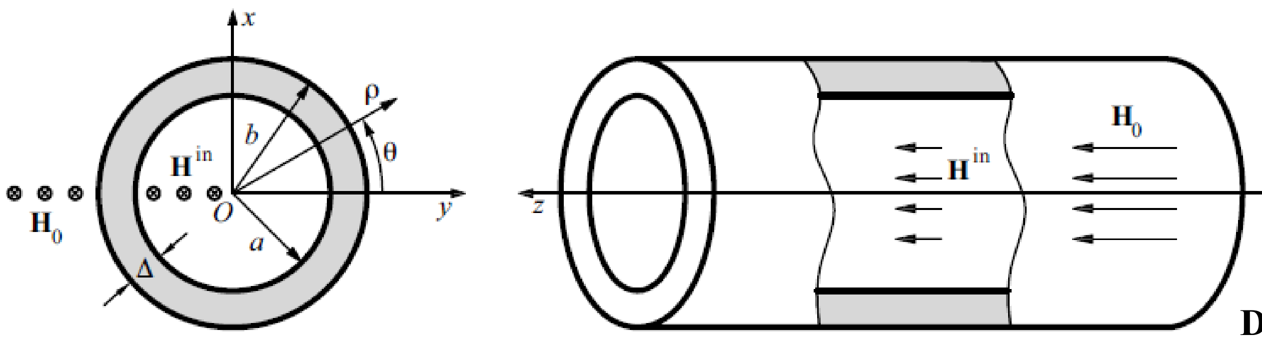
Benchmark problem 2
Cylindrical shell placed in an uniform external **transverse** magnetic field

[*] S. Celozzi, R. Araneo, G. Lovat, "Electromagnetic Shielding", *John Wiley & Sons, Inc., 2008, ISBN 978-0-470-05536-6, pages 293-300.*

Geometry and Materials

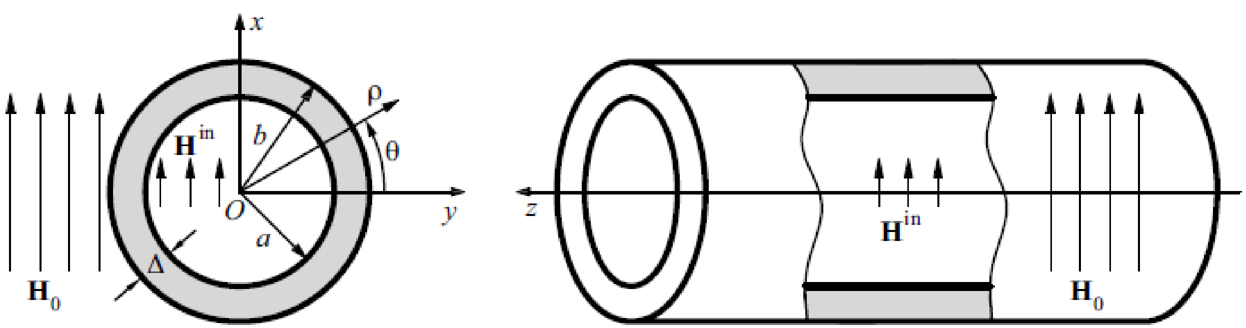
Benchmark problem 1

Cylindrical shell placed in uniform external **parallel** magnetic field



Benchmark problem 2

Cylindrical shell placed in uniform external **transverse** magnetic field



IRON-NICKEL ALLOY

IN Alloy

$\mu = 75000 \quad \sigma = 2 \times 10^6$ [S/m]

Radius - $\rho_0 = 30$cm

Thickness - $\Delta = 1.5$mm

DURANICKEL STAINLESS STEEL

DS Steel

$\mu = 10.58 \quad \sigma = 2.35 \times 10^6$ [S/m]

Radius - $\rho_0 = 30$cm

Thickness - $\Delta = 2$mm

COPPER CASTING ALLOY

CC Alloy

$\mu = 1.09 \quad \sigma = 1.18 \times 10^7$ [S/m]

Radius - $\rho_0 = 30$cm

Thickness - $\Delta = 2$mm

Model of Parallel Magnetic Field

Parameters of cylinder:

Length: L = 20 ρ_0 =600cm

Radius: ρ_0 = 30cm

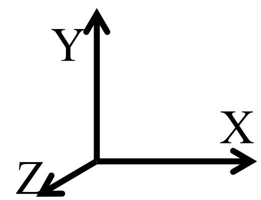
Parameters of coil:

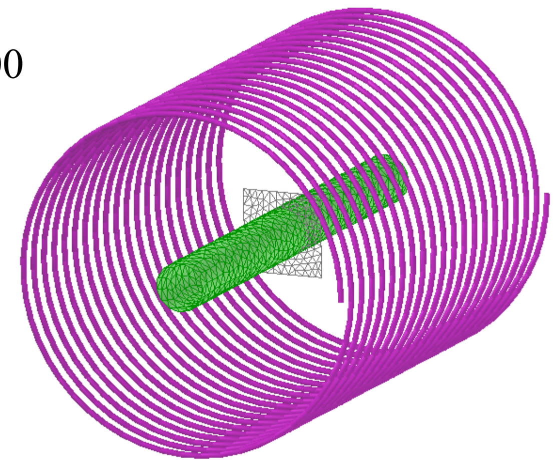
Length: L = 20 ρ_0 =600cm

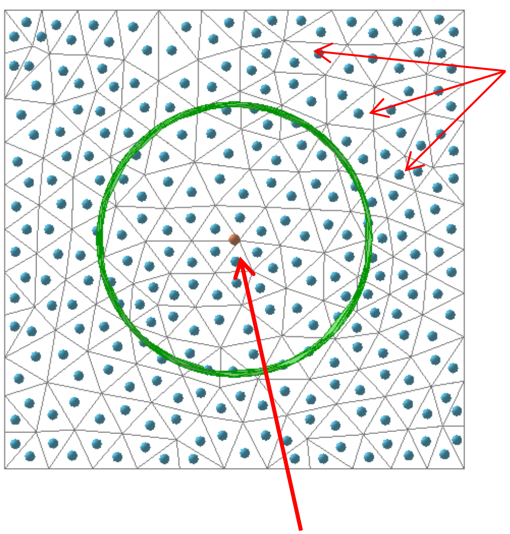
Radius: R = 7ρ_0 = 210cm

Number of turns: 20

Number of triangles: ~1400



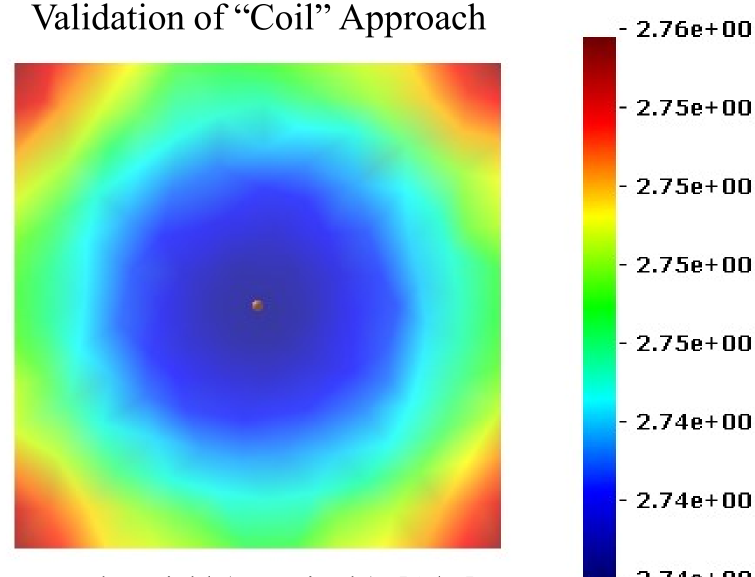




Field probes across the cylinder for monitoring H field.

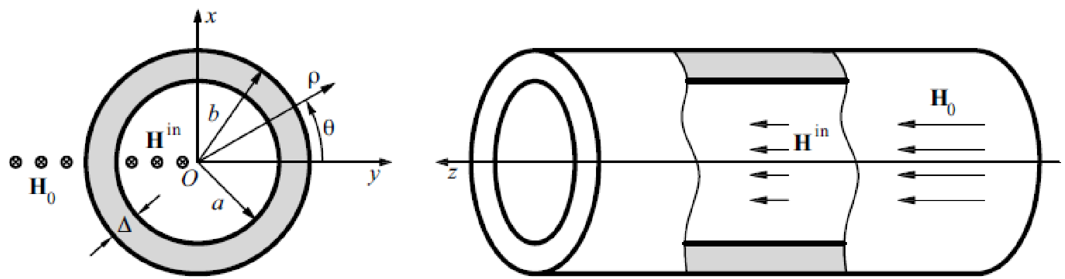
Observation point in the center at (0,0,0)

Validation of "Coil" Approach



Total H Field (Magnitude), [A/m]
at **10**KHz (Linear Scale)

Parallel Magnetic Field



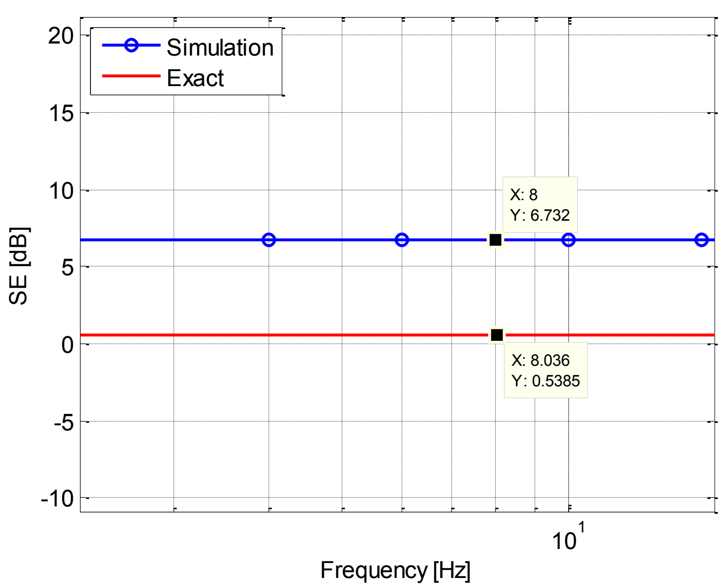
IRON-NICKEL ALLOY

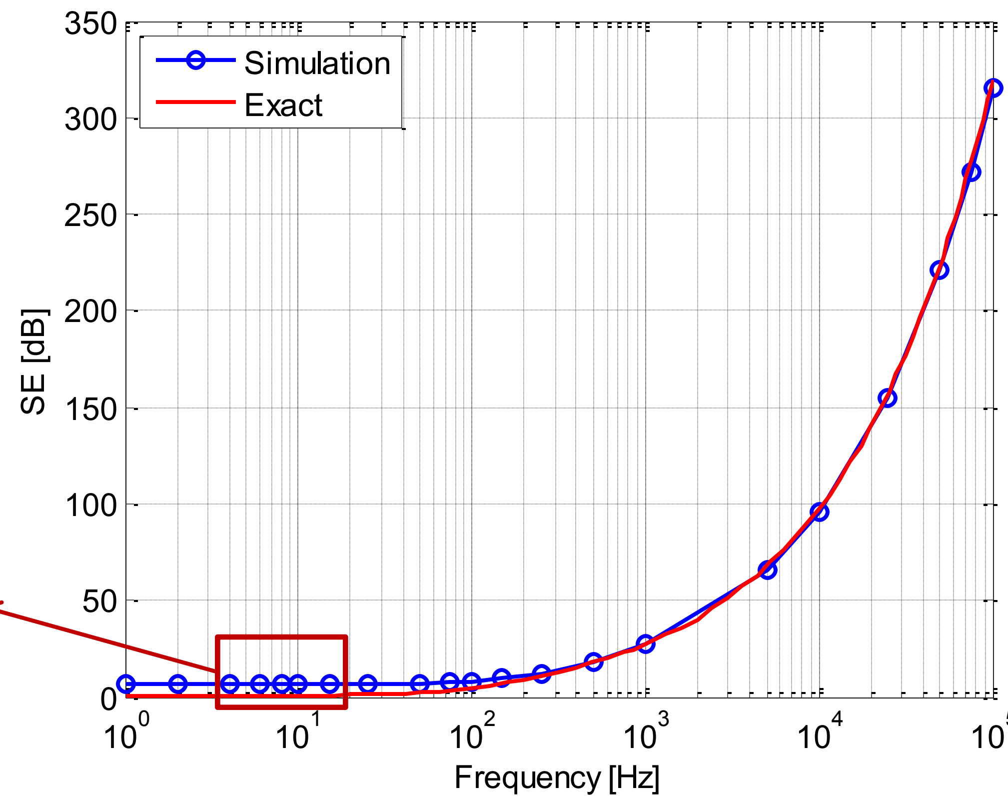
IN Alloy

μ =75000 σ = 2 x 10^6 [S/m]

Radius - ρ_0 = 30cm

Thickness - Δ = 1.5mm

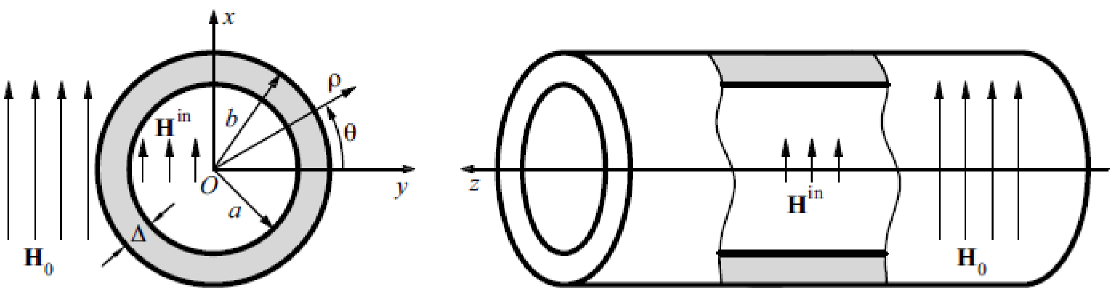


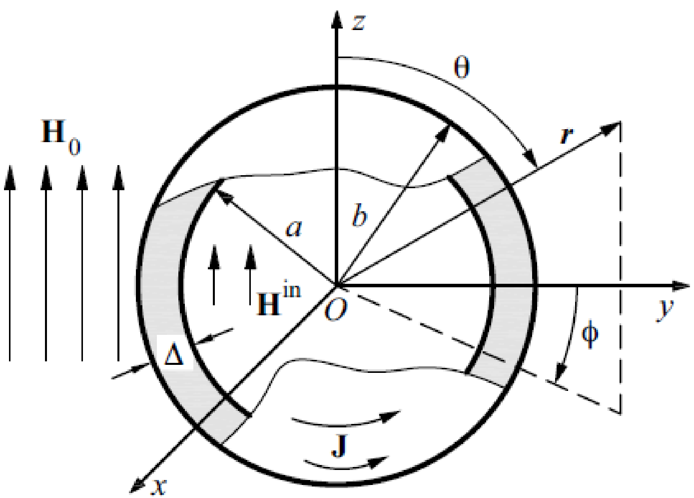


Parallel Magnetic Field

Benchmark problem 2

Cylindrical shell placed in an uniform external **transverse** magnetic field





Spherical shell placed in an uniform external **transverse** magnetic field

IRON-NICKEL ALLOY

IN Alloy

μ =75000   σ = 2 x 10^6 [S/m]

Radius - ρ_0 = 30cm

Thickness - Δ = 1.5mm

DURANICKEL STAINLESS STEEL

DS Steel

μ =10.58   σ = 2.35 x 10^6 [S/m]

Radius - ρ_0 = 30cm

Thickness - Δ = 2mm

COPPER CASTING ALLOY

CC Alloy

μ =1.09   σ = 1.18 x 10^7 [S/m]

Radius - ρ_0 = 30cm

Thickness - Δ = 2mm

Validation of Spherical and Cylindrical Shells Equivalently

Data acquired from [*].

According to the graph we can conclude that even as shield geometry changes, the shielding mechanisms remain always the same. So we can place Spherical shell instead of the Cylindrical in an uniform external **transverse** magnetic field.

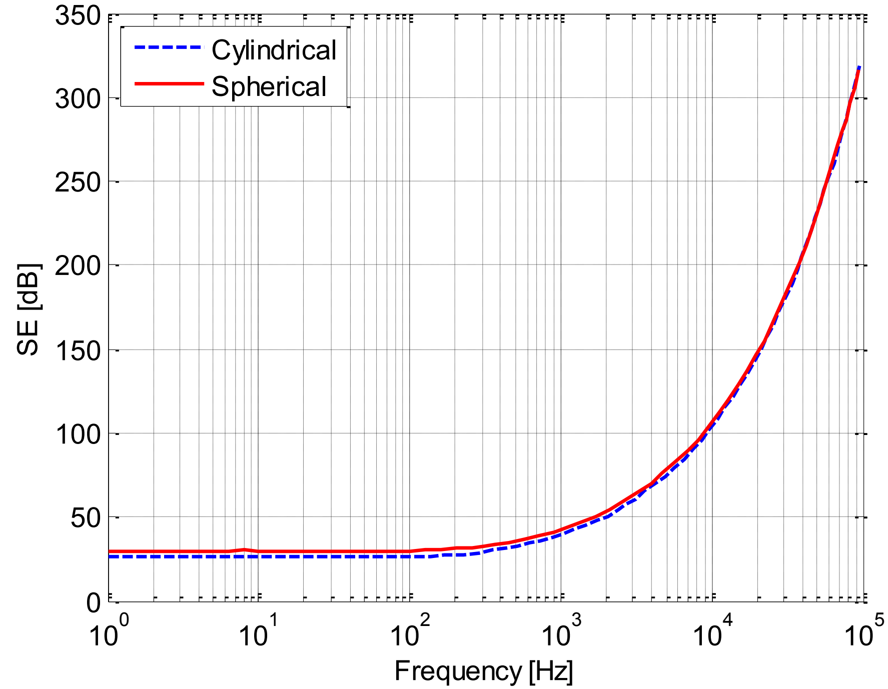
IRON-NICKEL ALLOY

IN Alloy

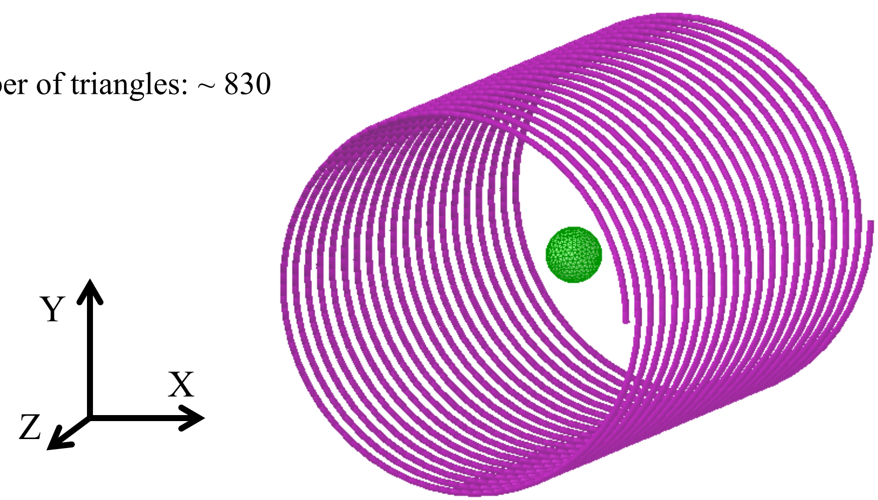
$\mu = 75000$ $\sigma = 2 \times 10^6$ [S/m]

Radius - $\rho_0 = 30$cm

Thickness - $\Delta = 1.5$mm



Number of triangles: ~ 830



Parameters of sphere:

Radius: $\rho_0 = 30$cm

Parameters of coil:

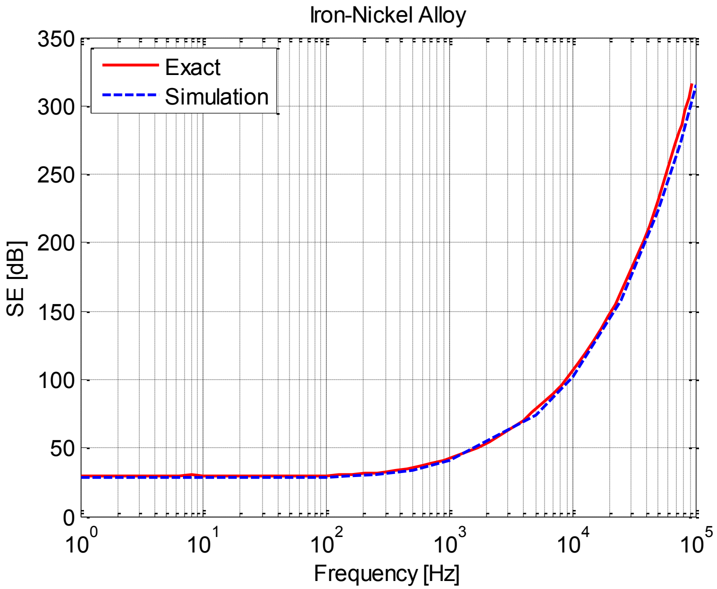
Length: L = 20 ρ_0 =600cm

Radius: R = $7\rho_0$ = 210cm

Number of turns: 20

[*] S. Celozzi, R. Araneo, G. Lovat, "Electromagnetic Shielding", *John Wiley & Sons, Inc., 2008, ISBN 978-0-470-05536-6, pages 294, 298.*

Transverse Magnetic Field



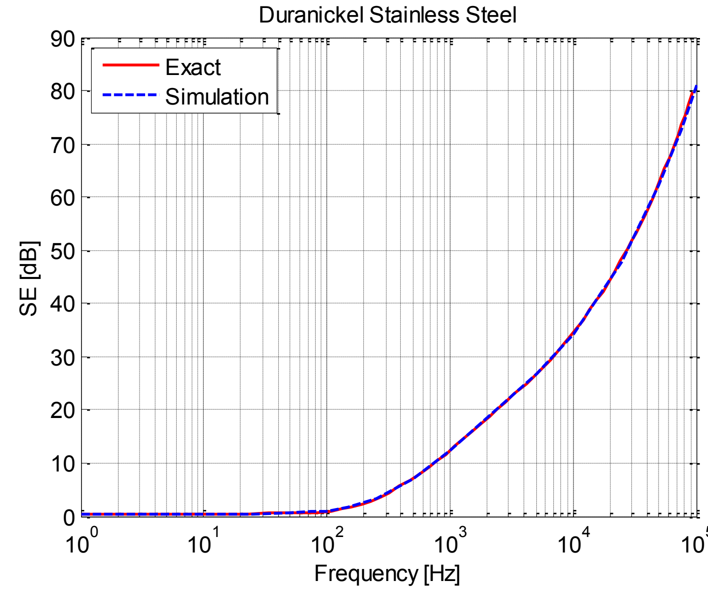
COPPER CASTING ALLOY

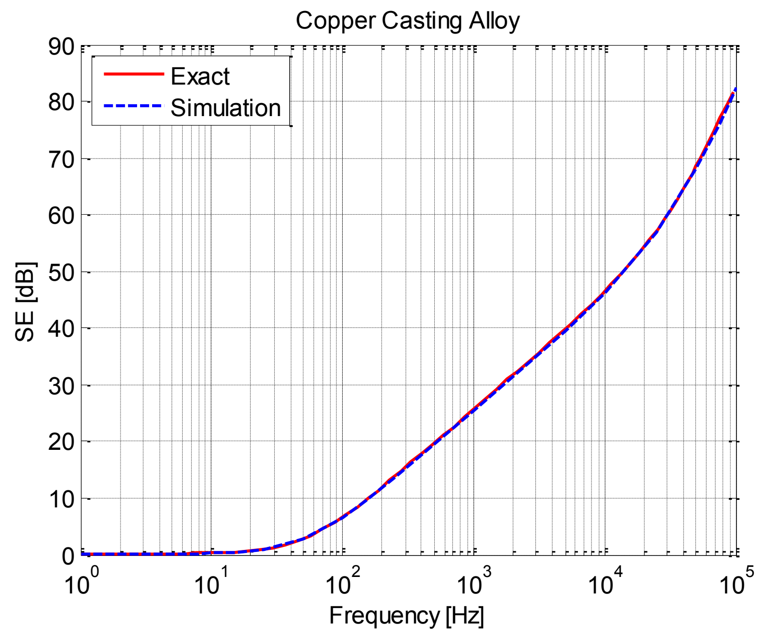
CC Alloy

μ =1.09 σ = 1.18 x 10^7 [S/m]

Radius - ρ_0 = 30cm

Thickness - Δ = 2mm





IRON-NICKEL ALLOY

IN Alloy

μ =75000 σ = 2 x 10^6 [S/m]

Radius - ρ_0 = 30cm

Thickness - Δ = 1.5mm

DURANICKEL STAINLESS STEEL

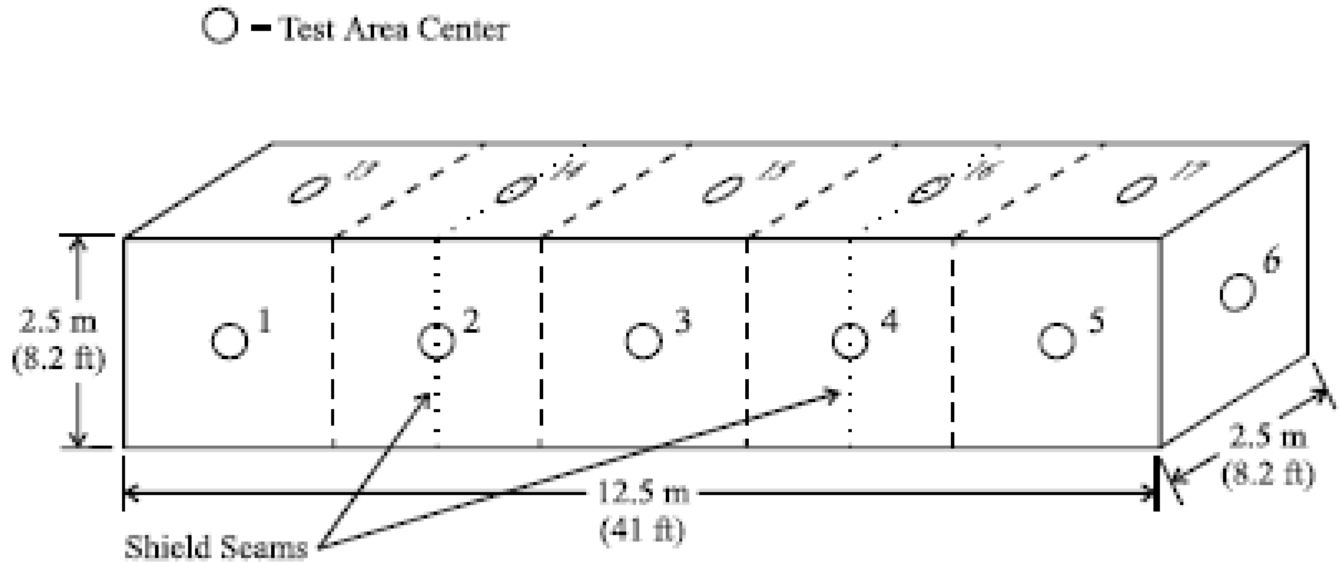
DS Steel

μ =10.58 σ = 2.35 x 10^6 [S/m]

Radius - ρ_0 = 30cm

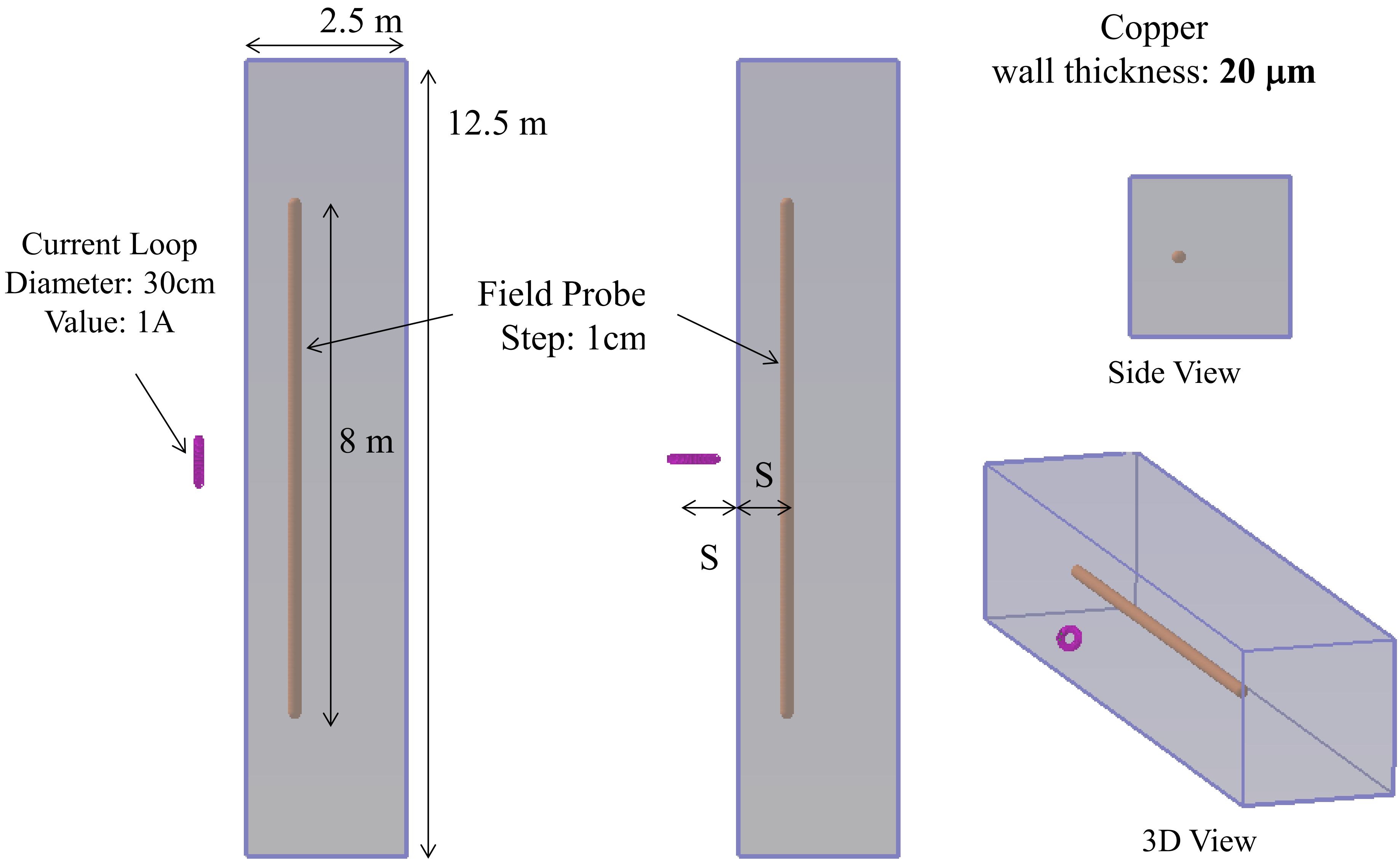
Thickness - Δ = 2mm

MIL STD 188-125-2 Test Setup



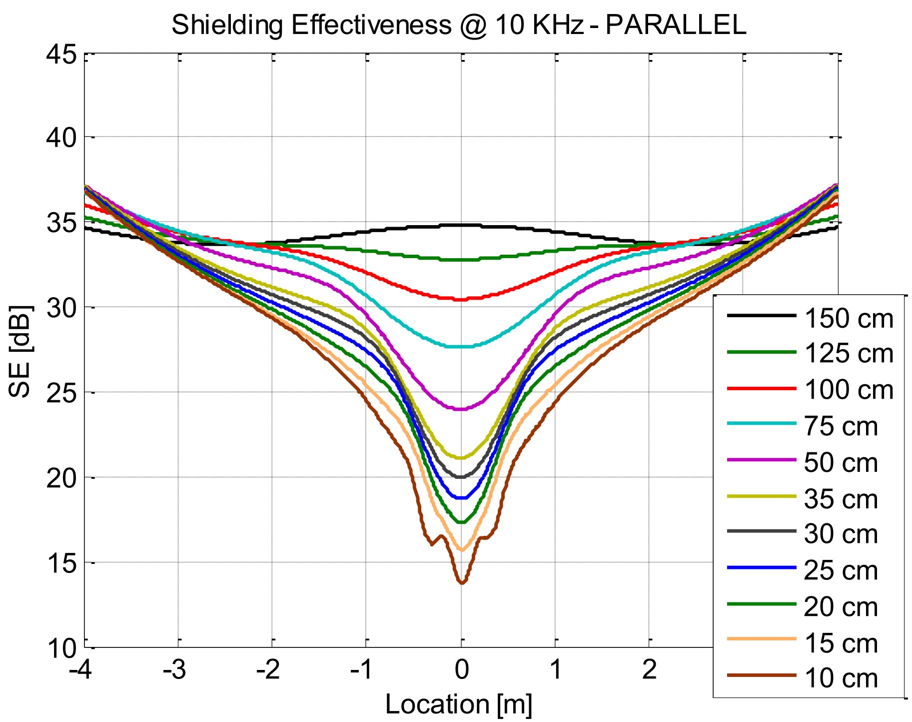
- Antenna diameter is 30 cm (12 inches)
- Antenna position is 1.5 m from the exterior wall, and 1.0 m inside the interior wall
- Antenna locations are shown as #1, 2, …

MIL STD 188-125-2: Model View

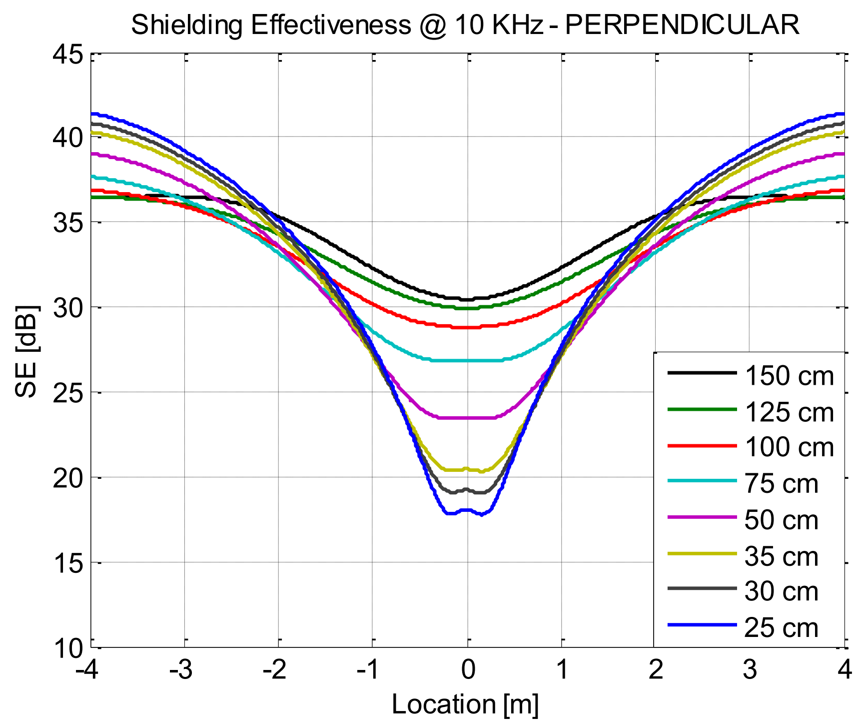


Loop parallel to the wall   Loop perpendicular to the wall

Shielding Effectiveness at Various Distances to Wall



Parallel Loop



Perpendicular Loop

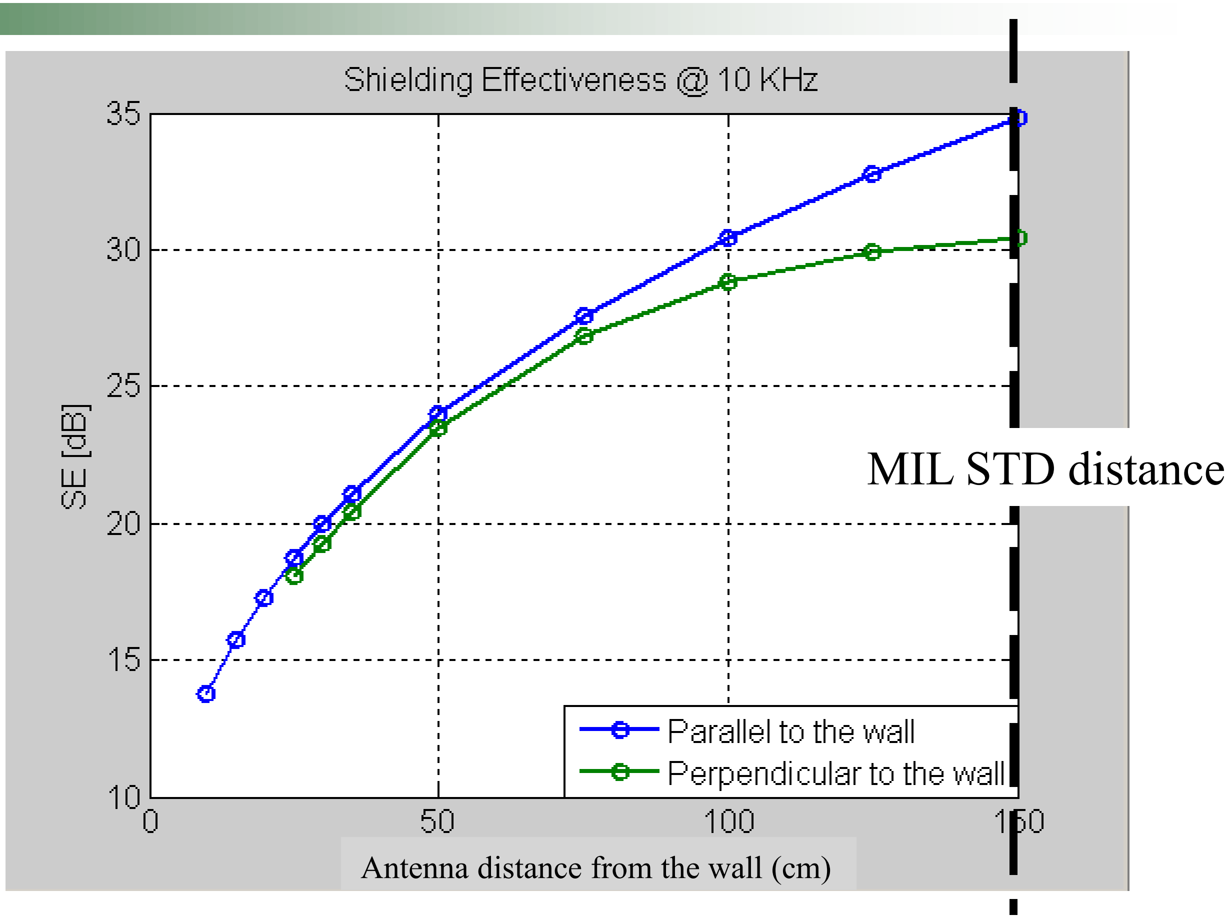
F = **10** KHz

COPPER

$\mu = 1 \quad \sigma = 58 \times 10^6$ [S/m]

$\Delta = 20$um

Simulation – Shielding Effectiveness @ 10 KHz



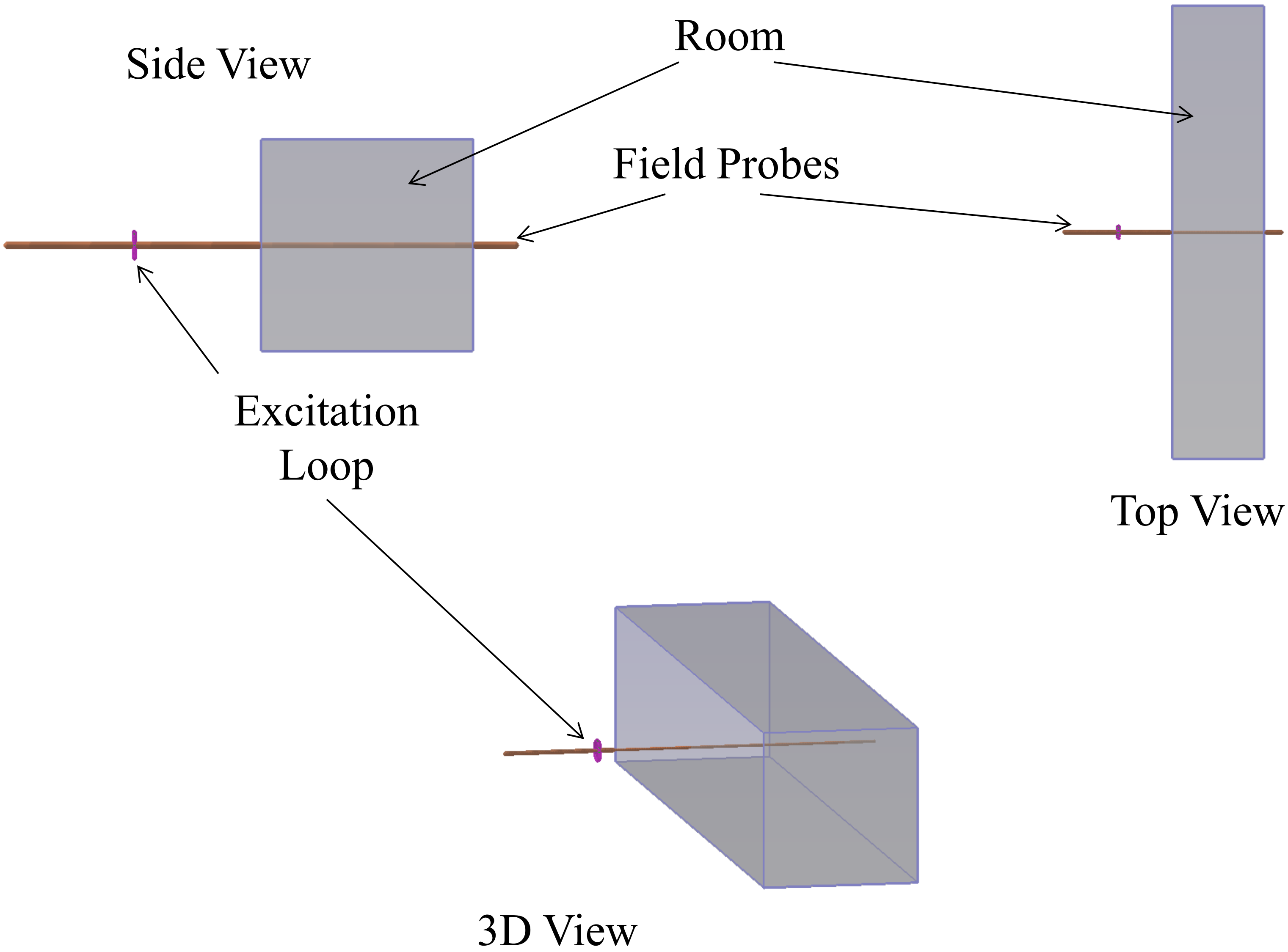
CENTER FIELD PROBE

F = 10 KHz

COPPER

$\mu = 1$ $\sigma = 58 \times 10^6$ [S/m] $\Delta = 20$um

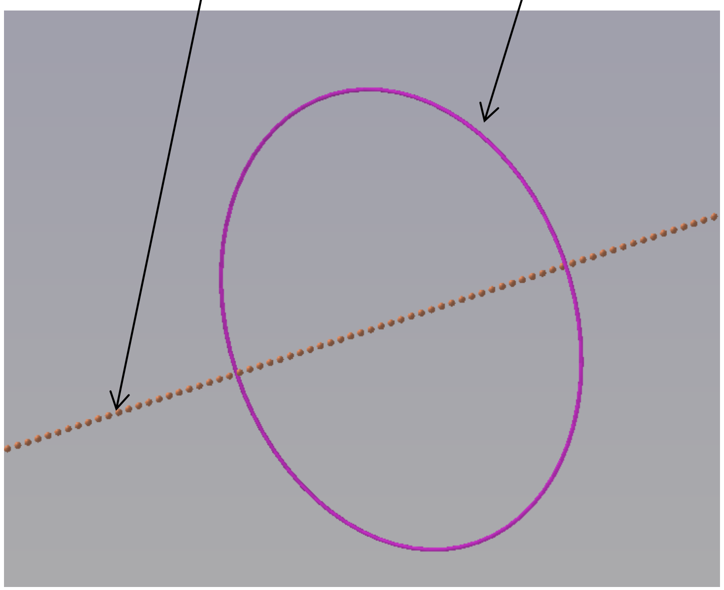
Simulation – Magnetic Field @ 10 KHz

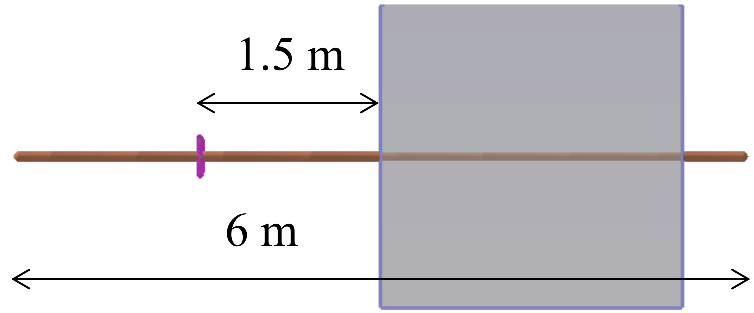


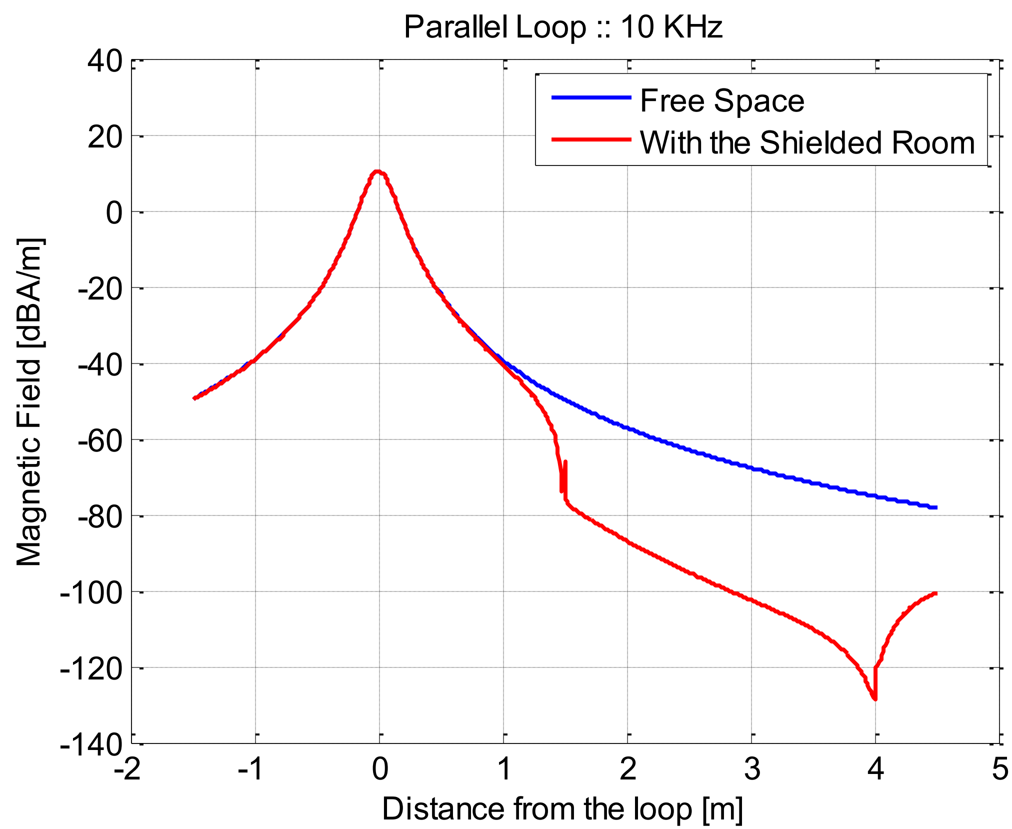
Simulation – Magnetic Field @ 10 KHz – Parallel Loop

Field Probes along the loop central axis with 1 cm step

1A Current Loop 30 cm diameter



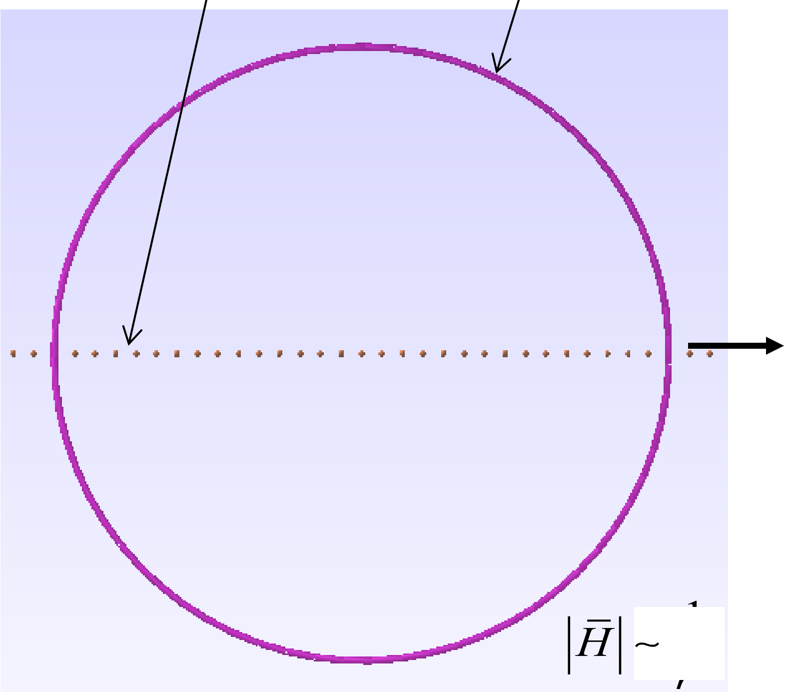


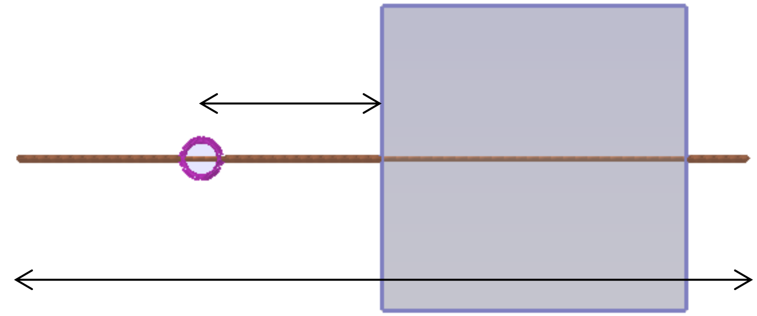


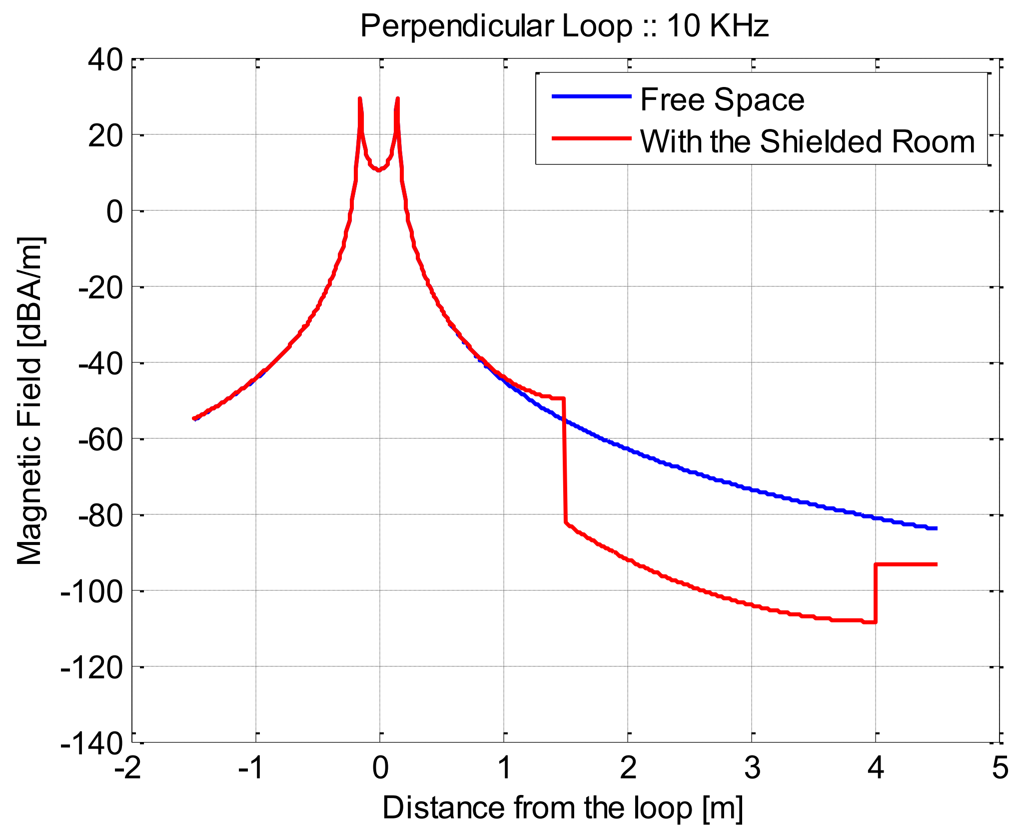
Simulation – Magnetic Field @ 10 KHz – Parallel Loop

Field Probes in plane of the loop with 1 cm step

1A Current Loop 30 cm diameter







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1. S. Celozzi, R. Araneo, G. Lovat, "Electromagnetic Shielding", *John Wiley & Sons, Inc., 2008, ISBN 978-0-470-05536-6, Chapter 4 and Appendix B*

2. C. R. Paul, "Introduction to Electromagnetic Compatibility", *John Wiley & Sons, Inc., 2006, Second Edition, ISBN 978-0-471-75500-5, pages 713-749*

3. H. W. Ott, "Electromagnetic Compatibility Engineering", *John Wiley & Sons, Inc., 2009, ISBN 978-0-470-18930-6, Chapter 6*

4. EMCoS EMC Studio 7.0, Low Frequency Magnetic Field solver http://www.emcos.com

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7. P. Bannister. "New theoretical expressions for predicting shielding effectiveness for the plane shield case", *IEEE Trans. Electromagnetic Compatibility, vol. 10, no. 1, pp. 2-7, Mar. 1968*