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Lucerne University of
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2009

Inductance of Magnetic Plated Wires as a Function of Frequency and Plating Thickness

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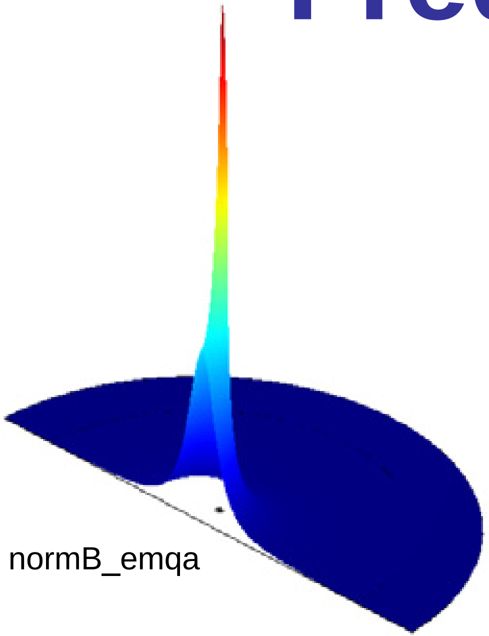
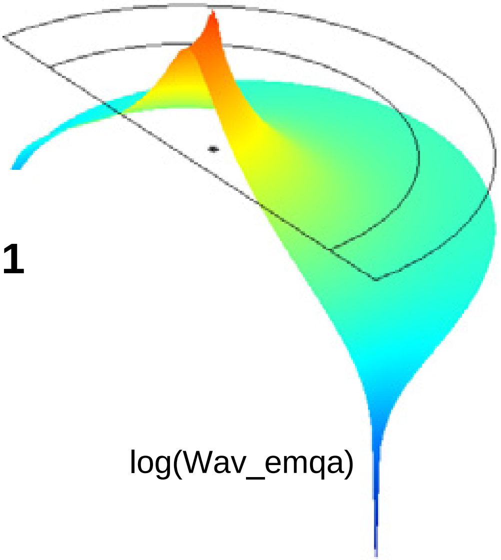
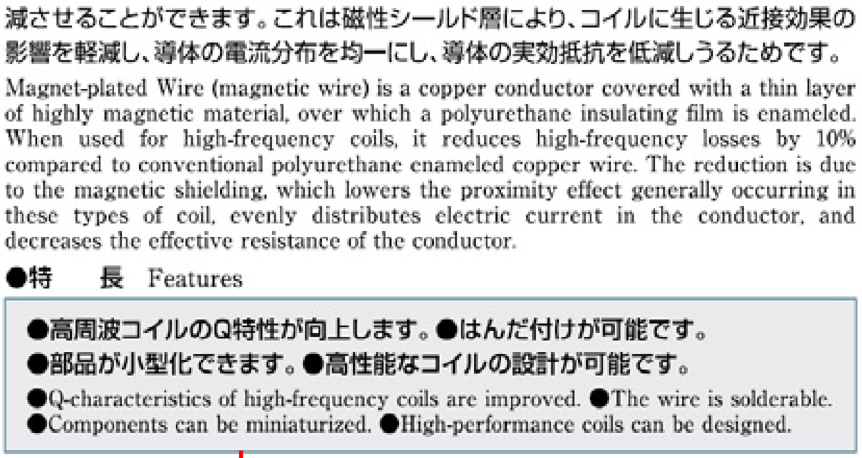


normB_emqa



log(Wav_emqa)

Motivation

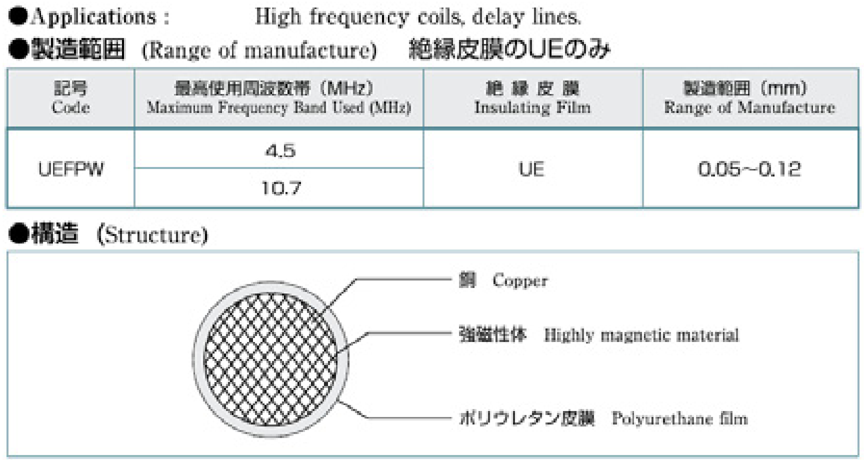


減させることができます。これは磁性シールド層により、コイルに生じる近接効果の影響を軽減し、導体の電流分布を均一にし、導体の実効抵抗を低減しうるためです。

Magnet-plated Wire (magnetic wire) is a copper conductor covered with a thin layer of highly magnetic material, over which a polyurethane insulating film is enameled. When used for high-frequency coils, it reduces high-frequency losses by 10% compared to conventional polyurethane enameled copper wire. The reduction is due to the magnetic shielding, which lowers the proximity effect generally occurring in these types of coil, evenly distributes electric current in the conductor, and decreases the effective resistance of the conductor.

●特　長　Features

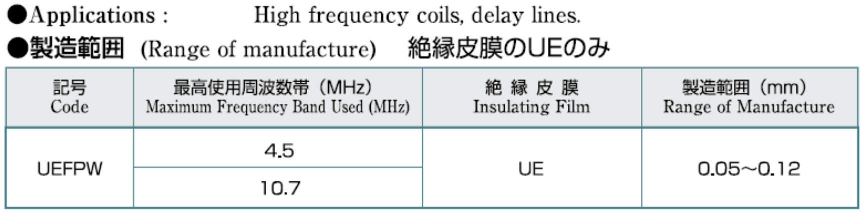
●高周波コイルのQ特性が向上します。●はんだ付けが可能です。
●部品が小型化できます。●高性能なコイルの設計が可能です。
●Q-characteristics of high-frequency coils are improved. ●The wire is solderable.
●Components can be miniaturized. ●High-performance coils can be designed.



●Applications : High frequency coils, delay lines.
●製造範囲 (Range of manufacture) 絶縁皮膜のUEのみ

記号 Code	最高使用周波数帯（MHz） Maximum Frequency Band Used (MHz)	絶 縁 皮 膜 Insulating Film	製造範囲（mm） Range of Manufacture
UEFPW	4.5	UE	0.05~0.12
	10.7		

●構造 (Structure)



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Improved Q-characteristics of high-frequency coils

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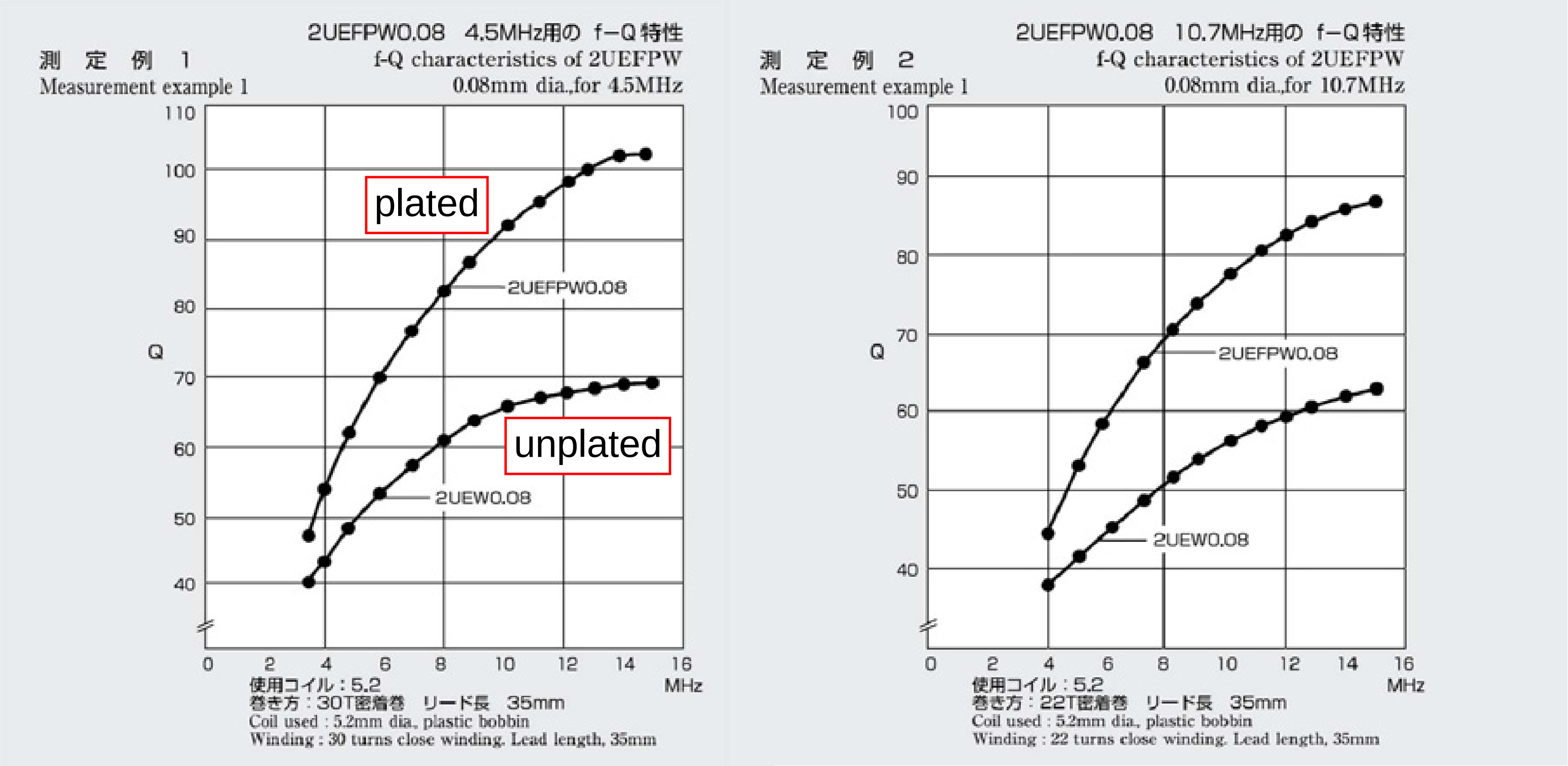

測 定 例 1
Measurement example 1

2UEFPW0.08 4.5MHz用の f−Q特性
f-Q characteristics of 2UEFPW
0.08mm dia.,for 4.5MHz

使用コイル：5.2
巻き方：30T密着巻 リード長 35mm
Coil used : 5.2mm dia., plastic bobbin
Winding : 30 turns close winding. Lead length, 35mm

測 定 例 2
Measurement example 1

2UEFPW0.08 10.7MHz用の f−Q特性
f-Q characteristics of 2UEFPW
0.08mm dia.,for 10.7MHz

使用コイル：5.2
巻き方：22T密着巻 リード長 35mm
Coil used : 5.2mm dia., plastic bobbin
Winding : 22 turns close winding. Lead length, 35mm

Outline

- Equations for Resistance R, Inductance L and Skin Depth δ_{Skin}

- Single Loop Analysis for a Microscopic Understanding
  - COMSOL Simulation
  - Results and Discussion
  - Scaling

- Coil Analysis and Comparison with Experiment
  - COMSOL Simulation
  - Results and Validation with Experiment

- Summary

Equations

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resistance **R**:

$$R = \mathrm{real}\left(\frac{V_{Loop}}{I}\right)$$

R via geometry and σ

loop circumference

$$R = \frac{1}{\sigma}\cdot\frac{L}{A_{eff}} \approx \frac{1}{\sigma}\cdot\frac{D\pi}{d\pi\cdot d_{eff}}$$

effective current cross-sectional area

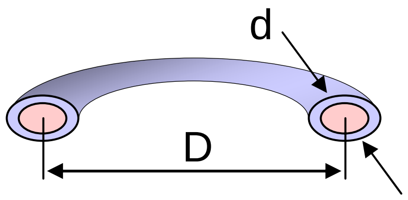
inductance **L**:

$$L_e = \mathrm{imag}\left(\frac{V_{Loop}}{I\cdot 2\pi f}\right)$$

via electric potential

$$L_m = 2\cdot\frac{E_{\text{mag. field}}}{I^2}$$

via magnetic field energy

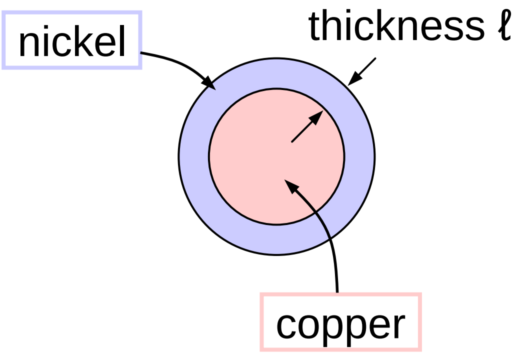


quality factor **Q**:

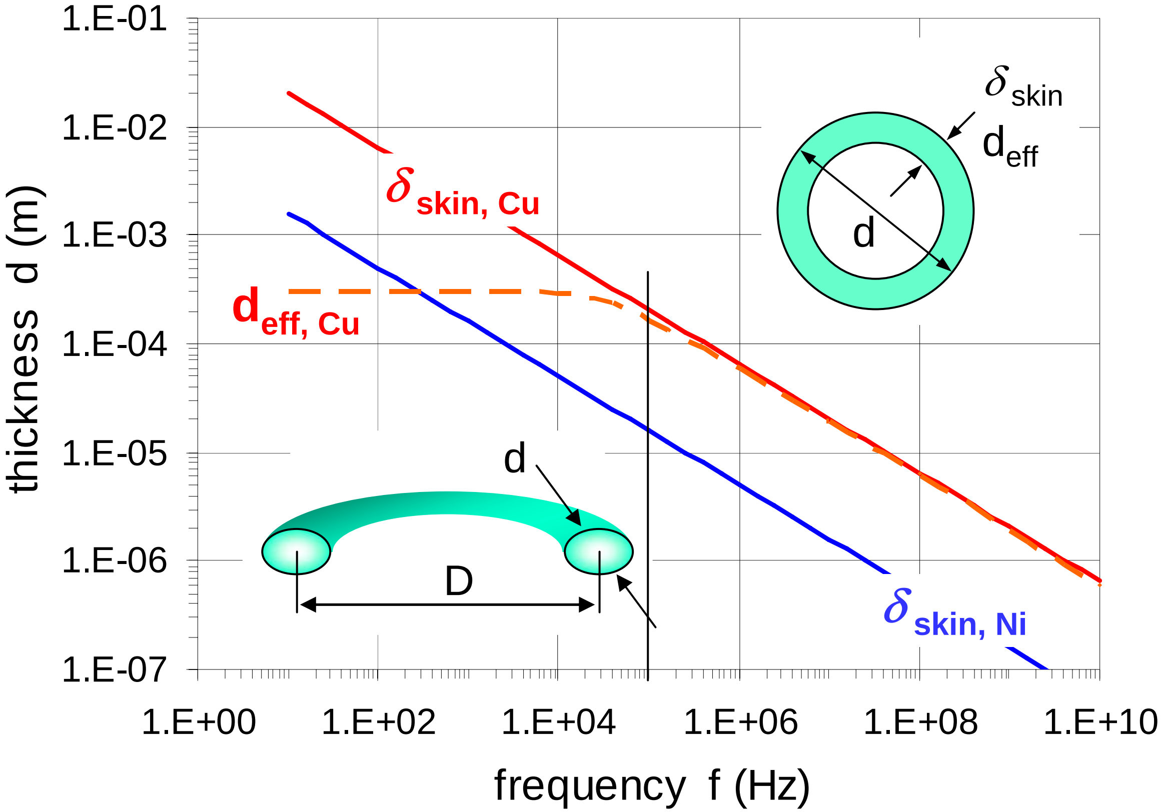
$$Q = \frac{2\pi f\cdot L}{R}$$

L_e

L_m



Current Layer d, δ vs. f



Analytic expression for skin depth (J.D Jackson, Classical ED):

$$\delta_{\text{skin}} = \sqrt{\frac{1}{\mu_0 \cdot \mu_r \cdot \pi f \cdot \sigma}}$$

$\mu_0 = 4\pi \times 10^{-7}$ T·m/A

μ_r = relative permeability

ω = 2π×frequency [1/s]

σ = conductivity [S/m]

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Effective layer thickness d_{eff} : $d_{\text{eff}} = \frac{1}{\sigma \cdot R} \frac{D}{d}$ $\boxed{\cong \delta_{\text{skin}}}$ ✓ $\left\{ \right.$ at high frequency

material and geometry

Behavior at High f

resistance **R**:

$$R_{eff} = \frac{1}{\sigma} \cdot \frac{L}{A_{eff}} \approx \frac{1}{\sigma} \cdot \frac{D\pi}{d\pi \cdot \delta_{skin}} = \frac{D}{d}\sqrt{\frac{\mu_0 \cdot \mu_r \cdot \pi}{\sigma}} \cdot \sqrt{f}$$

inductance **L**:

$$L_e = \text{imag}\left(\frac{V_{Loop}}{I \cdot 2\pi f}\right) \sim \frac{V_{Loop}}{I \cdot f} \sim \frac{R}{f} = \frac{1}{\sqrt{f}}$$

"**inner**" inductance, via electric potential:
depends on skin depth

$$L_m = 2 \cdot \frac{E_{\text{mag. field}}}{I^2} \sim \frac{B^2}{I^2} \sim \frac{I^2}{I^2} = \text{const.}$$

"**outer**" inductance, via magnetic field energy:
depends on geometry only

quality factor **Q**:

$$Q = \frac{2\pi f \cdot L}{R}$$

$$Q_e = \frac{2\pi f \cdot L_e}{R} \sim \frac{f \cdot f^{-1/2}}{\sqrt{f}}$$

$$Q_m = \frac{2\pi f \cdot L_m}{R} \sim \frac{f \cdot \text{const.}}{\sqrt{f}}$$

$$R_{inf}\left(f \to \infty\right) \sim f^{1/2}$$

$$L_e\left(\delta_{skin} \le \ell_{plating}\right) \sim f^{-1/2}$$

$$L_{m,inf}\left(f \to \infty\right) \sim \text{const.}$$

$$L[nH] \approx 2\frac{D\pi}{[cm]}\left(\ln\left(\frac{D\pi}{d}\right) - 1.07\right)$$

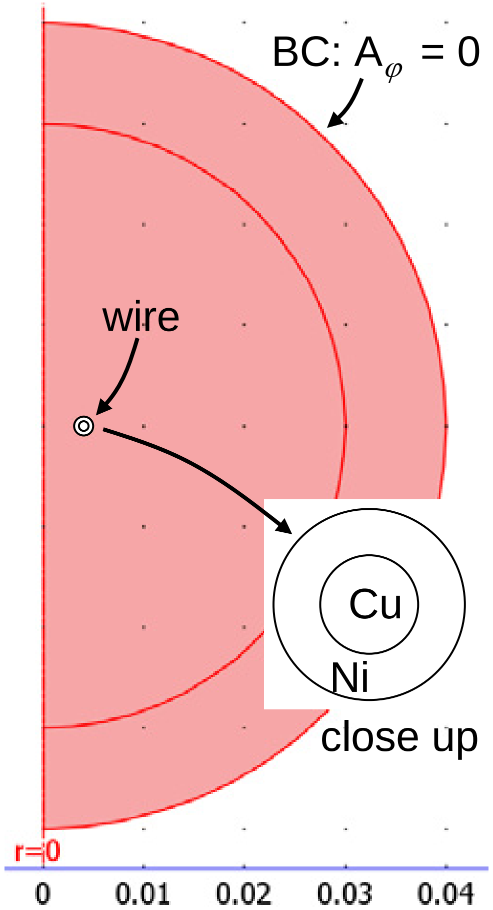
(D > 20d ; Meinke, Springer, 1992)

$$Q_e\left(\delta_{skin} \le \ell_{plating}\right) \sim \text{const.}$$

$$Q_{m,inf}\left(f \to \infty\right) \sim f^{1/2}$$

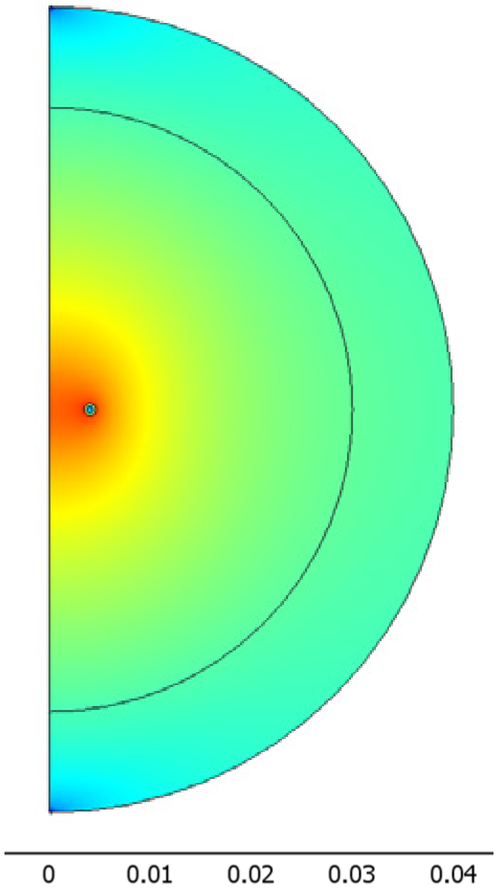
Cu-Ni Wire Loop

subdomains



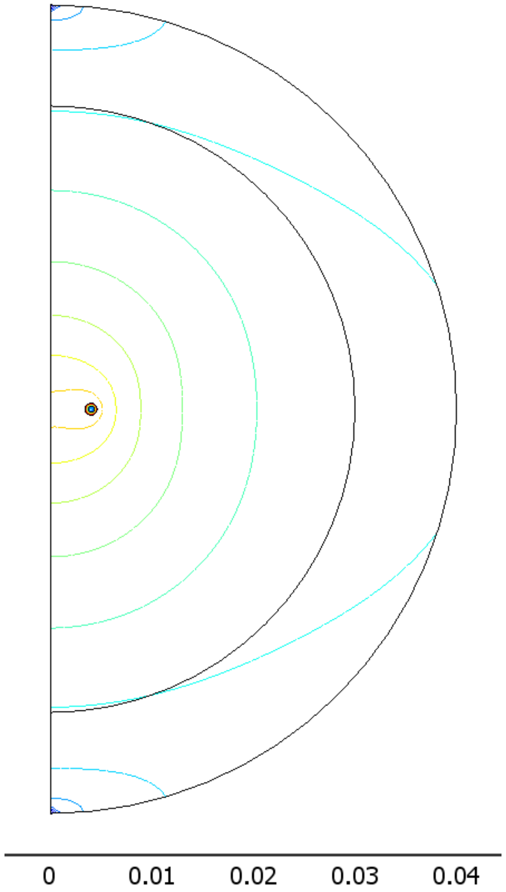
Magnetic energy density

log(Wmav_emqa), 10^5 Hz

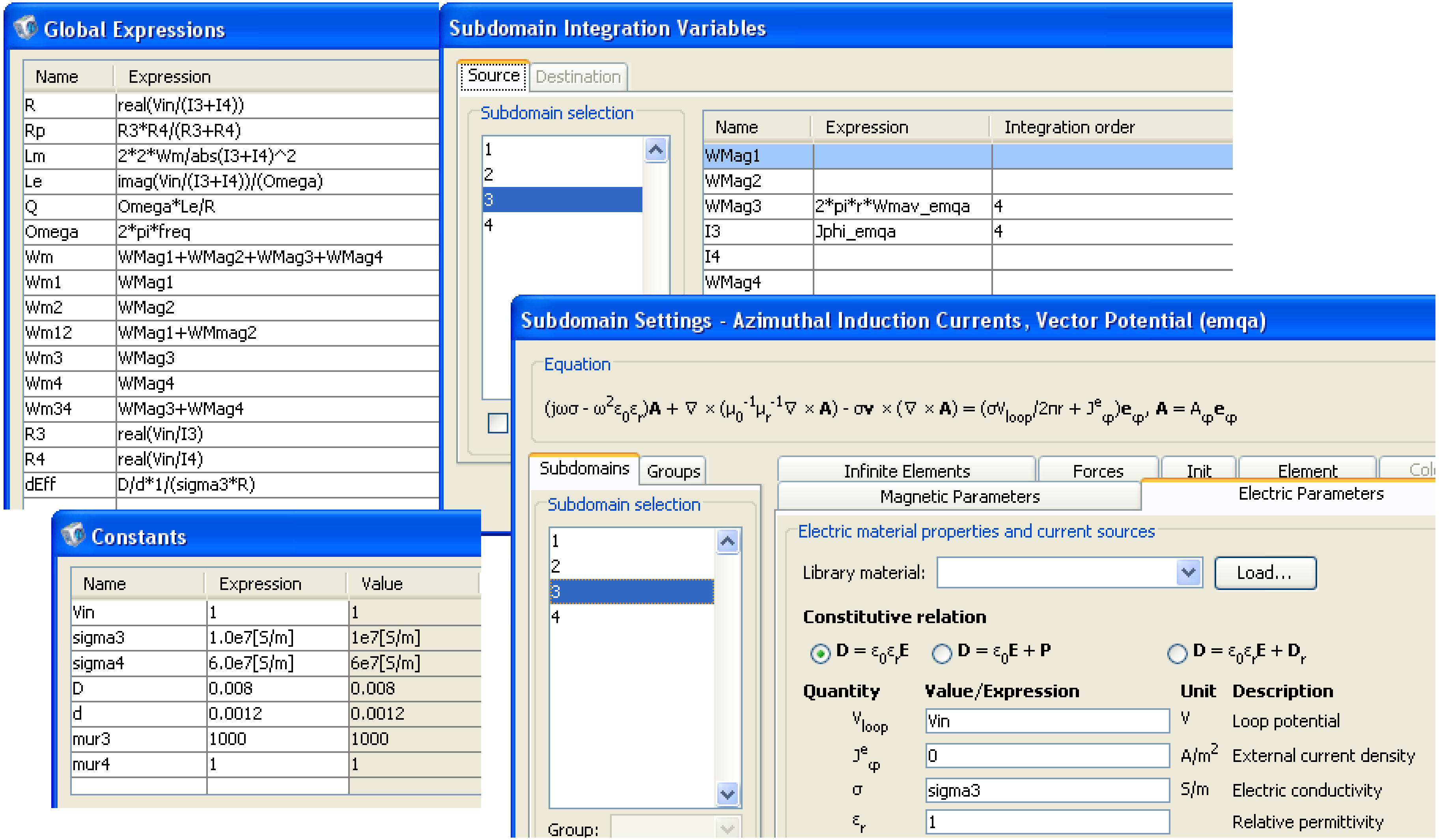


Magnetic flux density

log(normB_emqa), 10^5 Hz



Cu-Ni Wire Loop



Global Expressions

Name	Expression
R	real(Vin/(I3+I4))
Rp	R3*R4/(R3+R4)
Lm	2*2*Wm/abs(I3+I4)^2
Le	imag(Vin/(I3+I4))/(Omega)
Q	Omega*Le/R
Omega	2*pi*freq
Wm	WMag1+WMag2+WMag3+WMag4
Wm1	WMag1
Wm2	WMag2
Wm12	WMag1+WMmag2
Wm3	WMag3
Wm4	WMag4
Wm34	WMag3+WMag4
R3	real(Vin/I3)
R4	real(Vin/I4)
dEff	D/d*1/(sigma3*R)

Subdomain Integration Variables

Subdomain selection: 1, 2, 3 (selected), 4

Name	Expression	Integration order
WMag1		
WMag2		
WMag3	2*pi*r*Wmav_emqa	4
I3	Jphi_emqa	4
I4		
WMag4		

Constants

Name	Expression	Value
Vin	1	1
sigma3	1.0e7[S/m]	1e7[S/m]
sigma4	6.0e7[S/m]	6e7[S/m]
D	0.008	0.008
d	0.0012	0.0012
mur3	1000	1000
mur4	1	1

Subdomain Settings - Azimuthal Induction Currents, Vector Potential (emqa)

Equation

$$(j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)\mathbf{A} + \nabla \times (\mu_0^{-1}\mu_r^{-1}\nabla \times \mathbf{A}) - \sigma\mathbf{v} \times (\nabla \times \mathbf{A}) = (\sigma V_{loop}/2\pi r + J^e_\varphi)\mathbf{e}_\varphi,\ \mathbf{A} = A_\varphi\mathbf{e}_\varphi$$

Subdomain selection: 1, 2, 3 (selected), 4

Group:

Electric material properties and current sources

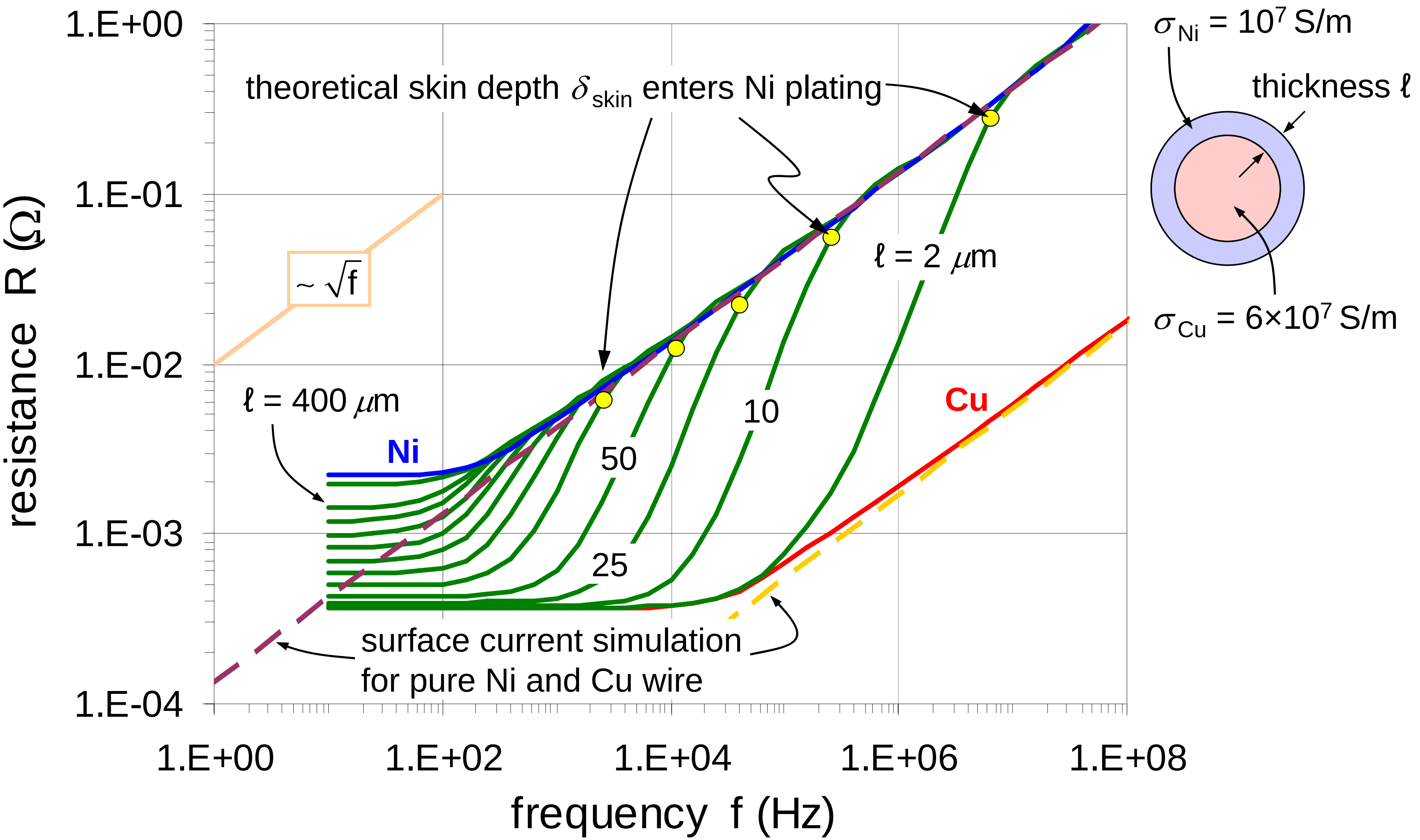
Library material:

Constitutive relation

● $D = \varepsilon_0\varepsilon_r E$ ○ $D = \varepsilon_0 E + P$ ○ $D = \varepsilon_0\varepsilon_r E + D_r$

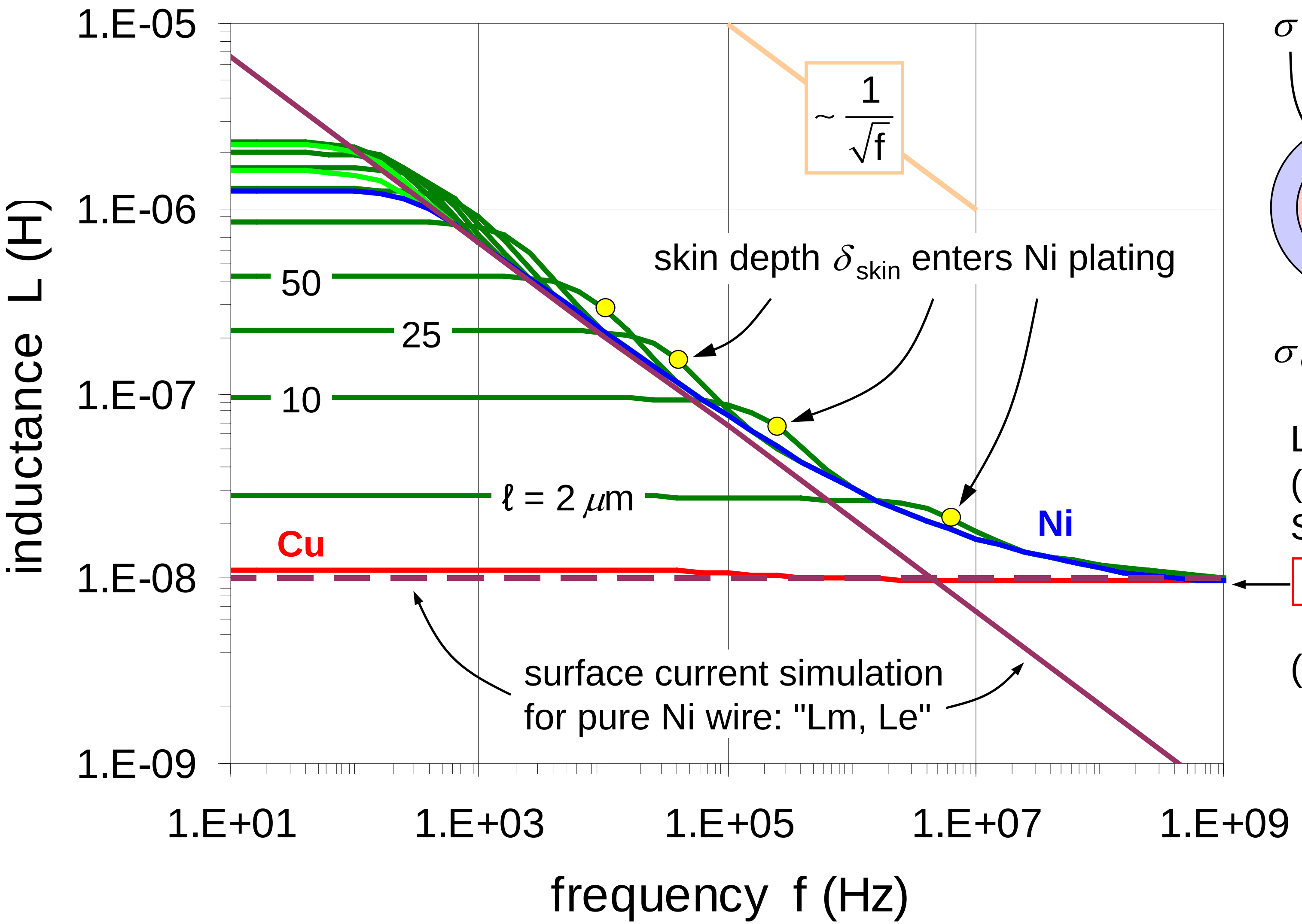
Quantity	Value/Expression	Unit	Description
V_{loop}	Vin	V	Loop potential
J^e_φ	0	A/m²	External current density
σ	sigma3	S/m	Electric conductivity
ε_r	1		Relative permittivity

R versus f and ℓ



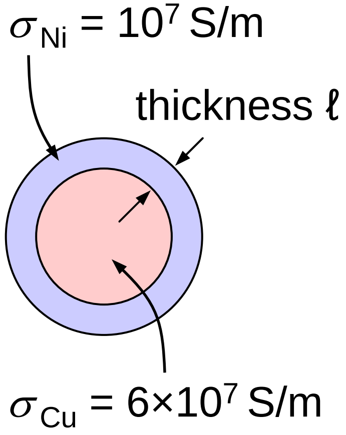
Loop

L versus f and ℓ



skin depth δ_{skin} enters Ni plating

surface current simulation
for pure Ni wire: "Lm, Le"



$\sigma_{Ni} = 10^7$ S/m

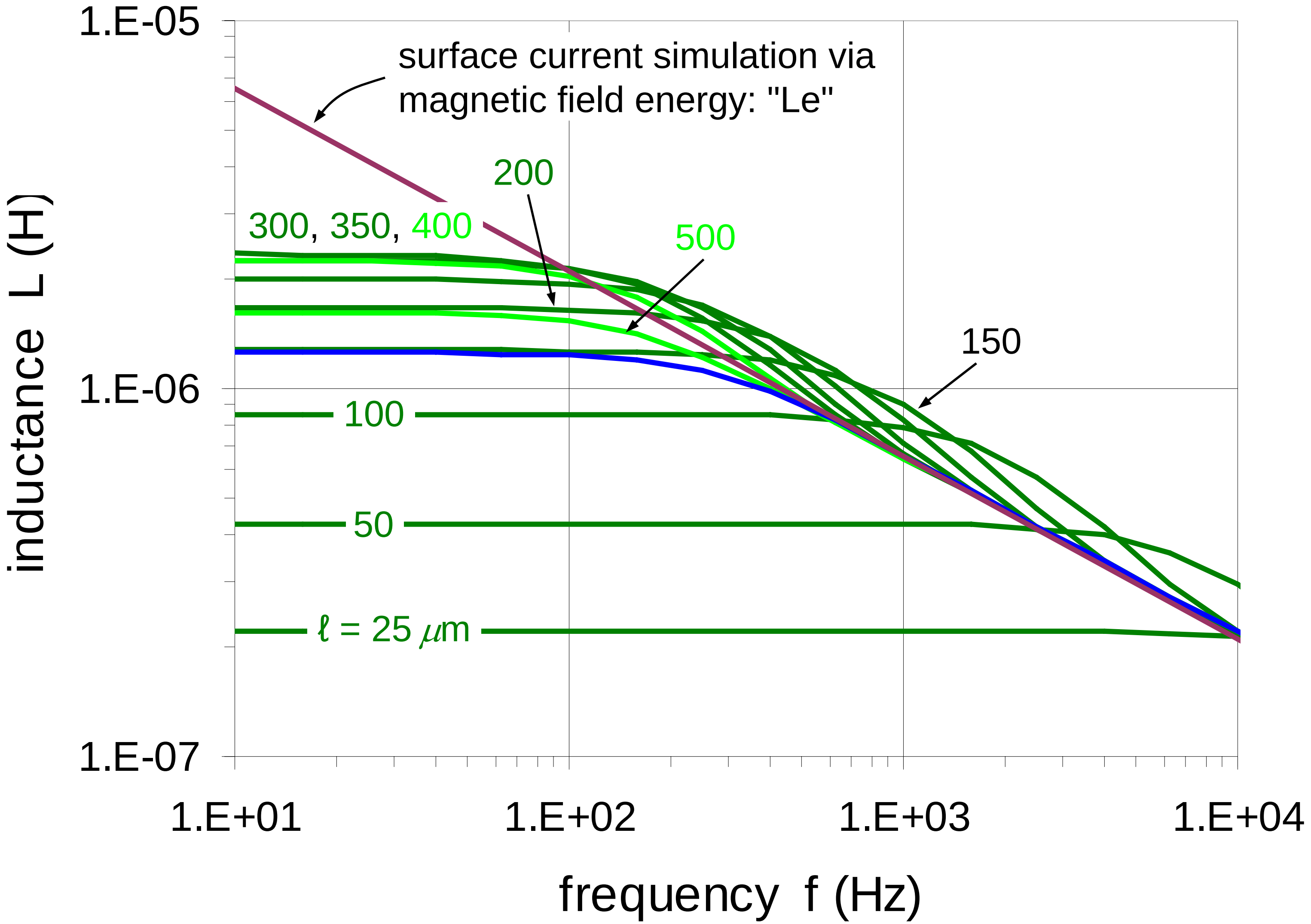
$\sigma_{Cu} = 6 \times 10^7$ S/m

Loop inductance
(Meinke, TdHF,
Springer, 1992):

$\boxed{9.9 \text{ nH}}$ ✓

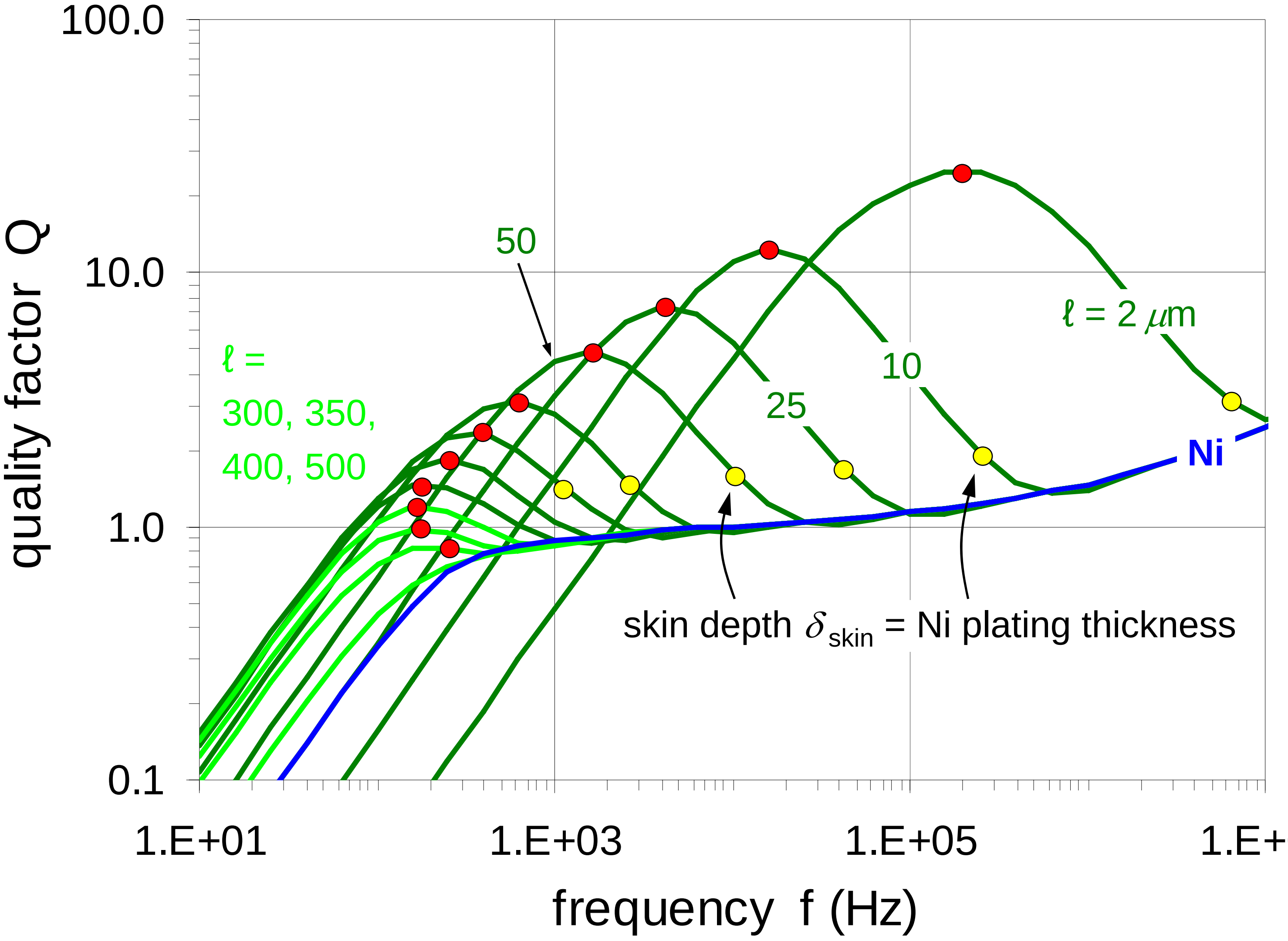
(D > 20d, high f)

L versus f and ℓ, Inset

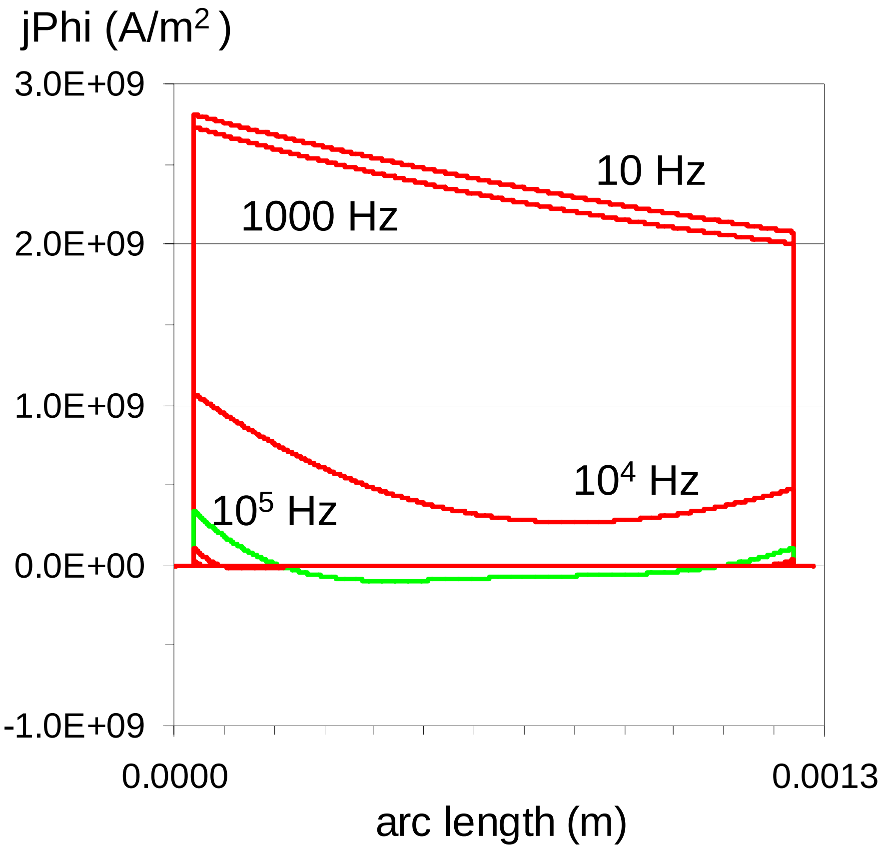


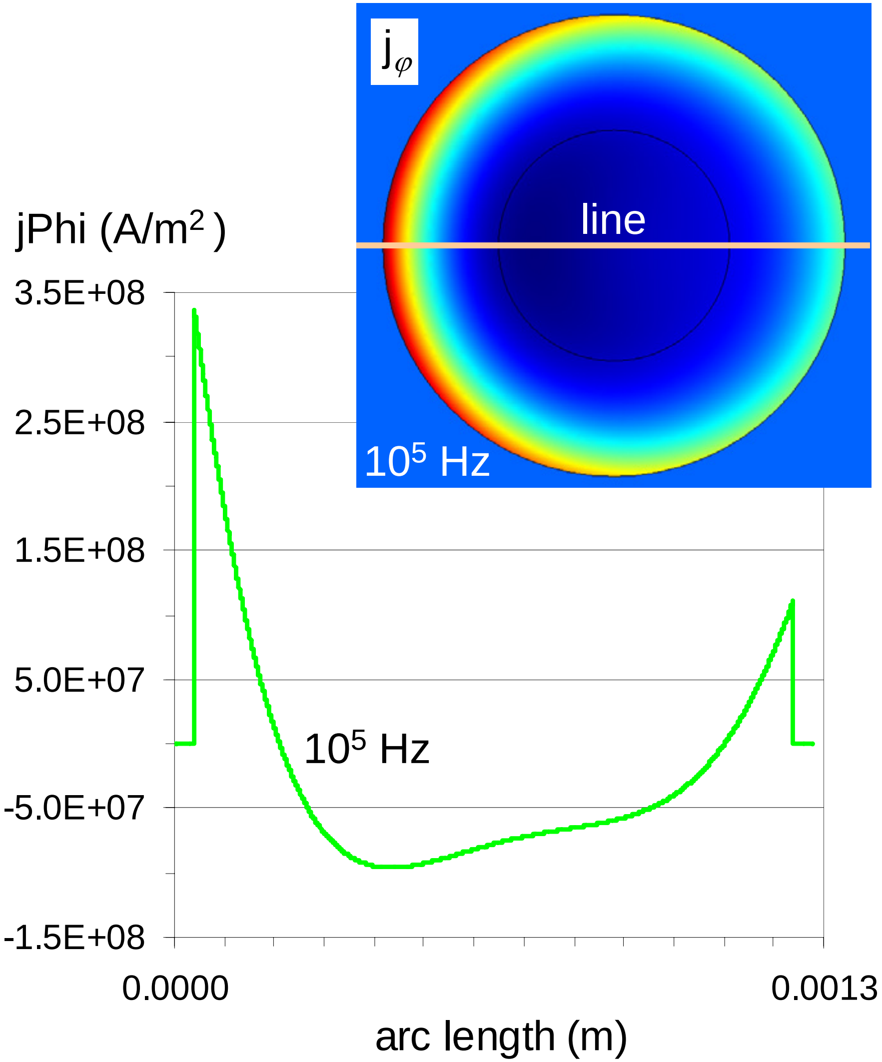
Loop

Q versus f and ℓ, Inset

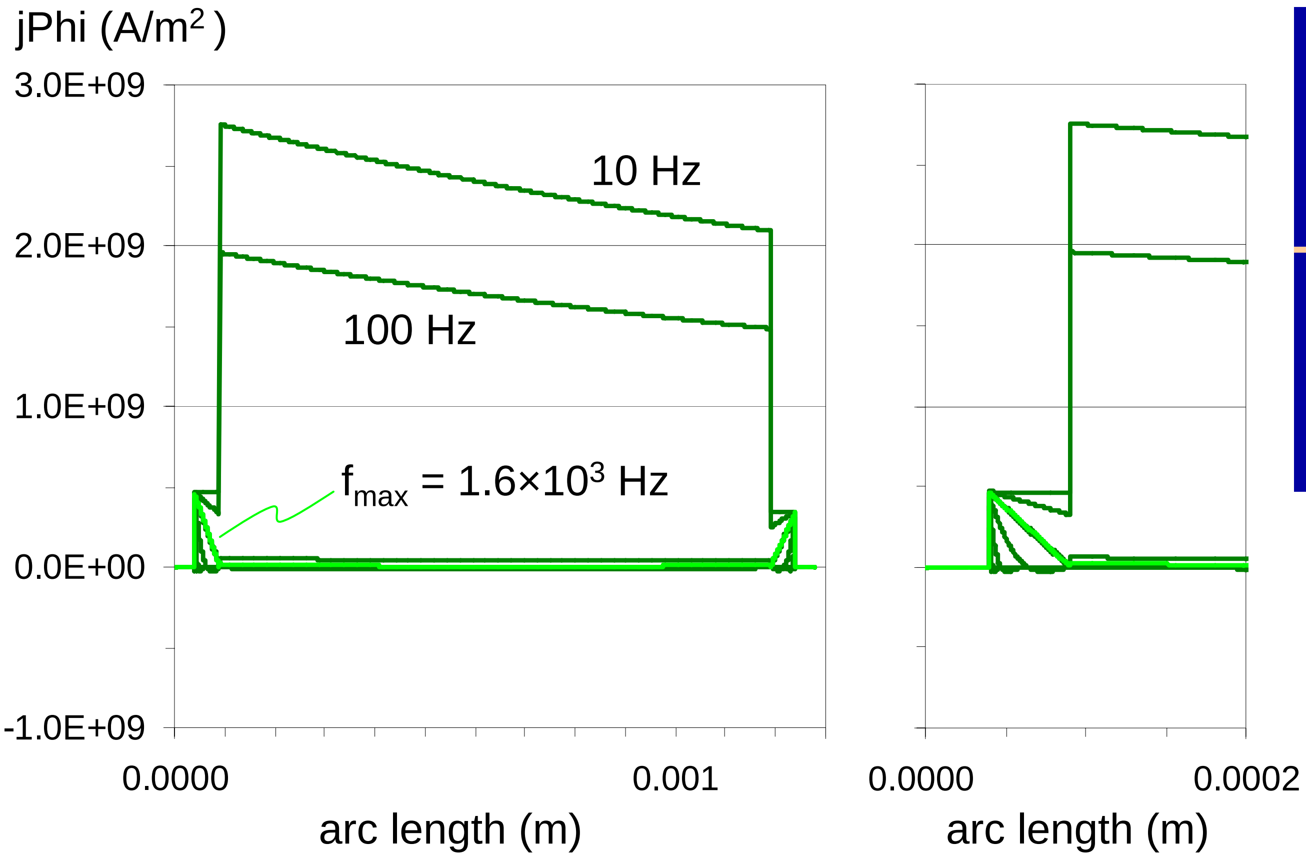


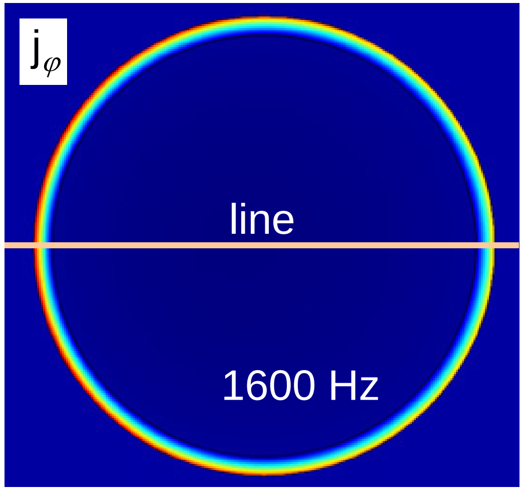
Cu-Loop, Line Plot: jPhi



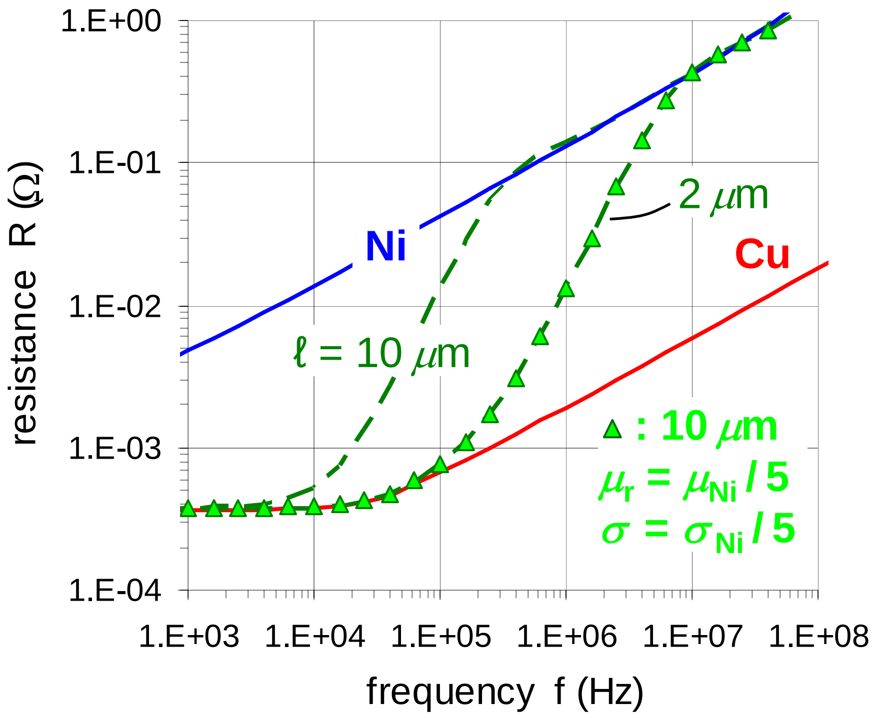


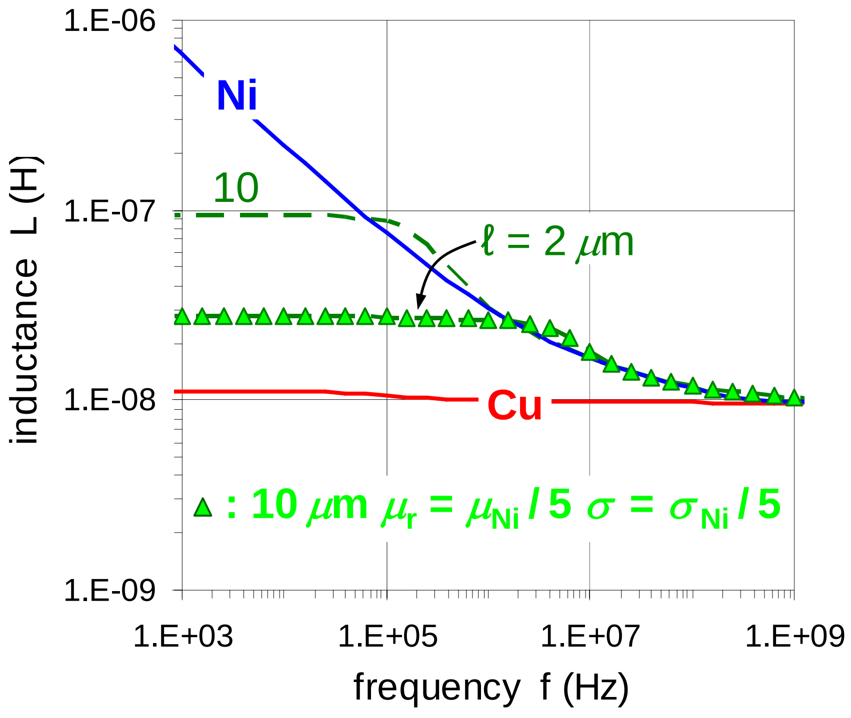
Ni(50μm)-Cu Loop, jPhi





Skaling





Same results, different plating thickness - Skaling for easier meshing ! Example: $d_{new} = \boxed{5} \times d_{old}$

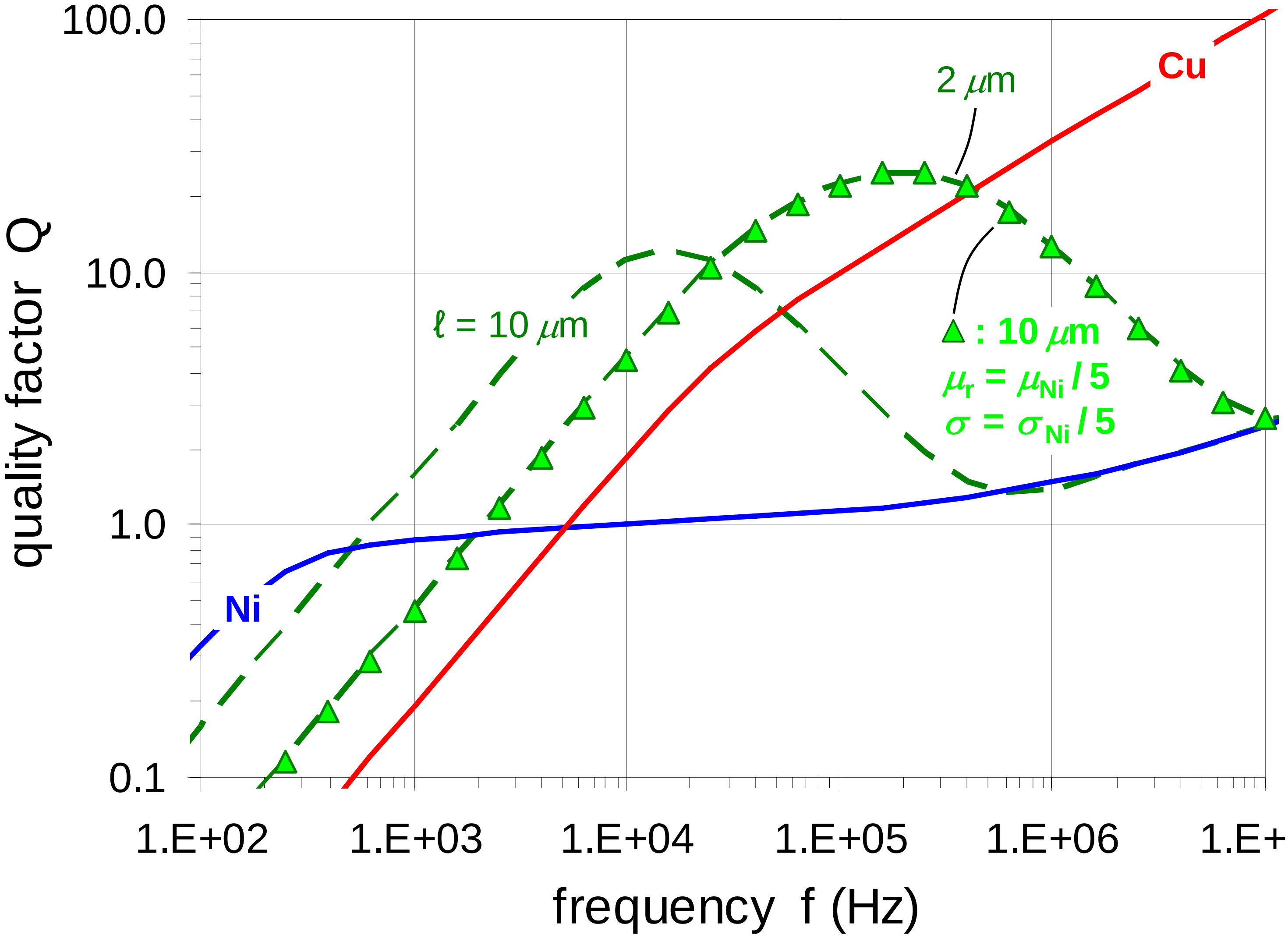
Increase δ_{skin} while keeping R = constant

$$\delta_{skin,new} \equiv \boxed{5} \times \delta_{skin,old} = \sqrt{\frac{1}{\mu_0 \cdot \mu_r / \boxed{5} \cdot \pi f \cdot \sigma / \boxed{5}}}$$

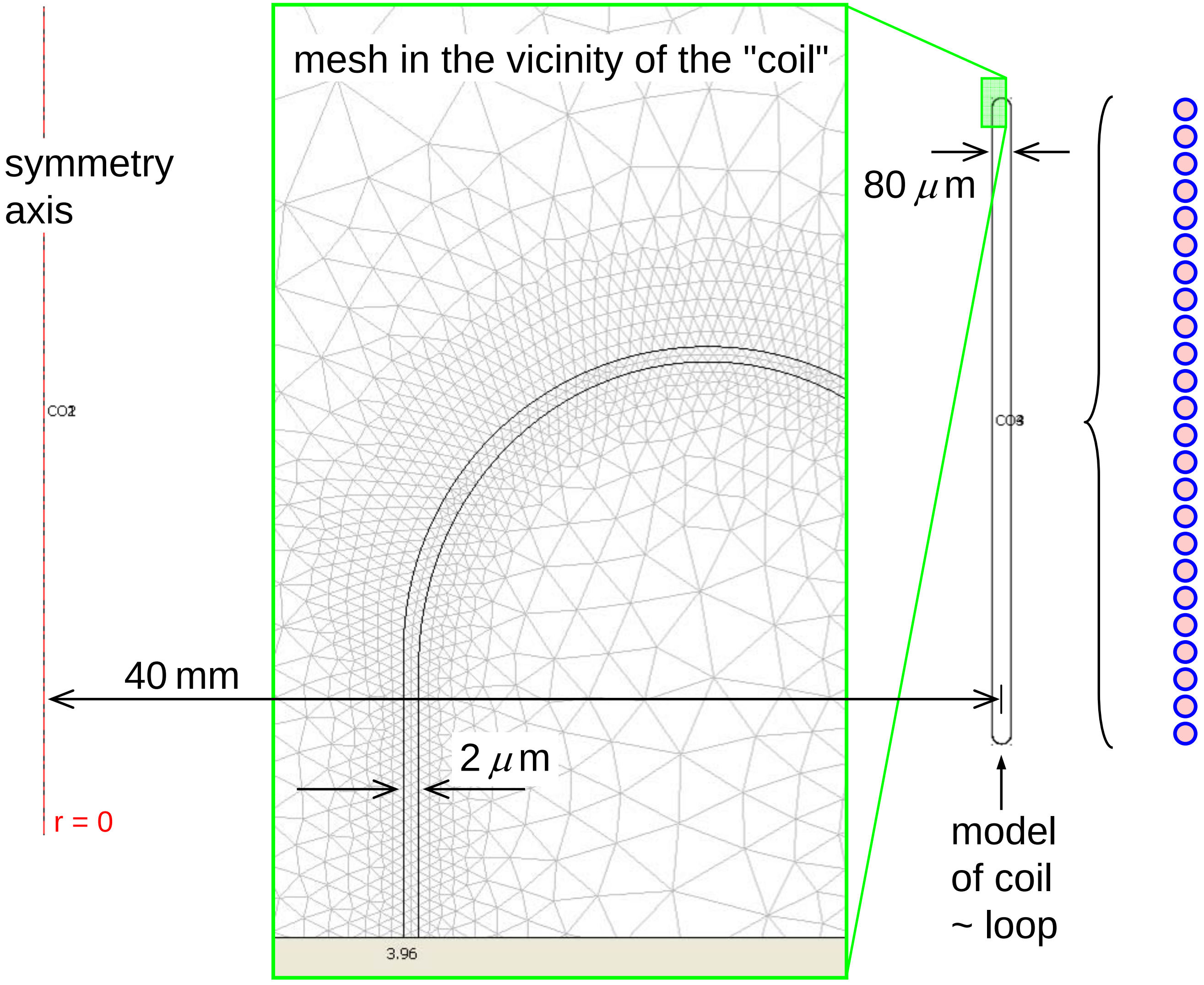
$$R_{new} \equiv R_{old} = \frac{D}{d} \cdot \frac{1}{\sigma / \boxed{5} \cdot d \cdot \boxed{5}}$$

Loop

Skaling

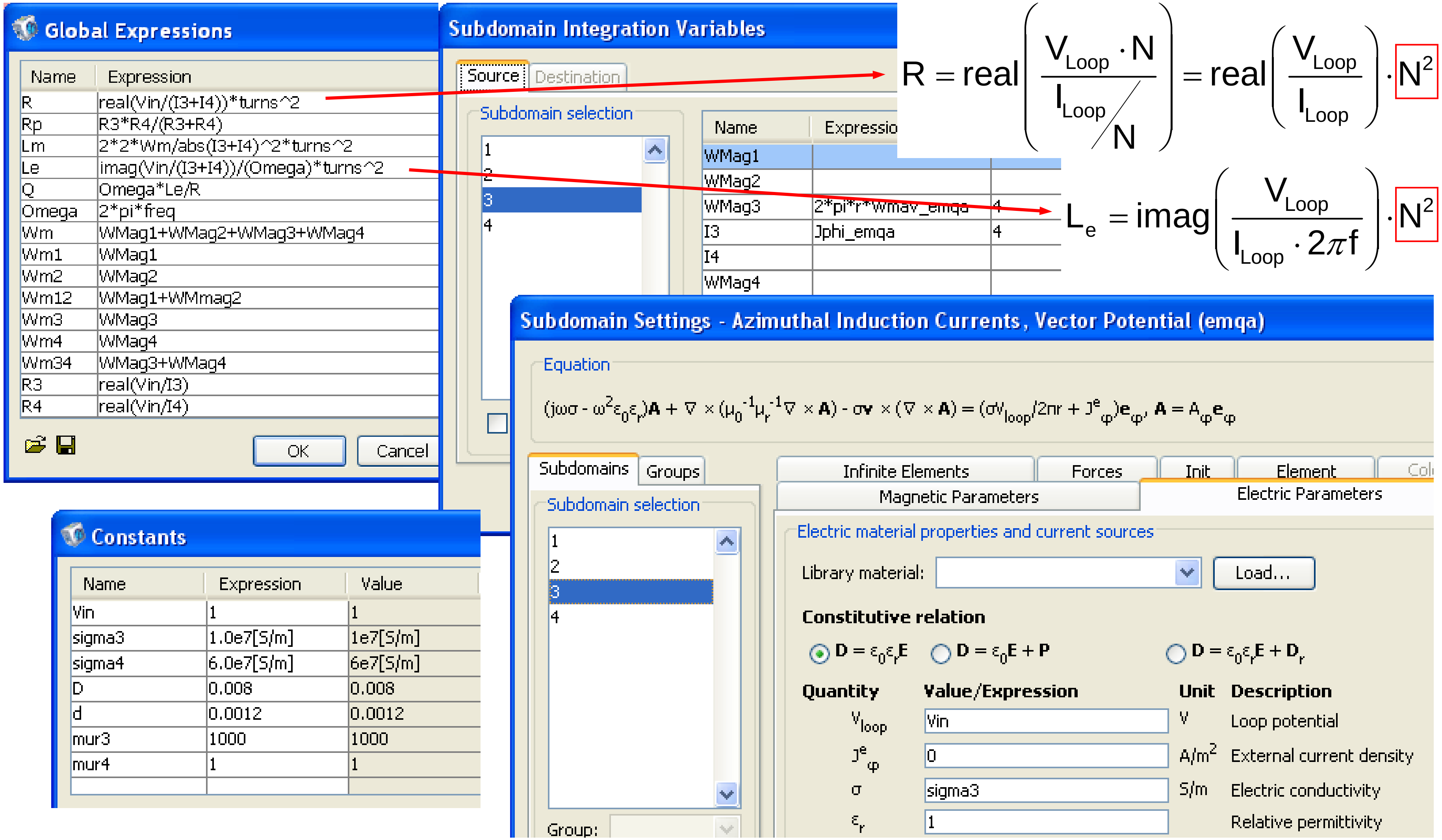

100.0
10.0
1.0
0.1
quality factor Q
1.E+02
1.E+03
1.E+04
1.E+05
1.E+06
1.E+07
frequency f (Hz)
Cu
2 μm
ℓ = 10 μm
▲ : 10 μm
μ_r = μ_Ni / 5
σ = σ_Ni / 5
Ni

Plated Coil



real coil:
N = 30 turns
ℓ = 2.7 mm, length of coil
D = 8.0 mm, diameter
d = 80 μm, wire diameter

Plated Coil



$$R = \mathrm{real}\left(\frac{V_{Loop} \cdot N}{I_{Loop} / N}\right) = \mathrm{real}\left(\frac{V_{Loop}}{I_{Loop}}\right) \cdot \boxed{N^2}$$

$$L_e = \mathrm{imag}\left(\frac{V_{Loop}}{I_{Loop} \cdot 2\pi f}\right) \cdot \boxed{N^2}$$

Global Expressions

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R	real(Vin/(I3+I4))*turns^2
Rp	R3*R4/(R3+R4)
Lm	2*2*Wm/abs(I3+I4)^2*turns^2
Le	imag(Vin/(I3+I4))/(Omega)*turns^2
Q	Omega*Le/R
Omega	2*pi*freq
Wm	WMag1+WMag2+WMag3+WMag4
Wm1	WMag1
Wm2	WMag2
Wm12	WMag1+WMmag2
Wm3	WMag3
Wm4	WMag4
Wm34	WMag3+WMag4
R3	real(Vin/I3)
R4	real(Vin/I4)

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I4		
WMag4		

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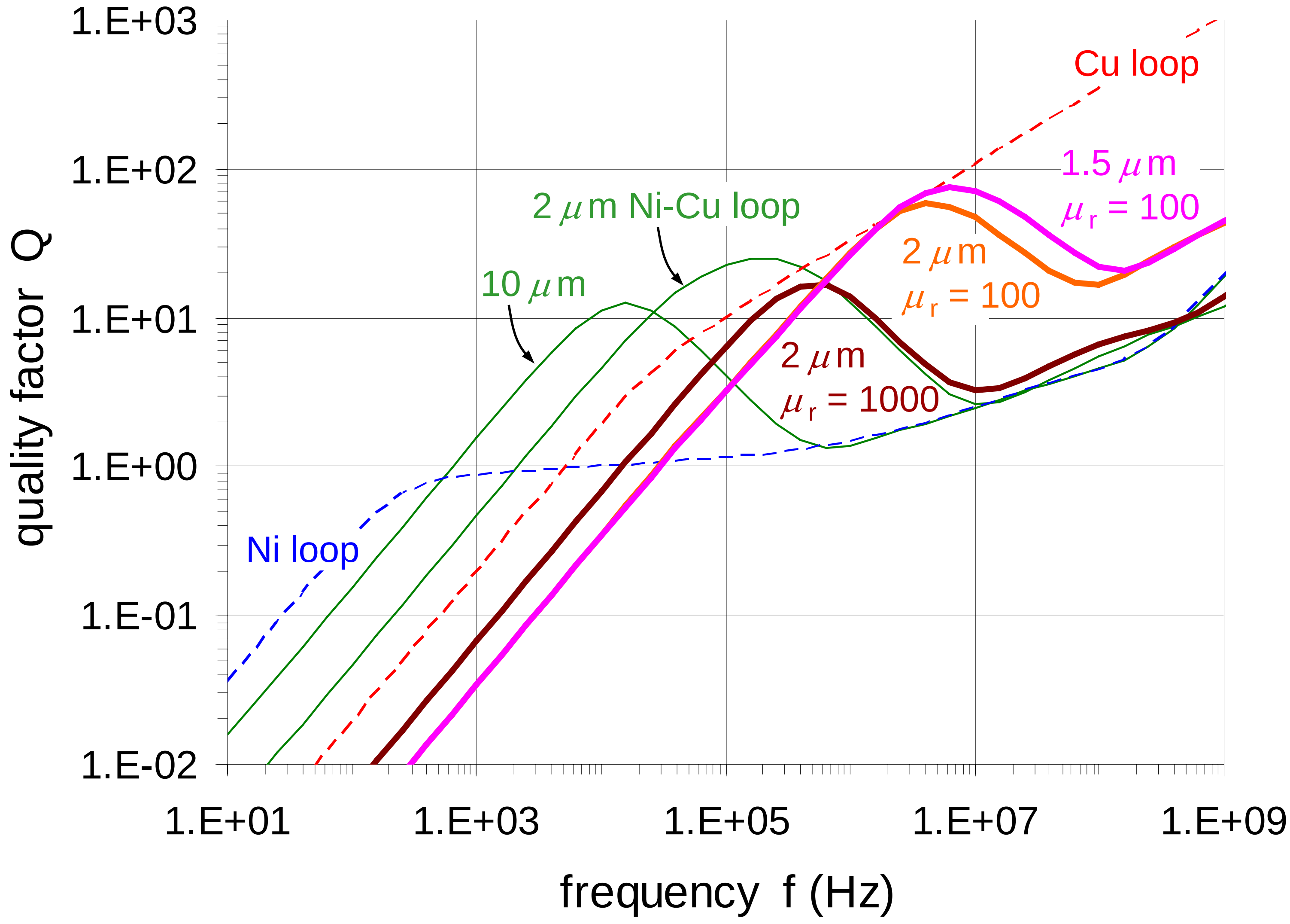
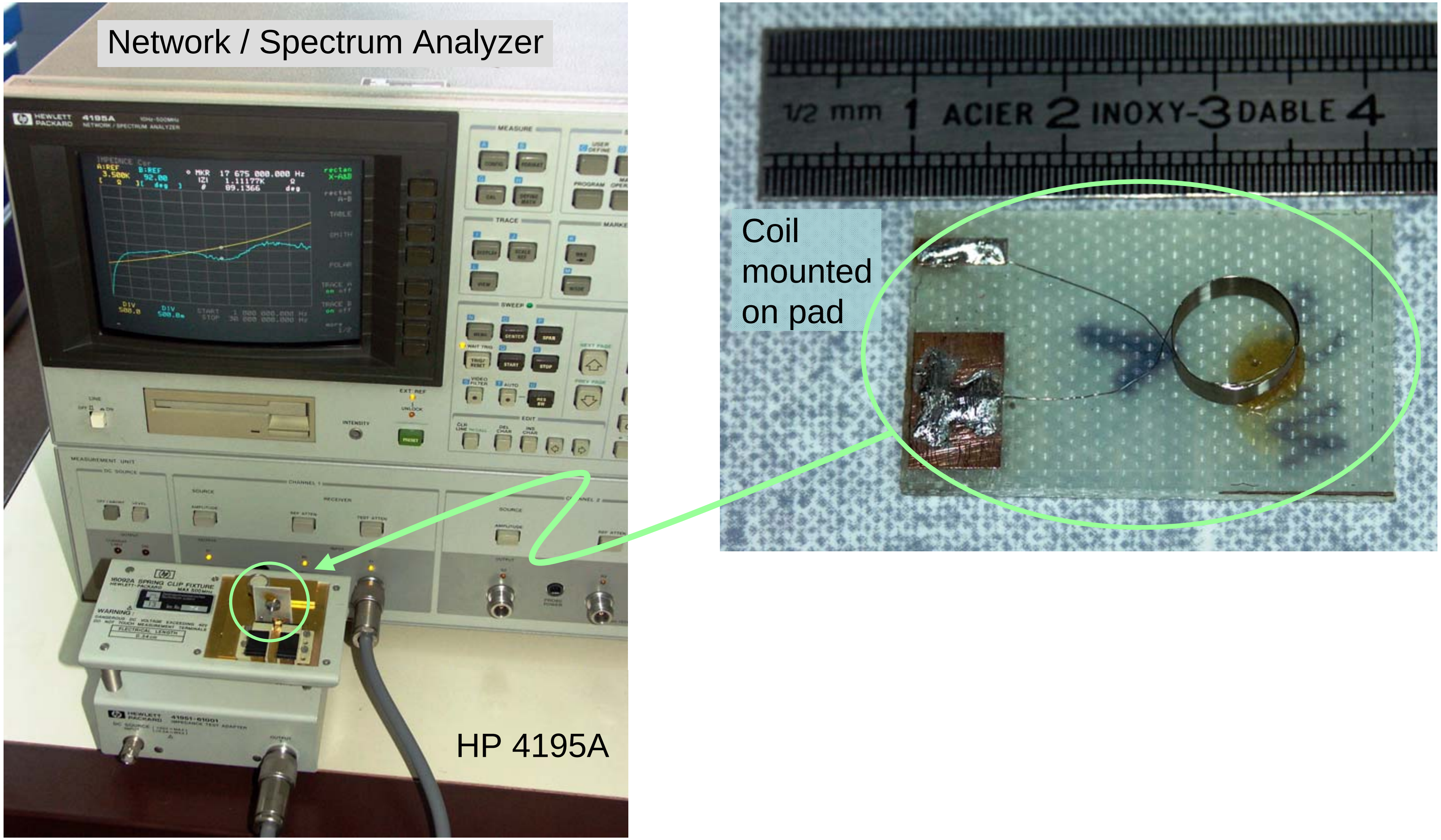
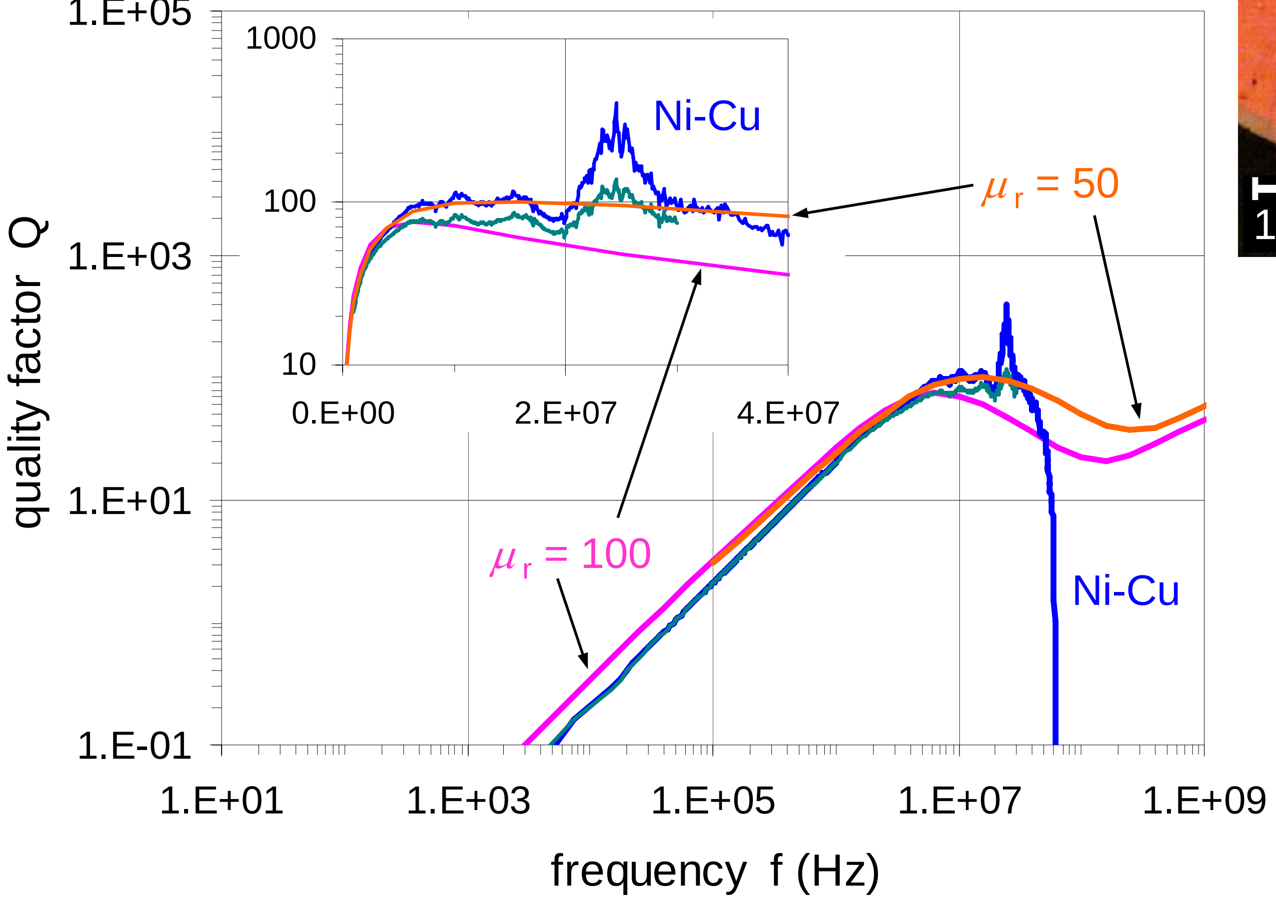
Q of Plated Coil

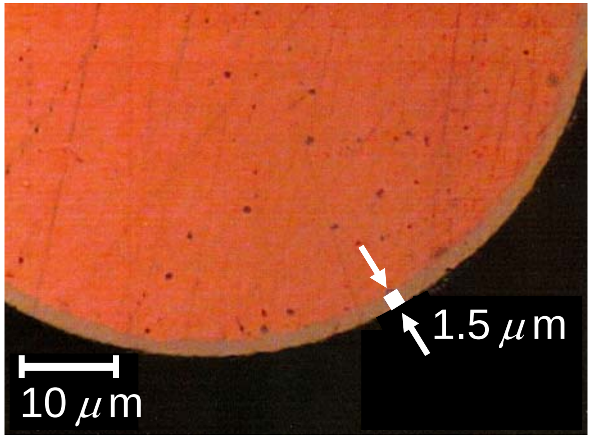


Measurement



Simul. vs. Experiment





Summary

1. R, L and Q of plated loops and coils can be simulated with the classical electrodynamics AC/DC module of COMSOL
2. For each plating thickness there exists a regime where Q is much larger than for pure copper or pure nickel loops and coils
3. A true application of this phenomenon is not yet found, if not for the power transfer by magnetic resonance (Science, 317, p83, 2007)
4. Excellent agreement between simulation and experiment can be found at modest frequencies below 10 MHz
5. Comparison between simulation and experiment at higher frequncy is not possible due to a stray capacitance and the occurence of a resonance