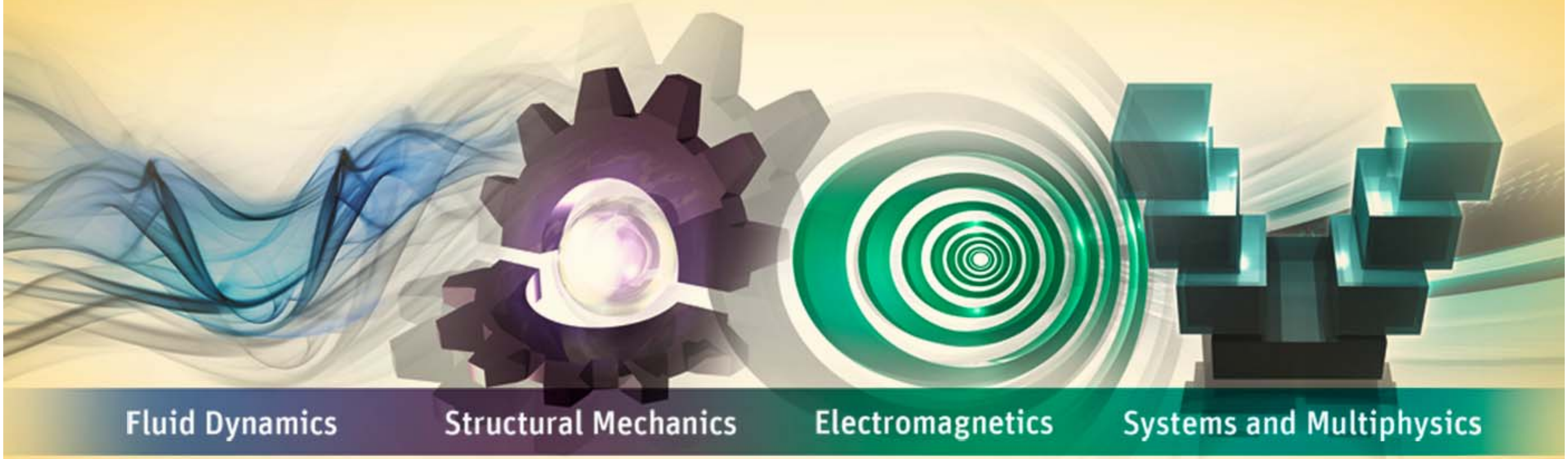
ANSYS

Realize Your Product Promise™

Wireless Power Transfer for EV



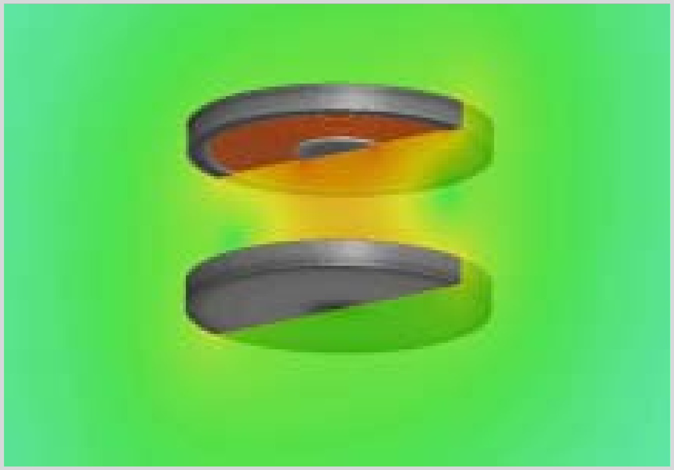
2011 REGIONAL CONFERENCES

ANSYS Japan K.K.

Takahiro Koga

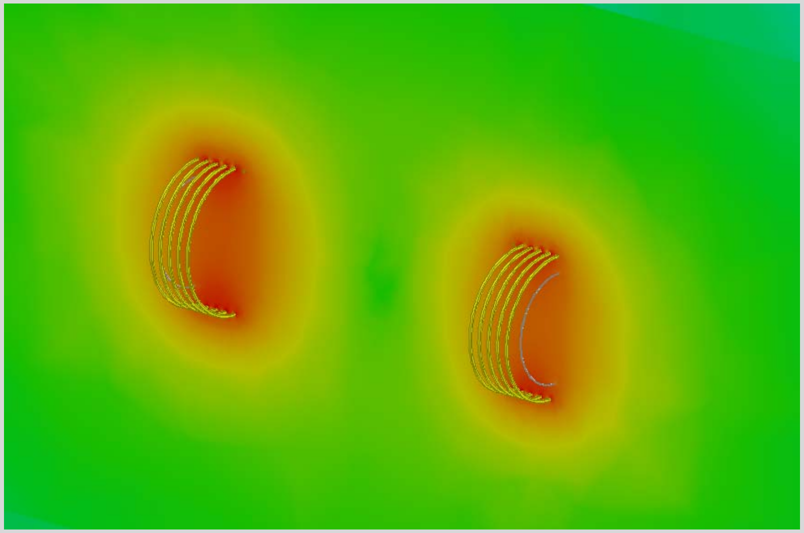
Agenda

1. **Electromagnetic tools for Wireless Power Transfer**



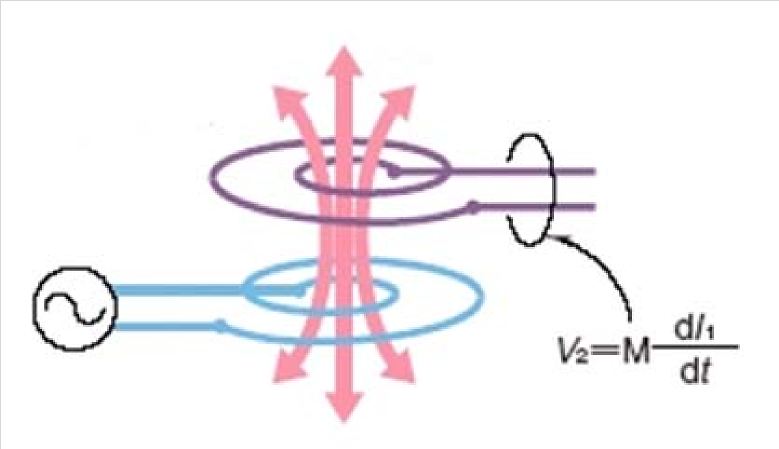
2. **Coupling Simulation:**
   Electromagnetic - Electrical Circuit

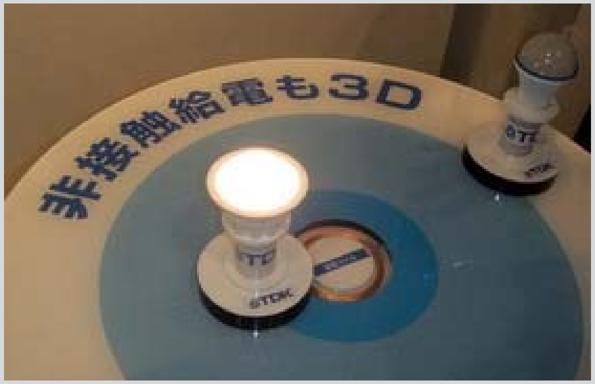
3. **Application for Wireless Power Supply**
   - **Inductive type**
   - **Magnetic resonance type**



Wireless Power Supply

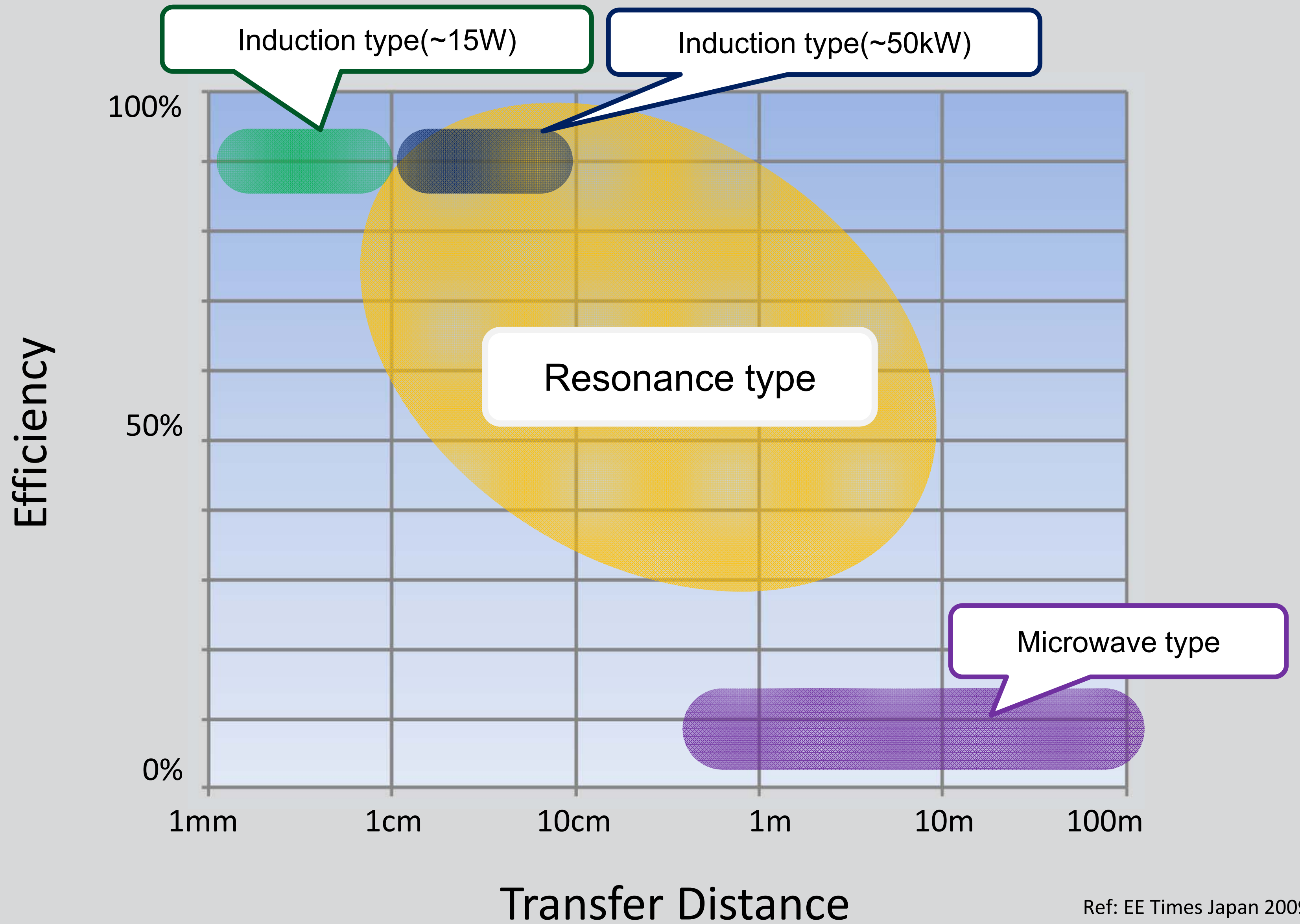
- Method :
  - ✓– **Electromagnetic Induction**
  - ✓– **Magnetic Resonance**
  - – Microwave





Ref.: Nikkei Electronics Mar. 2007
EE Times Japan Oct. 2009, Nov. 2010

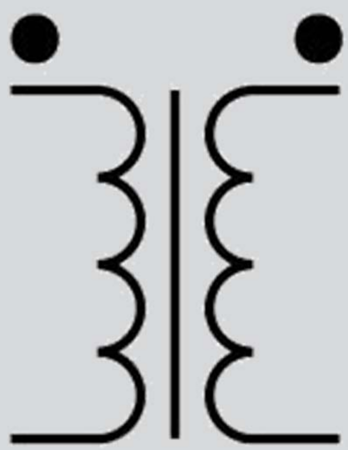
Method Map



Ref: EE Times Japan 2009.10

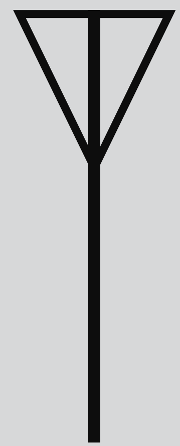
Which is the optimal simulation tool ?

"Low Freq."



Maxwell

"High Freq."



HFSS

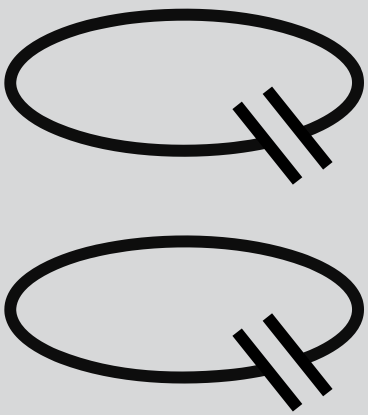
Differentiating Features

- **Maxwell: Low Frequency Field Simulator**
  - Separated Solver "Magnetic" and "Electric"
  - Time Transient and Lumped Circuit: L,R,C
  - Linear and Nonlinear Material
  - Application: Motor, Transformer/Inductor for power machine, Inductive noise

- **HFSS: High Frequency Structure Simulator**
  - Electromagnetic Full Wave Solver
  - Distributed Circuit: S,Z,Y
  - Linear Material
  - Application: Antenna, Transformer/Inductor for signal, Radiation noise

Resonance Type Coupling

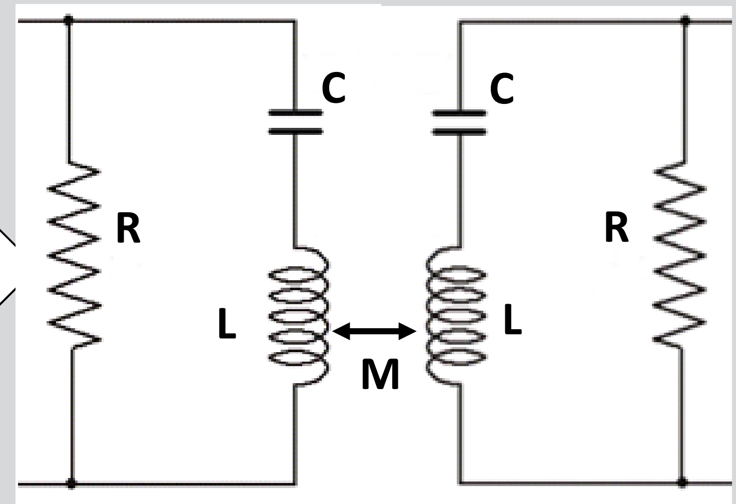
1. **Self Capacitance**
2. **External Capacitance**



Magnetic → R, L, M

Maxwell

Electrostatic → C

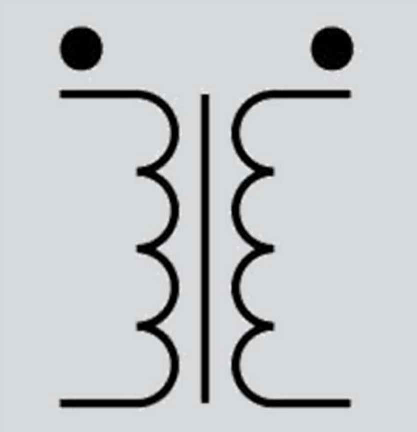


Use Maxwell parasitic extraction and couple with circuit simulator for resonance

Reference: Wireless Power Transfer via Strongly Coupled Magnetic Resonaces
A.Kurs, A.Kralis, R.Moffatt,B.J.Jonnapoulos, P.Fisher, Vo;.317, pp.83-86, July 2007

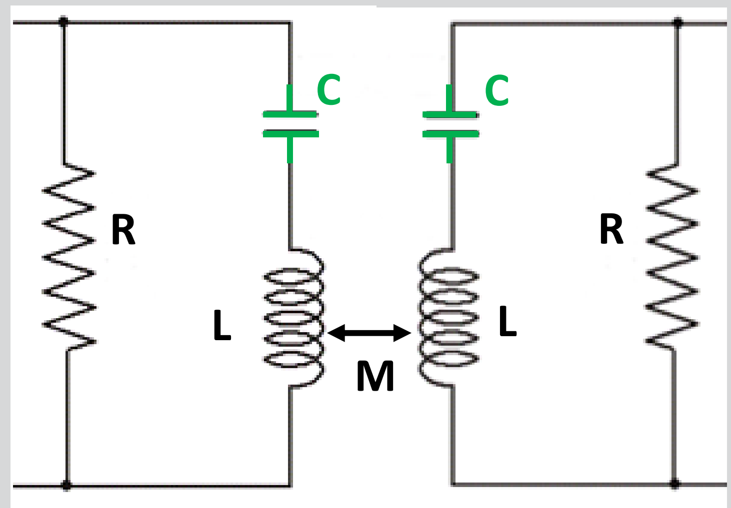
Inductive Type Coupling

Principle physics is magnetic coupling



Magnetic → R, L, M

Maxwell

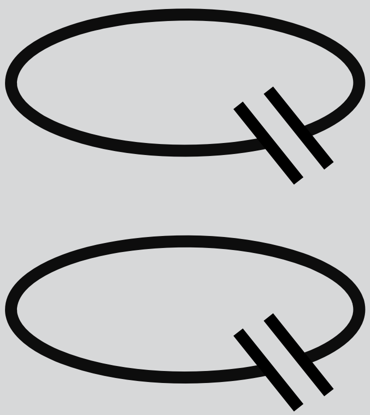


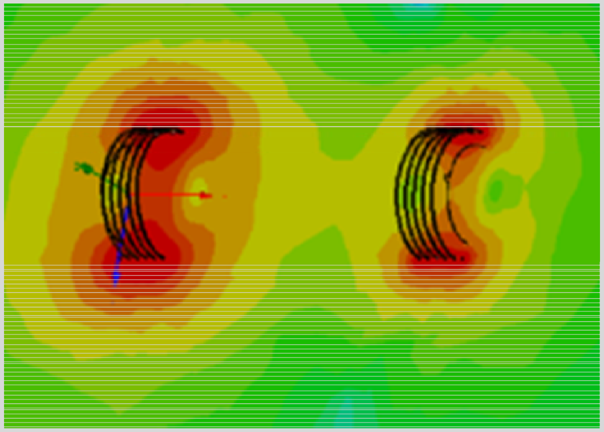
The resonant circuit is full realized via a lumped capacitance solved using circuit simulator

Resonance Type Coupling

1. Self Capacitance
2. External Capacitance

HFSS

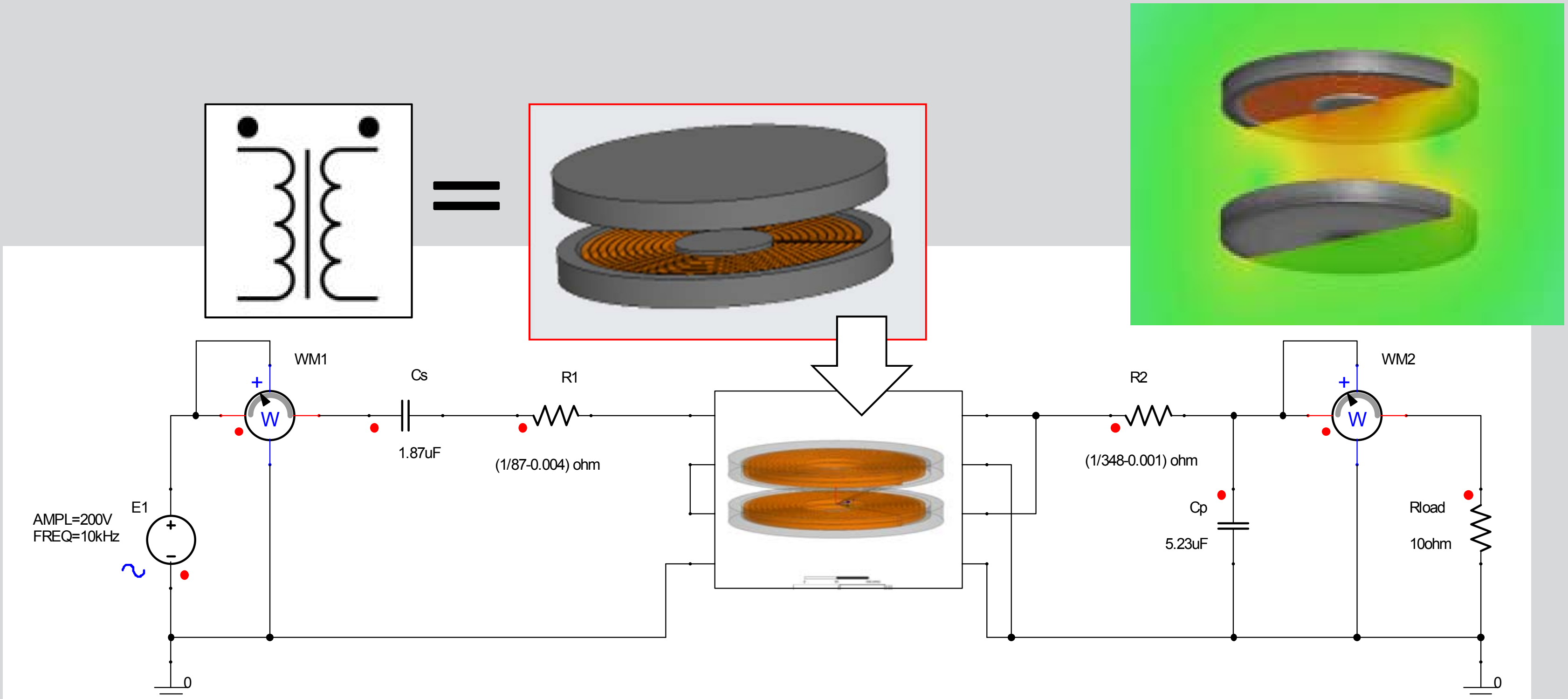


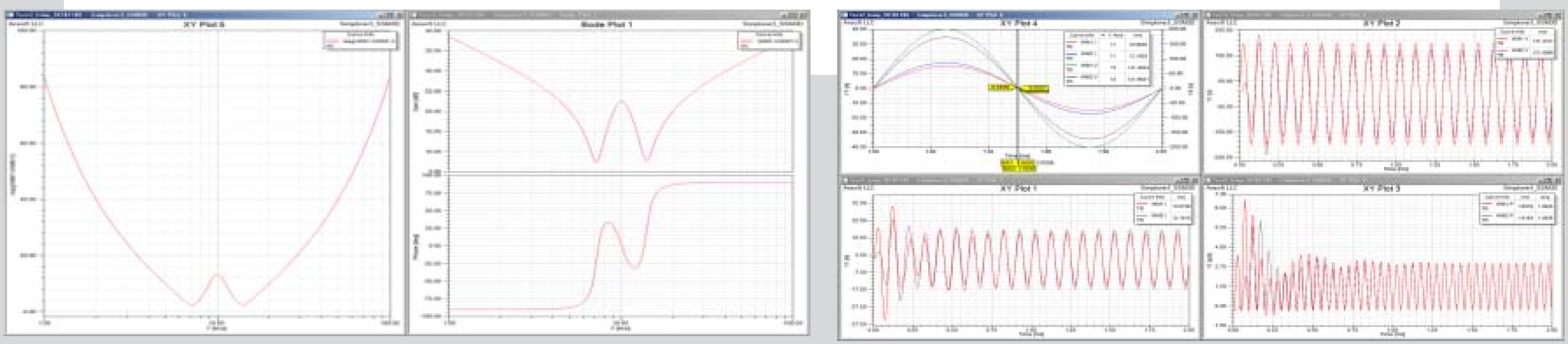


Use HFSS' full wave capability when the resonance occurs by self capacitance

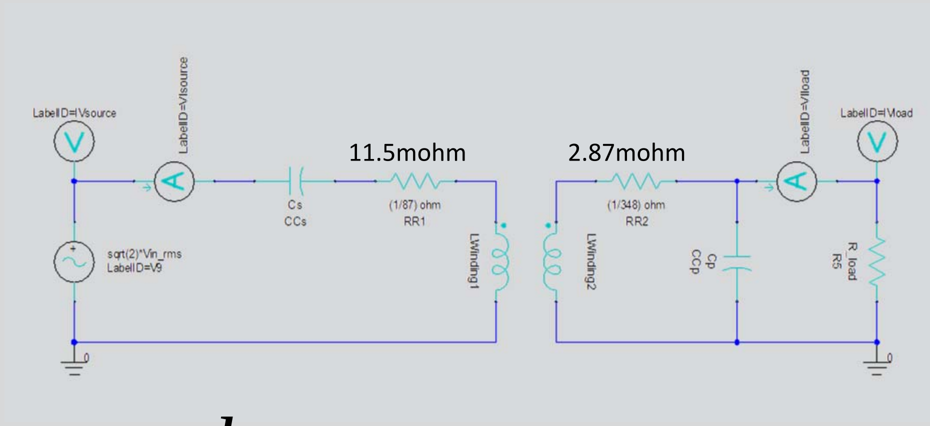
Reference:
Wireless Power Transfer via Strongly Coupled Magnetic Resonaces
A.Kurs, A.Kralis, R.Moffatt,B.J.Jonnapoulos, P.Fisher, Vo;.317, pp.83-86, July 2007

Coupling Simulation Electromagnetic and Circuit





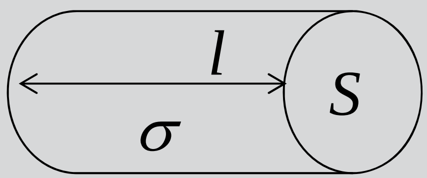
Calculation of Coil Resistance

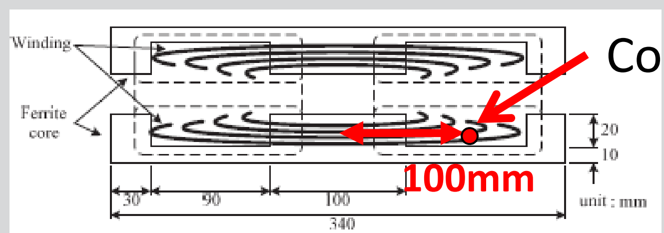


Coil

- Litz : 0.25ϕ × 384parallel
- σ : 5.8×10^{7}[S/m]
- Primary : 20 turns
- Secondary : 10 turns x 2parallel

$$R = \frac{l}{\sigma S}$$





Coil slot center

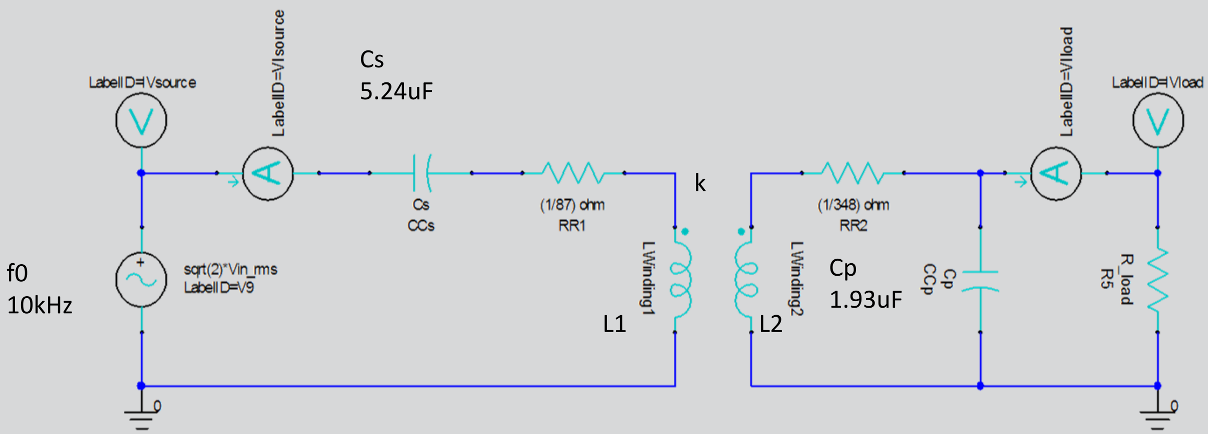
<u>Primary Coil:</u>

R1 = (2*100*pi*1e-3)/(5.8e7*(0.25/2)^2*pi*1e-6)*(1/384)*20 = <u>11.5mohm</u>

<u>Secondary Coil:</u>

R2 = (2*100*pi*1e-3)/(5.8e7*(0.25/2)^2*pi*1e-6)*(1/384)*10/2 = <u>2.87mohm</u>

Capacitance Calculation



	Current1	Current2
Current1	0.19267	0.054602
Current2	0.054602	0.048166

	Current1	Current2
Current1	1	0.5668
Current2	0.5668	1

L_1 = 0.19267mH

L_2 = 0.048166mH

k = 0.5668

$$C_p = \frac{1}{\omega_0^2 L_2}$$

Cp:

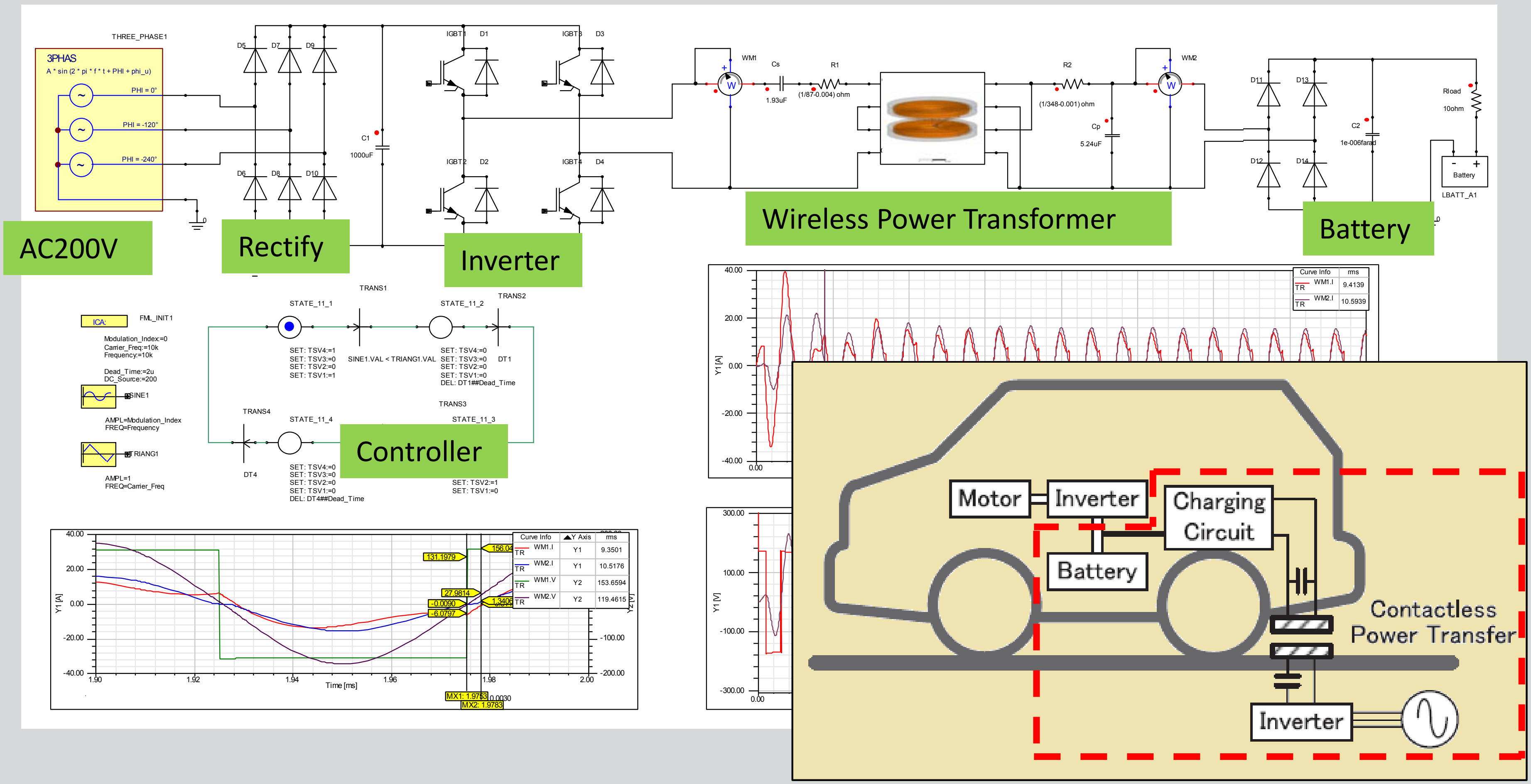
1/((2*1e4*pi)^2*0.0048166) = 5.24e-6 F = 5.24uF

$$C_s = \frac{1}{\omega_0^2 \left(1 - k^2\right) L_1}$$

Cs:

1 /((2*1e4*pi)^2*(1-0.5668^2)*0.0019267) = 1.93e-6 F = 1.93uF

System Simulation



Distinguishing Features for Coupled Simulation

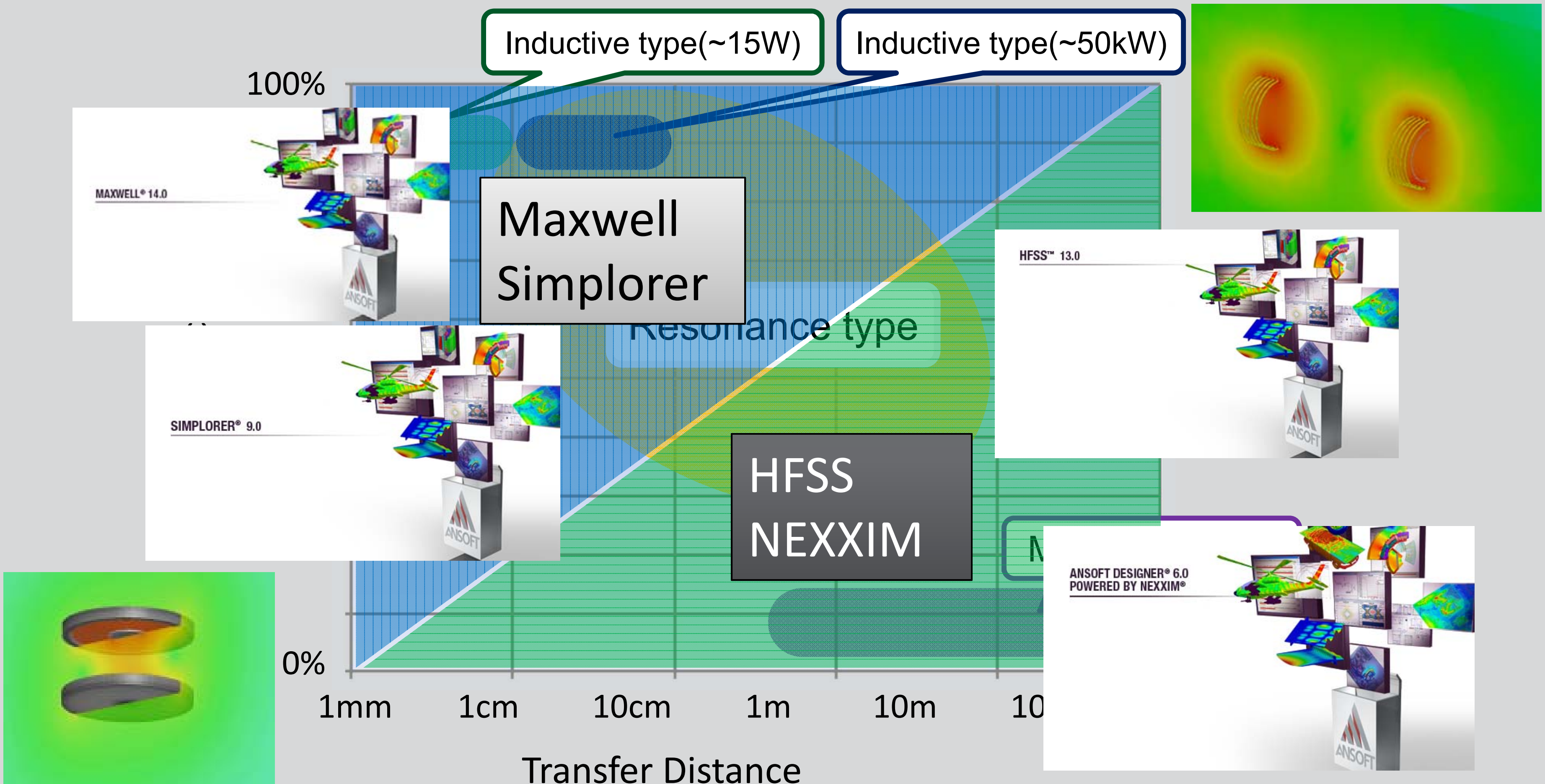
- **Integrated design environment**
  - **Easy and intuitive user interface**

- **Dynamically linked parameters between the Circuit and 3D FEA model**
  - **Geometry / Material / Gap etc…**

Efficient workflow design enables Simulation Driven Product Development™

Application

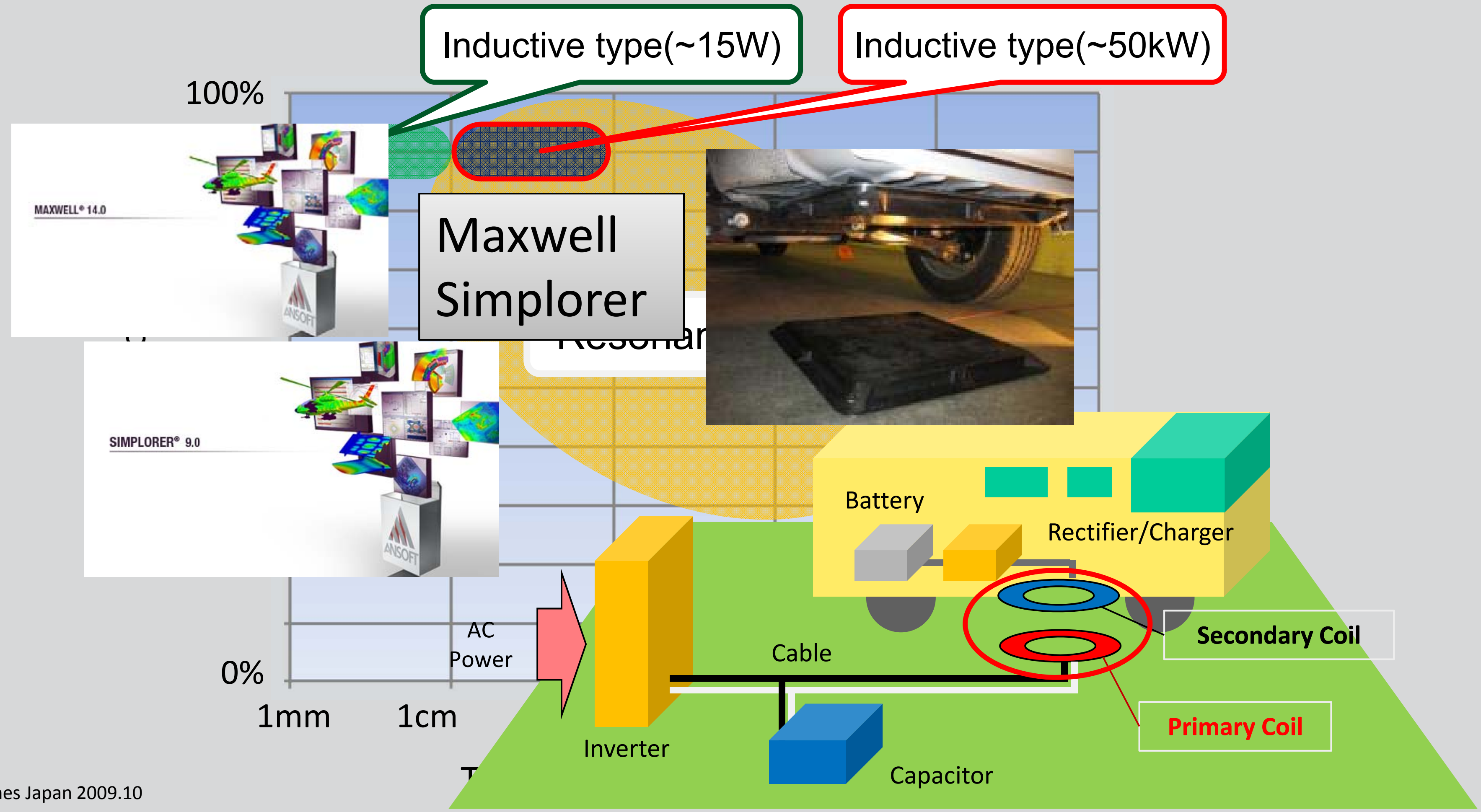
- **ANSYS Products for Wireless Power Supply**



Ref: EE Times Japan 2009.10

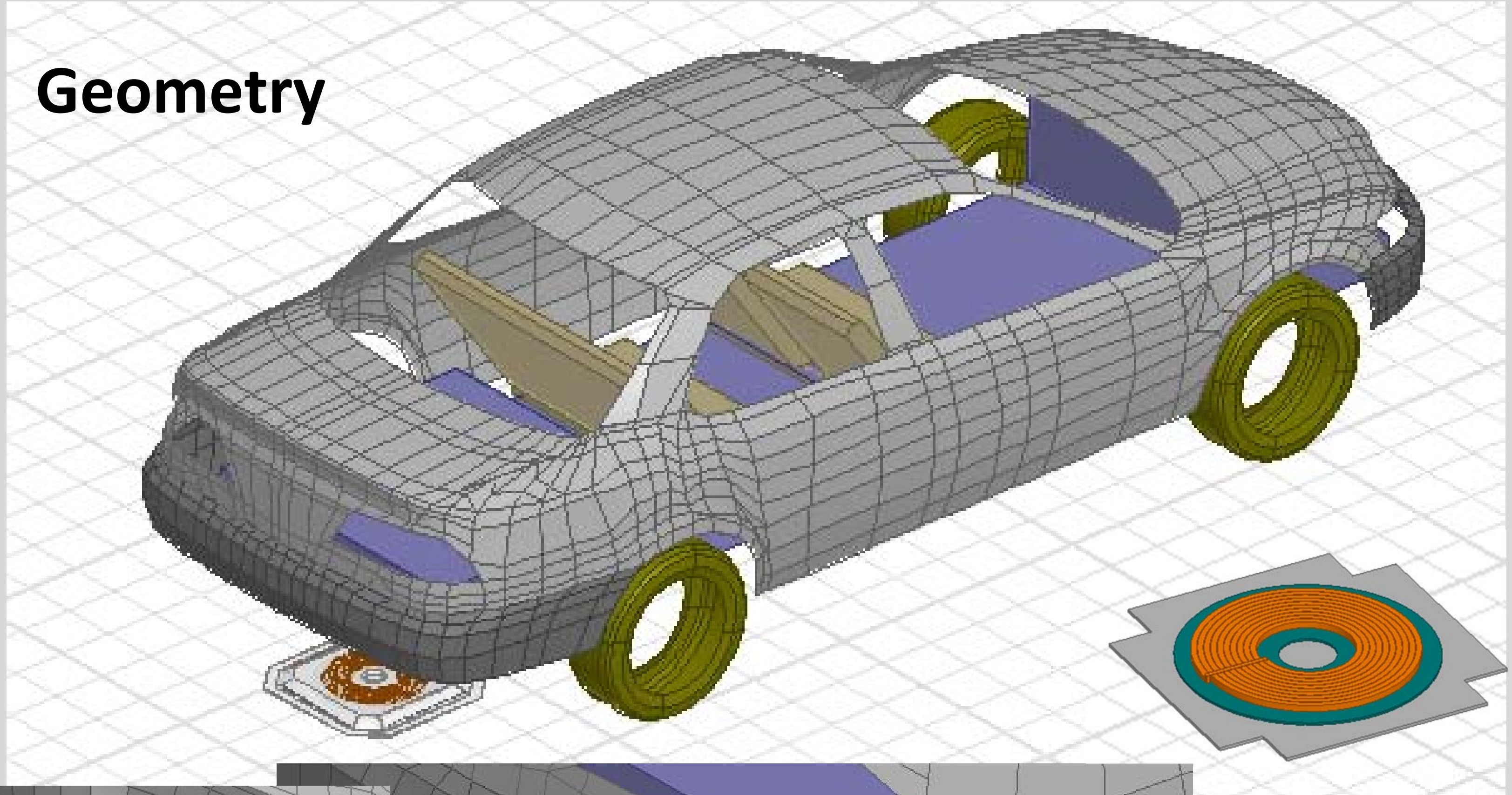
Wireless Power Supply System for EV

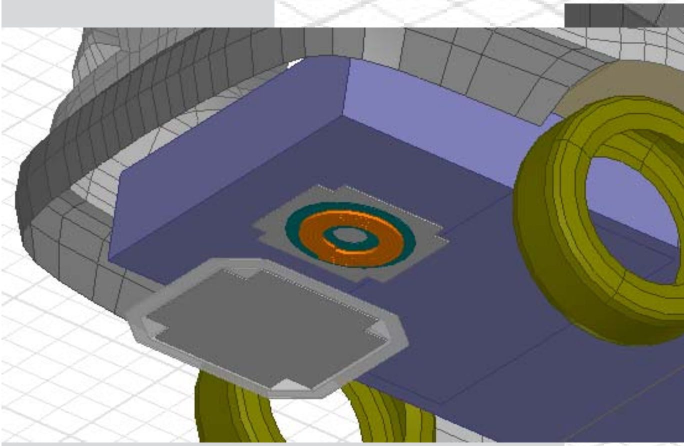
- **Inductive type**

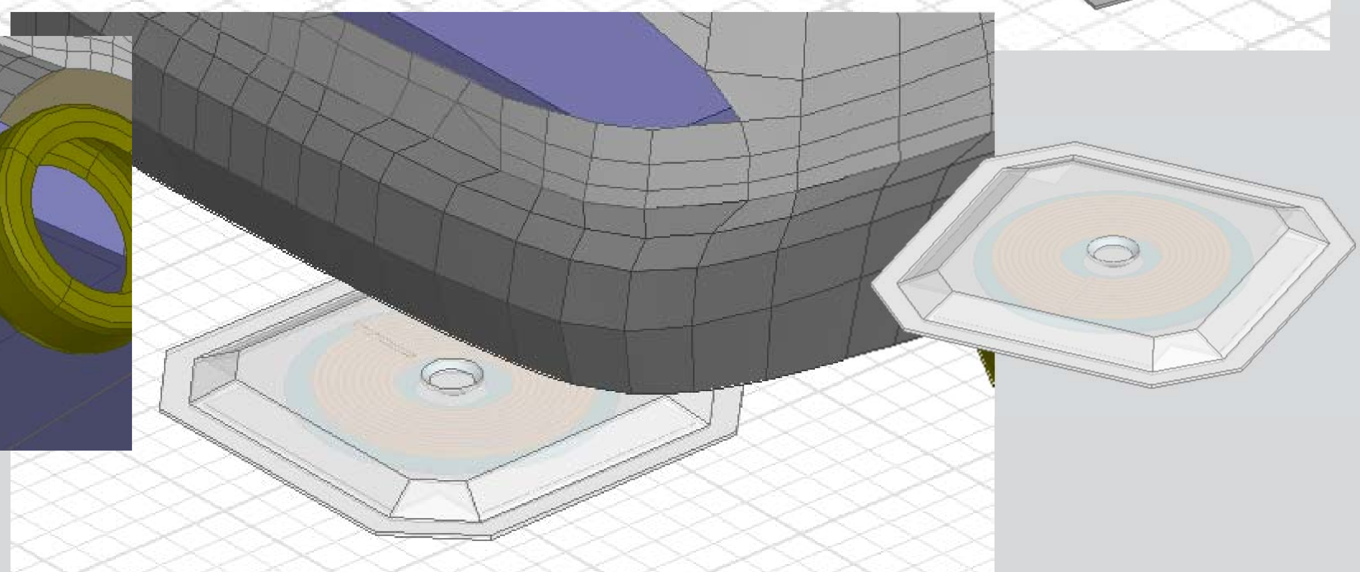


Ref: EE Times Japan 2009.10

Geometry







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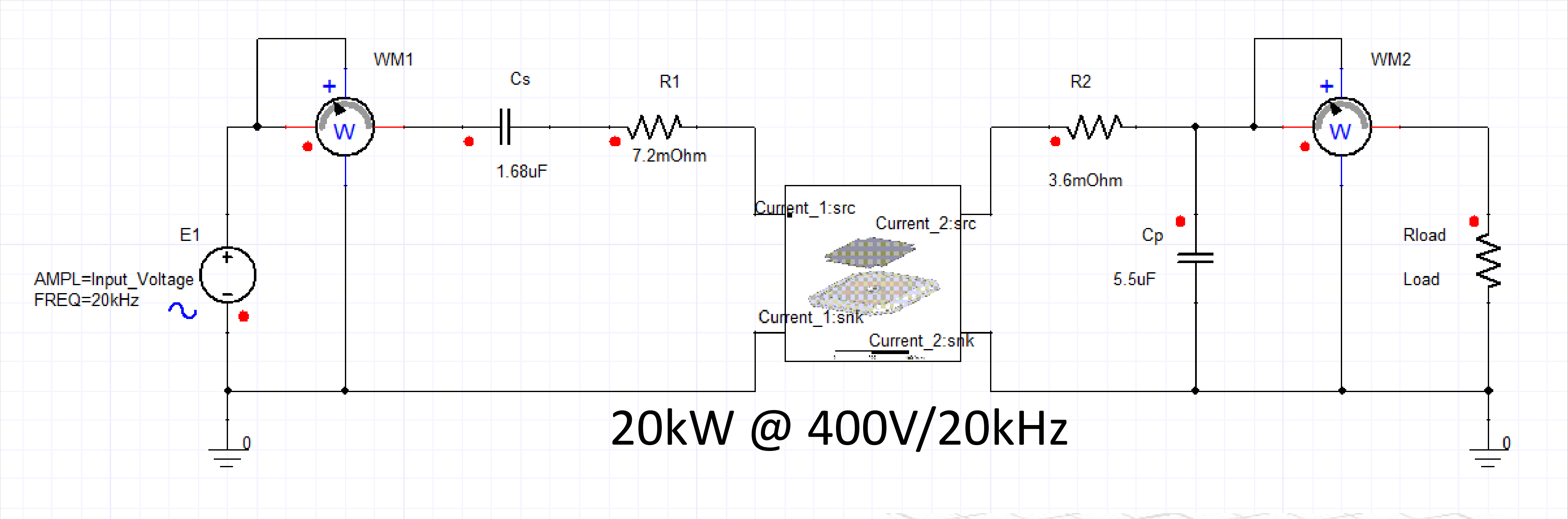
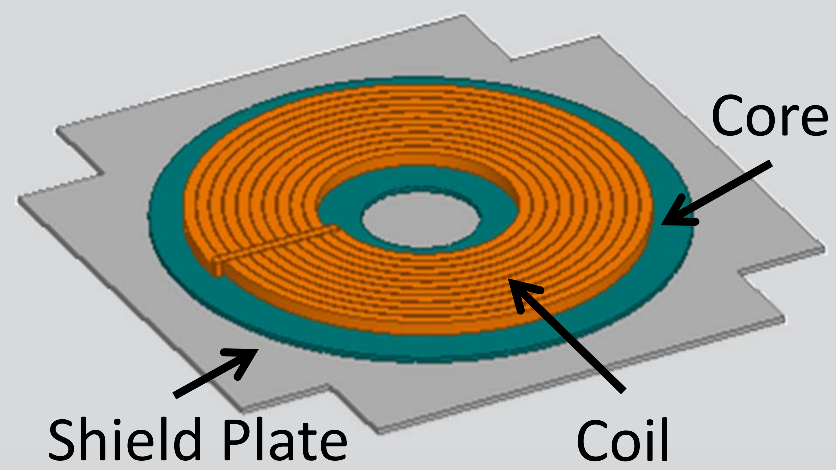
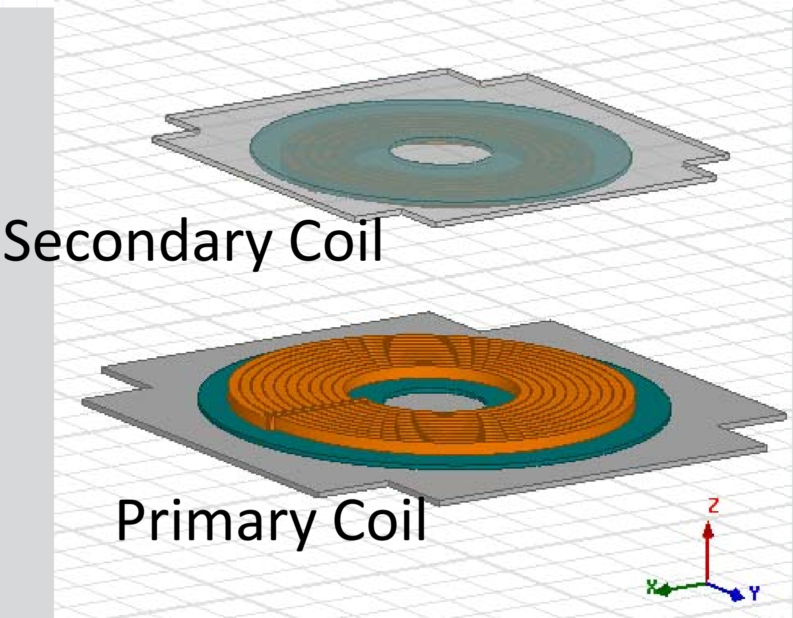
Schematic



20kW @ 400V/20kHz





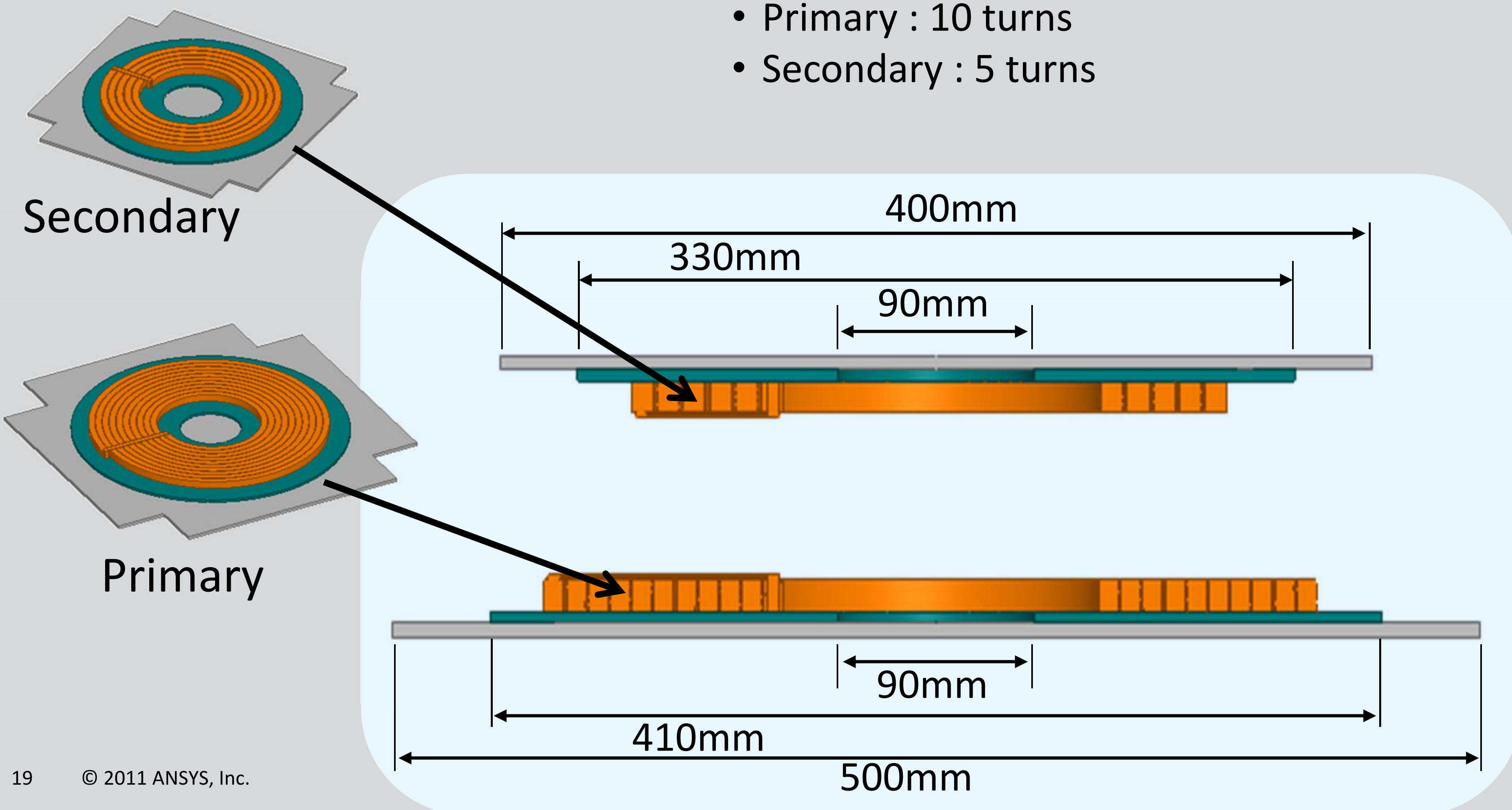
Materials

Core

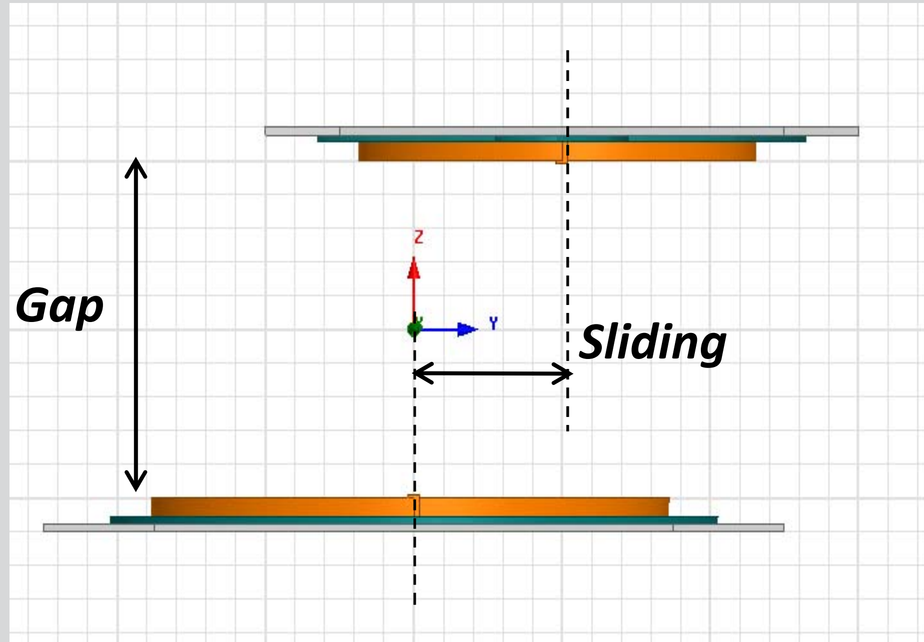
- Material : FDK 6H40 (Bs=0.53T, μi=2400)

Coil

- Litz wire : 0.25ϕ × 384 parallel turns
- Conductivity : 5.8×10^{7}[S/m]
- Primary : 10 turns
- Secondary : 5 turns



Solution Flow Chart



- **Maxwell + Simplorer**

Maxwell Magnetostatic

Core, Winding

Maxwell Eddy Current

Impedance Model

Maxwell Eddy Current

Field, Loss

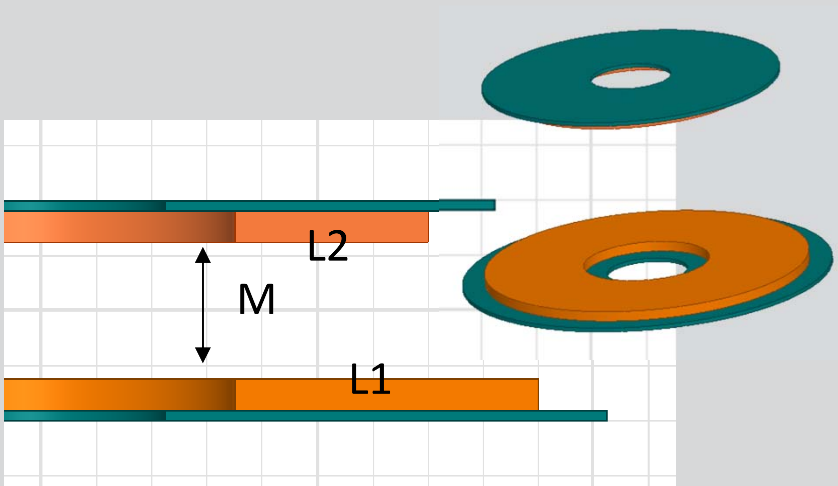
Simplorer

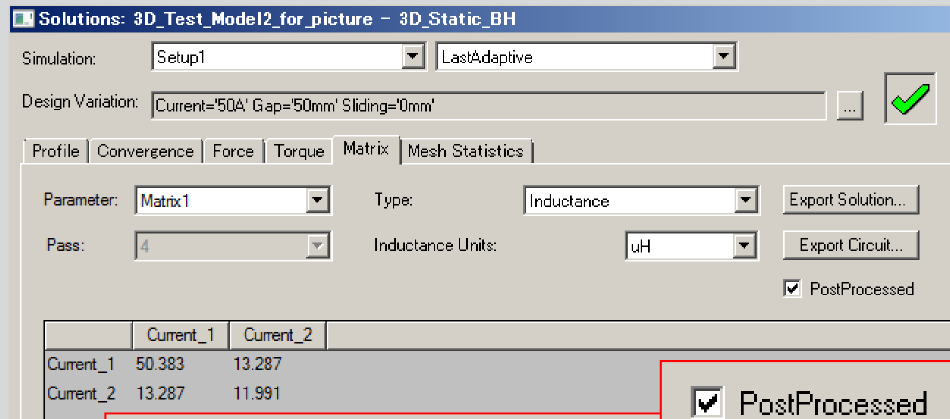
AC / TR

Circuit / Drive / Controller design
Waveform, Efficiency, Power factor, Response

Maxwell / Magnetostatic

- **L, M, k :**
  - **Self Inductance**
  - **Mutual Inductance**
  - **Coupling Coefficient**





PostProcessed

	Current_1	Current_2
Current_1	50.383	13.287
Current_2	13.287	11.991

L1 M
M L2

Matrix

Setup | Post Processing

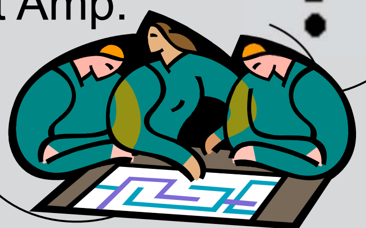
Entry	Turns
Current_1	10
Current_2	5

	Current_1	Current_2
Current_1	1	0.54056
Current_2	0.54056	1

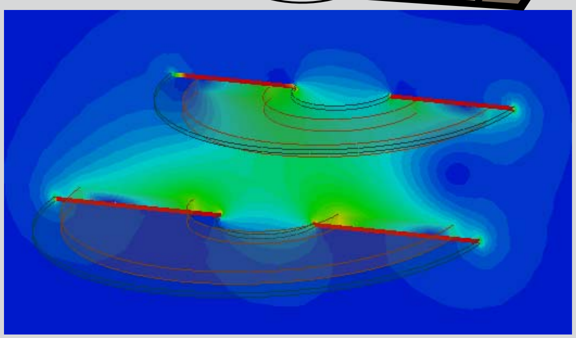
k=0.54

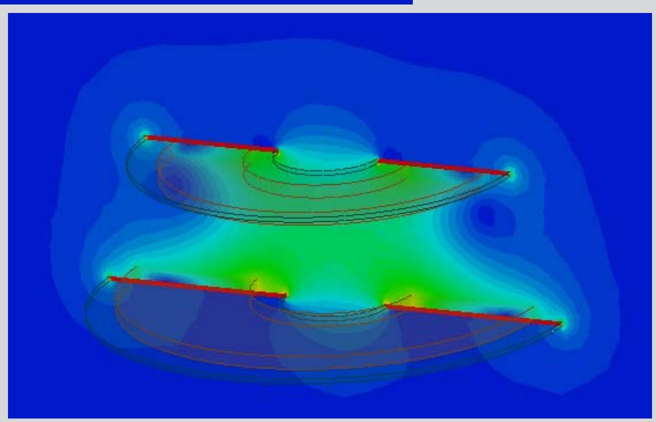
Maxwell / Magnetostatic

Core Shape/Material
Number of turns
Current Amp.
Gap

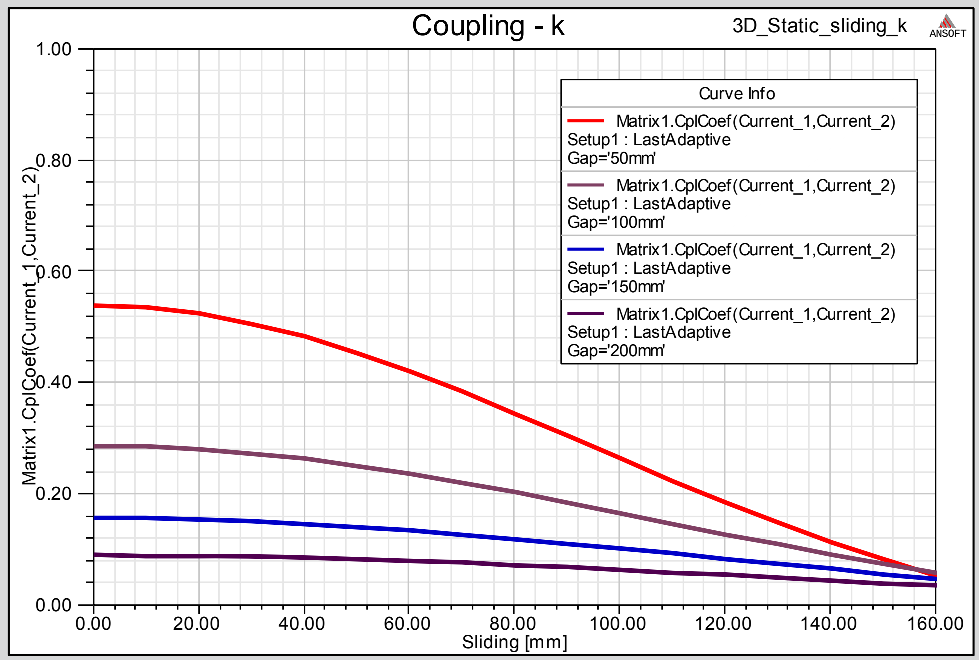


Inductance L, M
Coupling factor k
Field
Core saturation





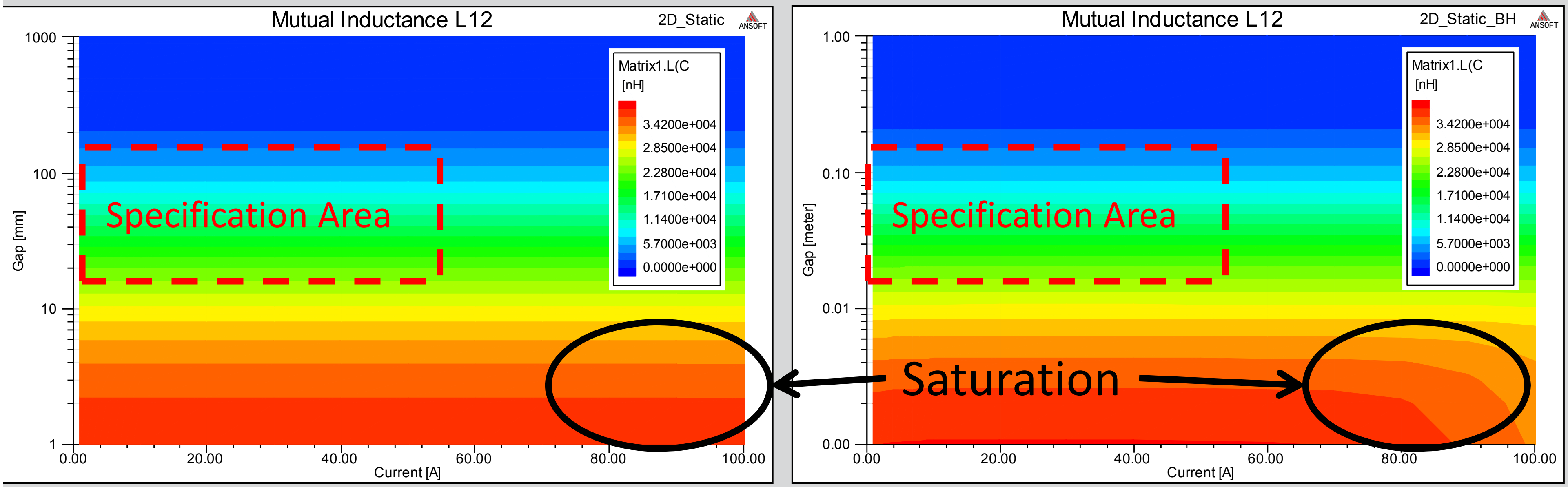
Mag B



Maxwell / Magnetostatic

Verification for core saturation: $M = k\sqrt{L_1 L_2}$

X: Gap [mm] / Y: Input Current [A] / Z: Mutual inductance [nH]



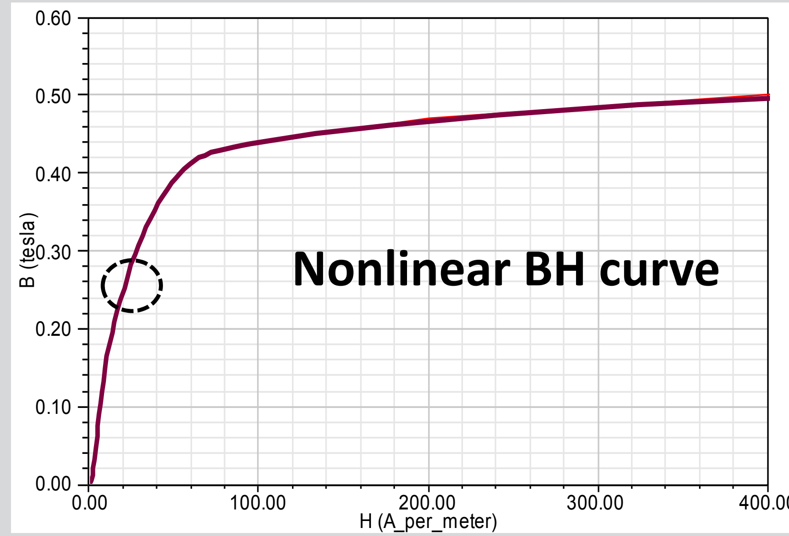
Linear Material
(Initial permeability)

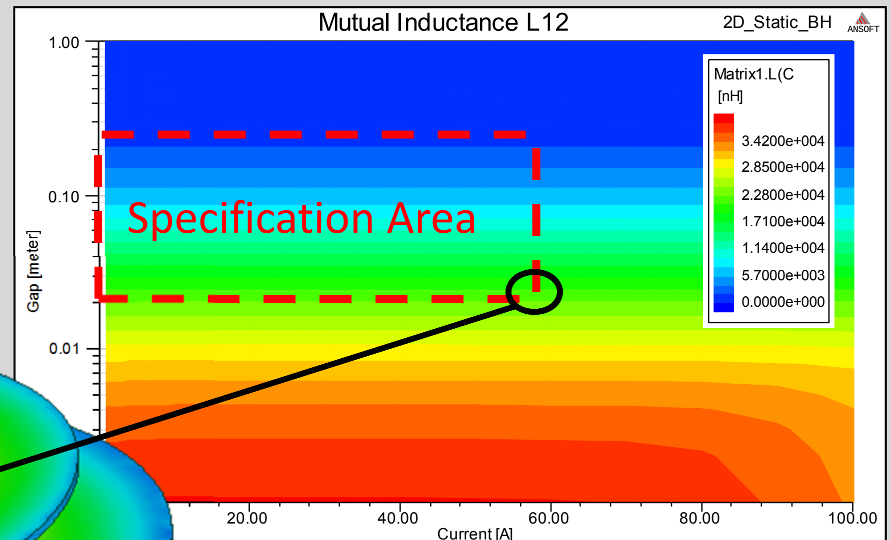
Nonlinear Material
(BH curve)

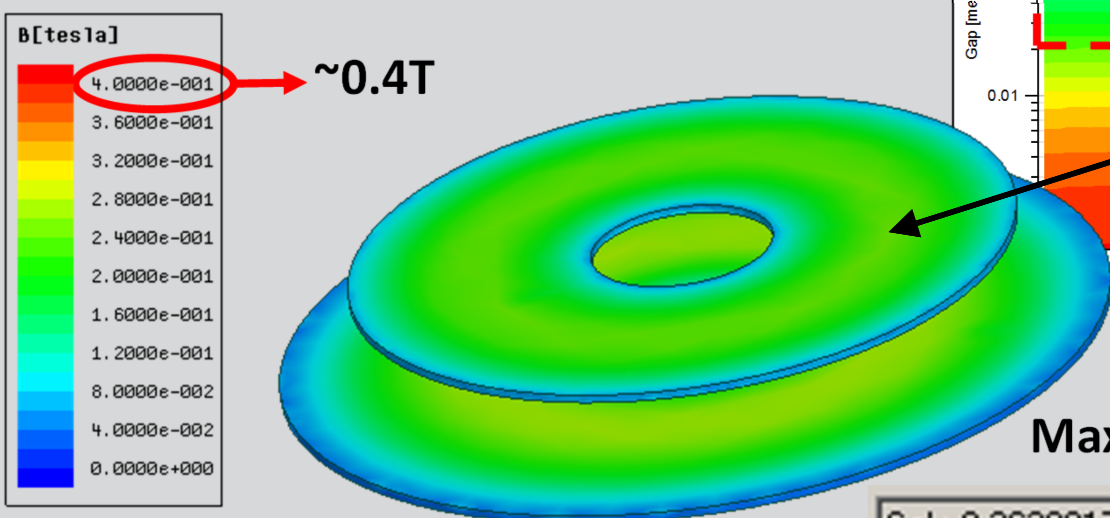
ANSYS

Maxwell / Magnetostatic

- **Verification for core saturation**
  - Core's BH curve, Mag_B field plot
  - No magnetic saturation







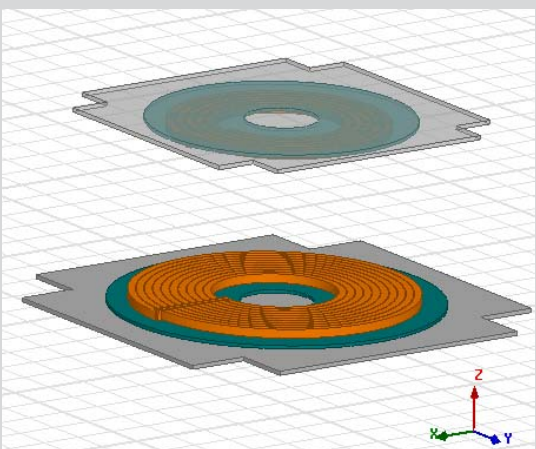
Maximum point : 0.26T

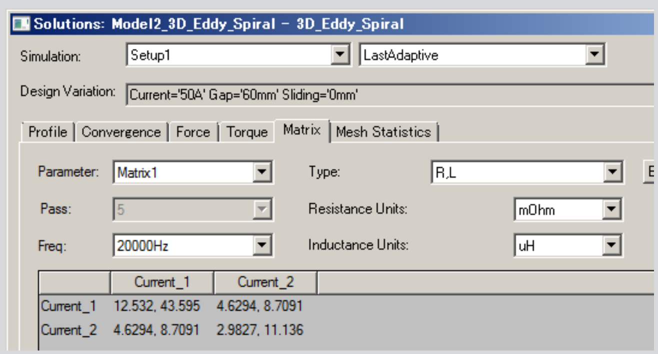
Scl : 0.263981733295126
Scl : Maximum(Volume(Core_1st), Smooth(Mag(<Bx,By,Bz>)))

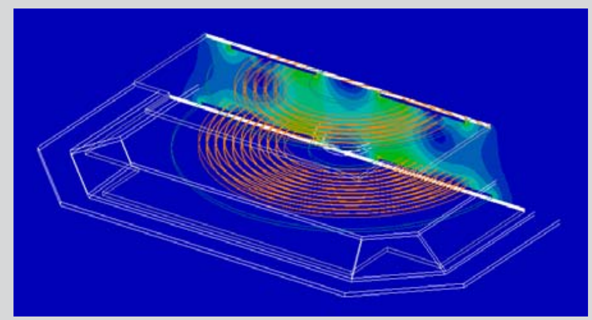
Maxwell / Eddy Current

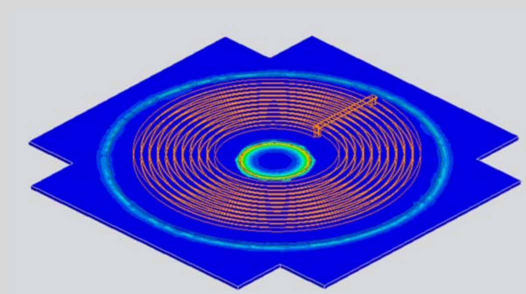
- **State Space Modeling for Simplorer**
  - **Frequency domain impedance(R,L) model for circuit simulation**

- **AC Field and Loss (after circuit simulation)**



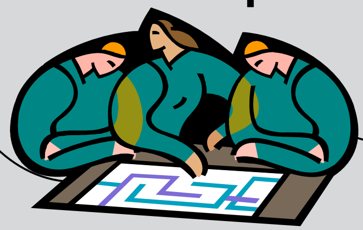






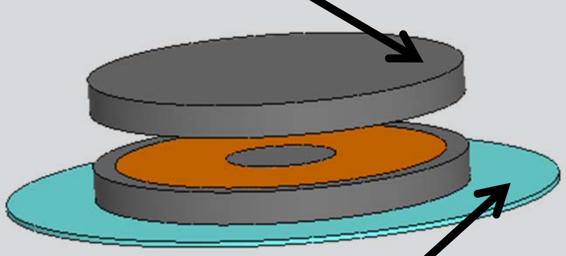
Maxwell / Eddy Current Solver

Core Shape/Material
Number of turns
Frequency
Gap
Shield Shape/Material

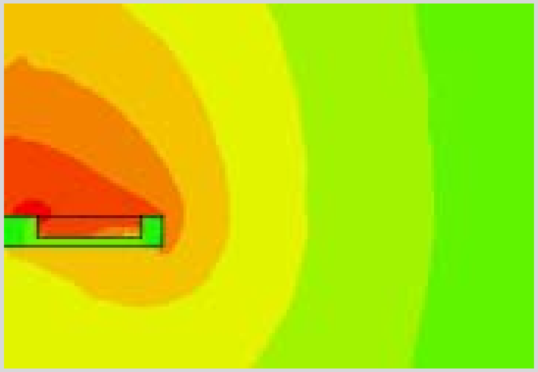


AC Characteristics
Inductance L, M
Coupling factor k
Field
Core Hysteresis
Shield

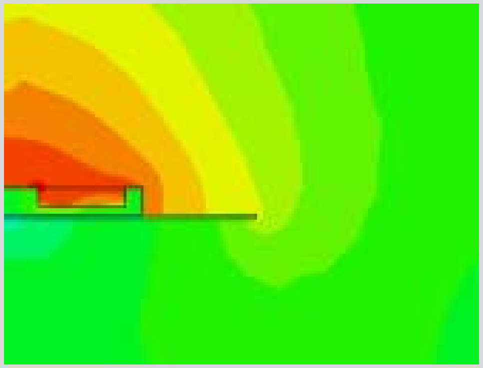
Core(Power Ferrite)



Shield Plate (Aluminum)

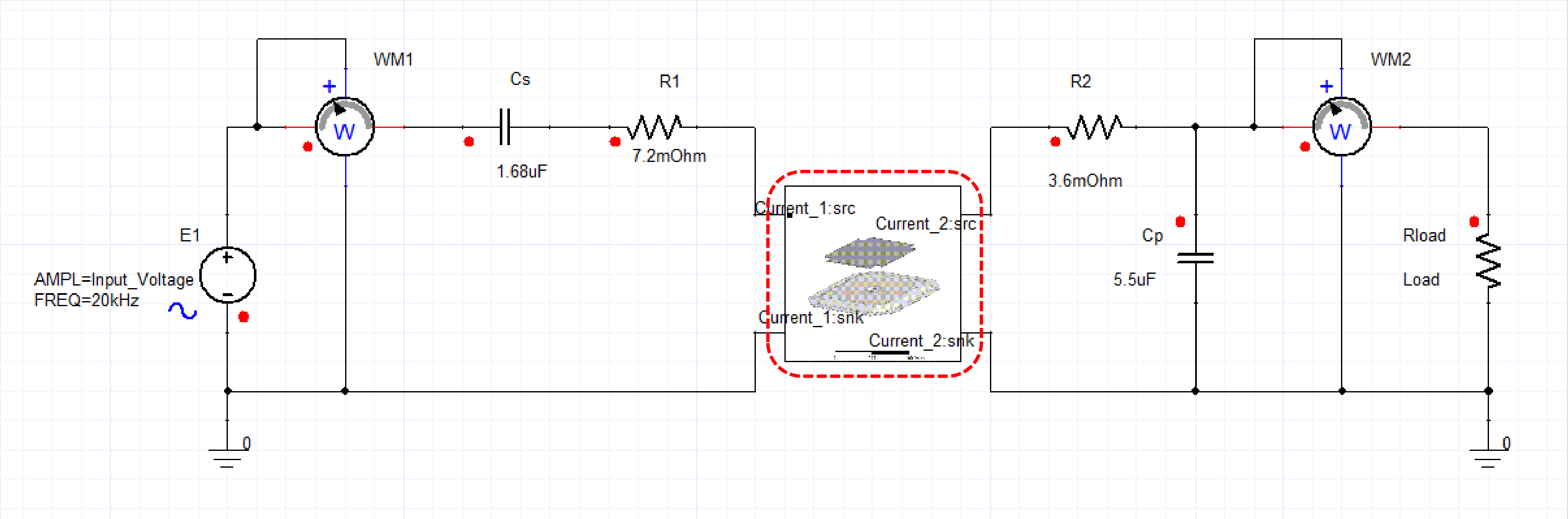


No Shielding

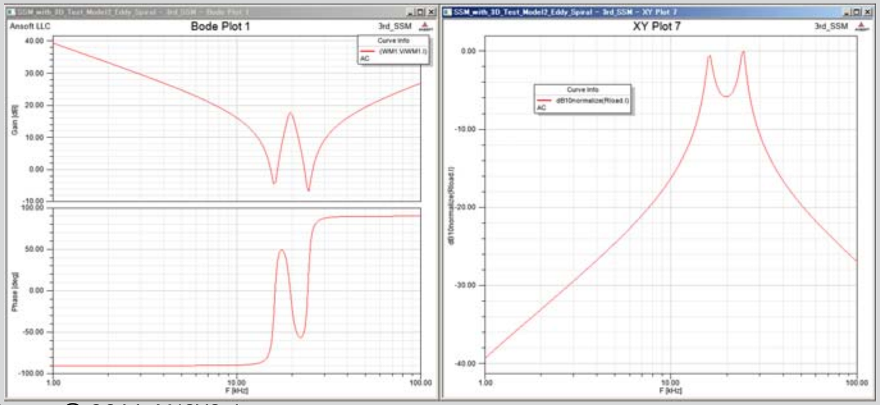


Shielding

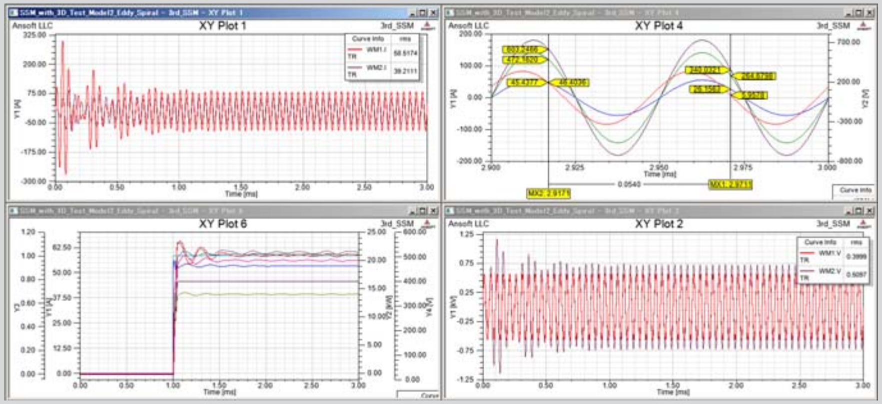
Simplorer with Maxwell State Space Model



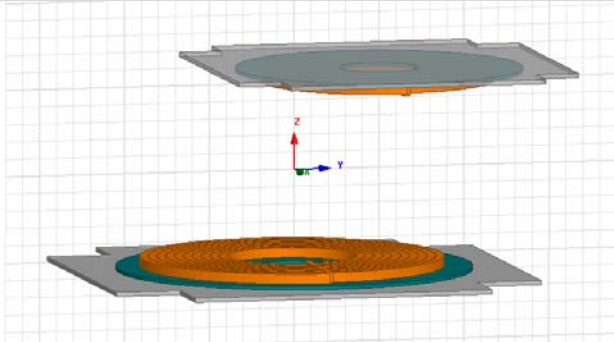
AC / Frequency domain



TR / Time domain



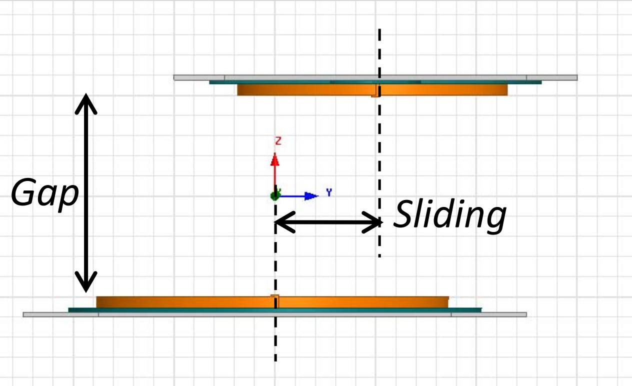
Efficiency Map

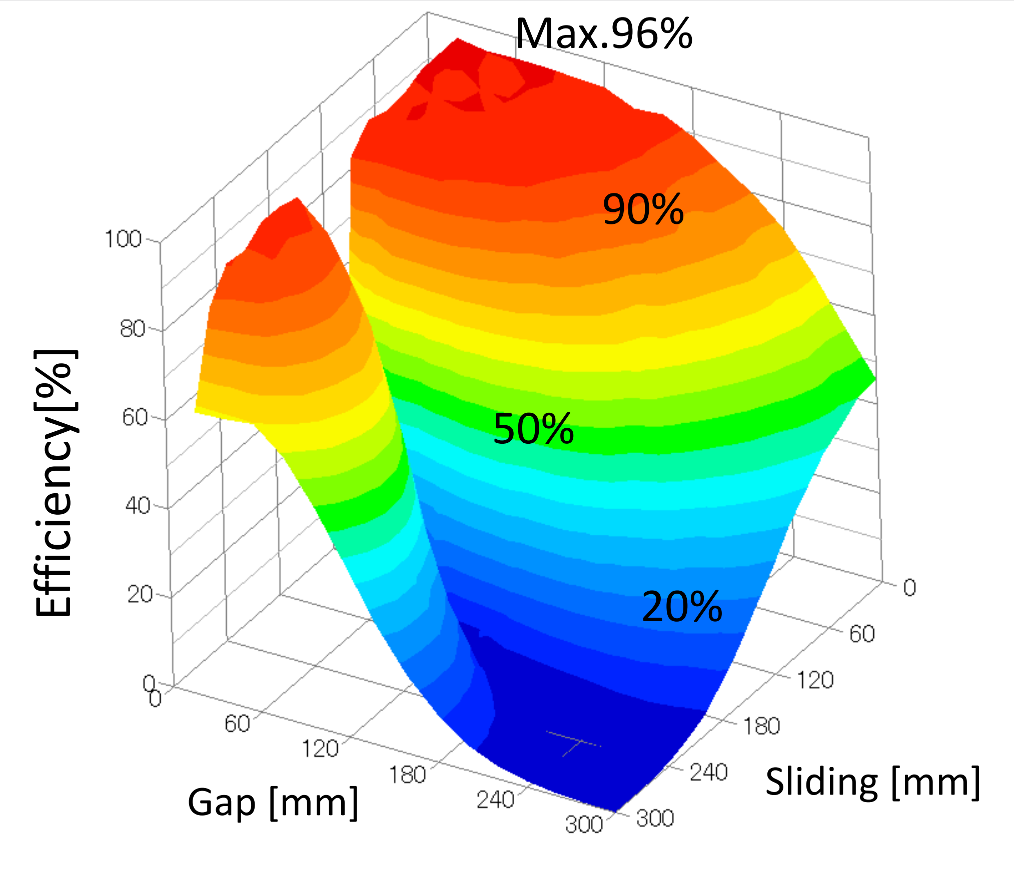


- **Output/Input Power**
- **Tuned capacitance for each conditions**

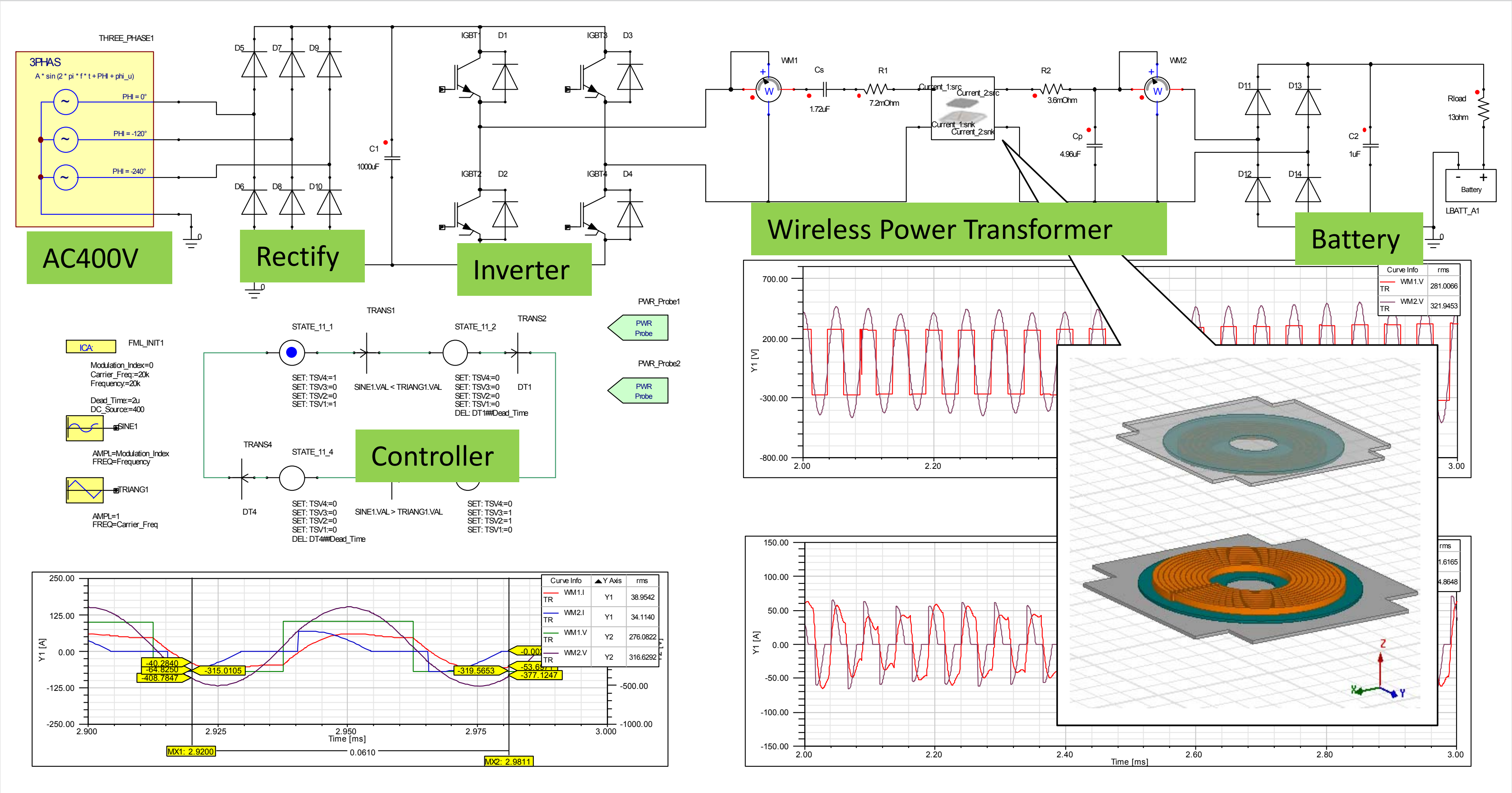
$$P = VI\cos\theta$$

$$\eta = \frac{P_{out}}{P_{in}} \times 100[\%]$$





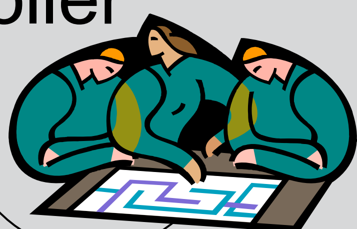
Maxwell – Simplorer System Simulation



Simplorer: Design by Circuit Level Simulation

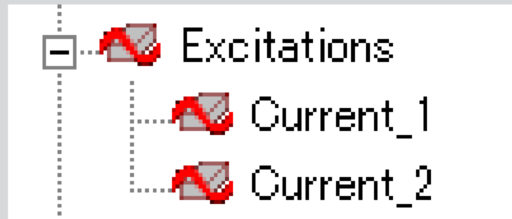
Circuit
Driver
Controller

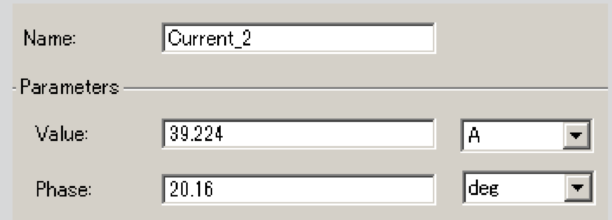
?

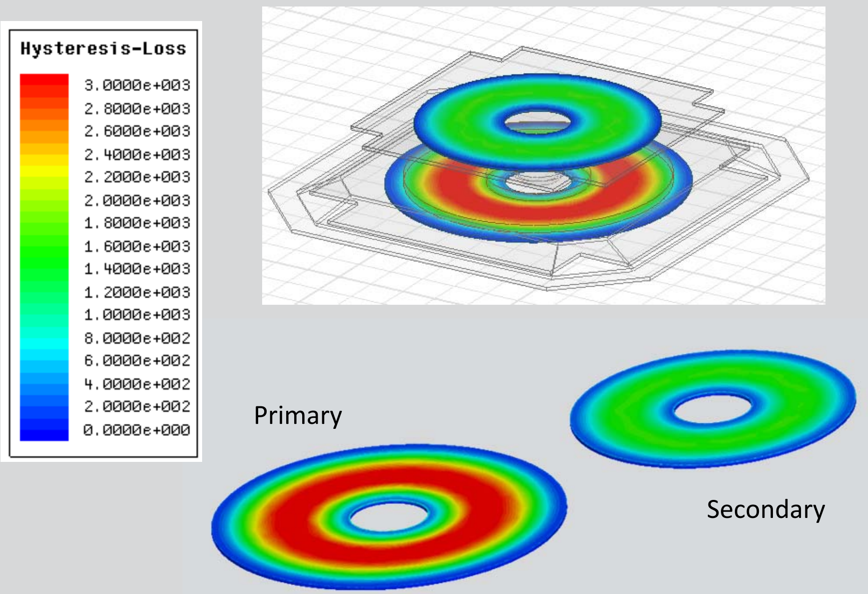


AC/TR Response
Waveform
Efficiency

Back to Maxwell: Core Hysteresis Loss Using the Current Amplitude and Phase from Simplorer



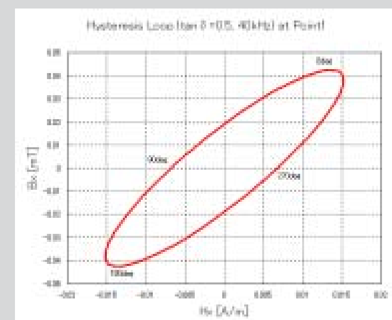




Hysteresis Loss

Considering Magnetic Loss tangent

$$\begin{aligned}\mu &= \mu' - j\mu'' \\ &= \mu'\left(1 - j\tan\delta\right)\end{aligned}$$



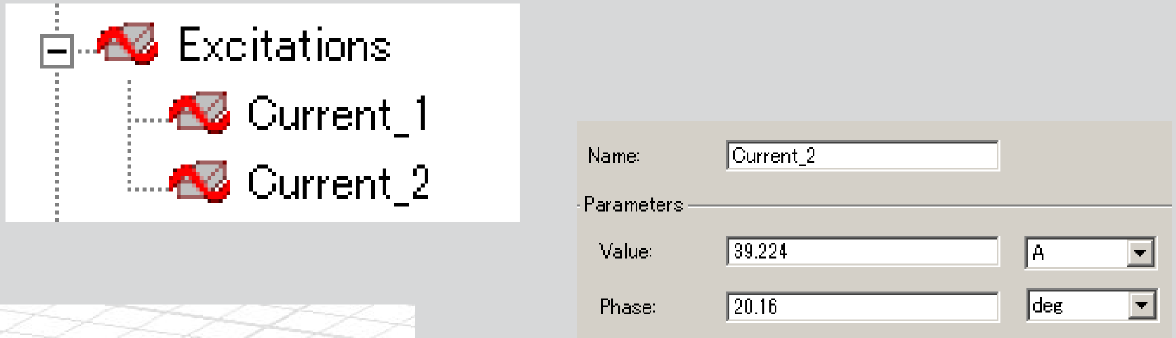
Core Loss — 3D_Eddy — ANSOFT

	Freq [kHz]	Core1st_Loss Setup1 : LastAdaptive Phase='0deg'	Core2nd_Loss Setup1 : LastAdaptive Phase='0deg'
1	20.000000	0.909102	0.313144

Core loss[W]

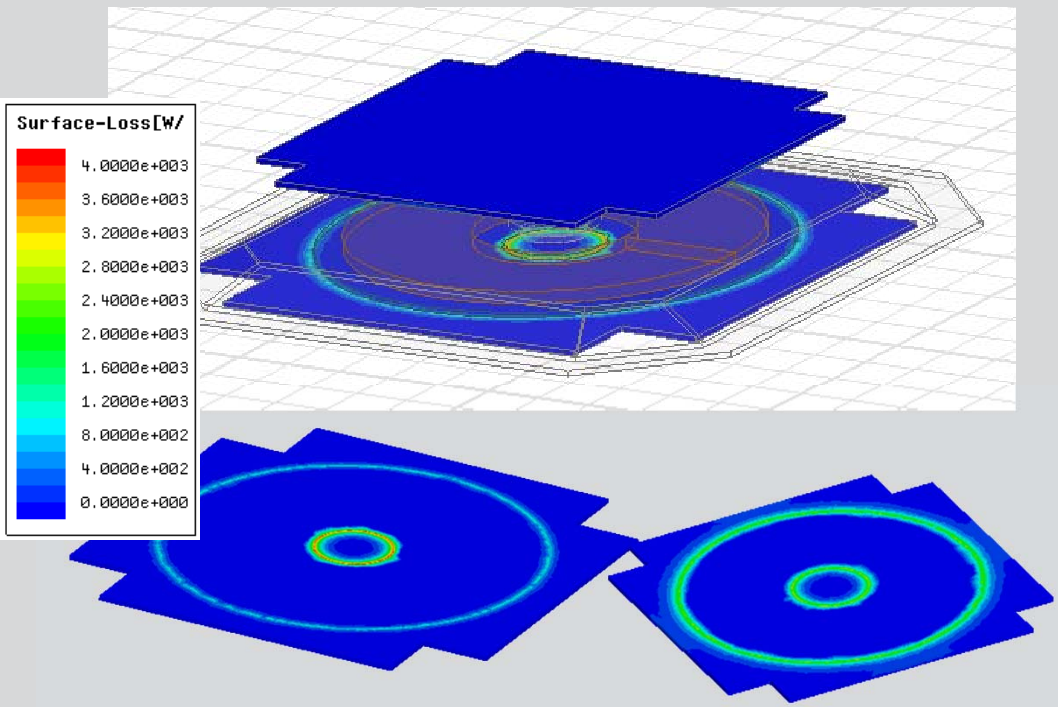
Scl : 0.909102009858301
Scl : Integrate(Volume(Core_1st), Hysteresis-Loss)

Back to Maxwell: Shield Surface Loss Using the Current Amplitude and Phase from Simplorer



Key Point:

Impedance boundary BC



Primary

Secondary

Surface Loss

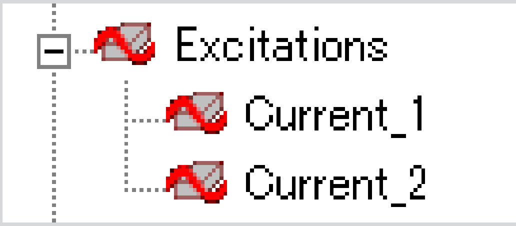
Shield Loss — 3D_Eddy — ANSOFT

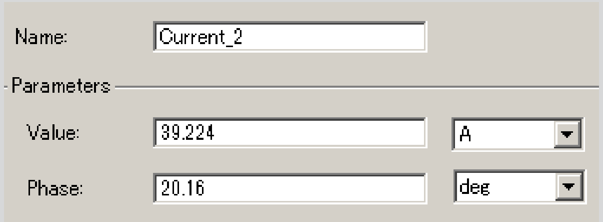
	Freq [kHz]	Shield1st_Loss Setup1 : LastAdaptive Phase='0deg'	Shield2nd_Loss Setup1 : LastAdaptive Phase='0deg'
1	20.000000	22.938675	37.886583

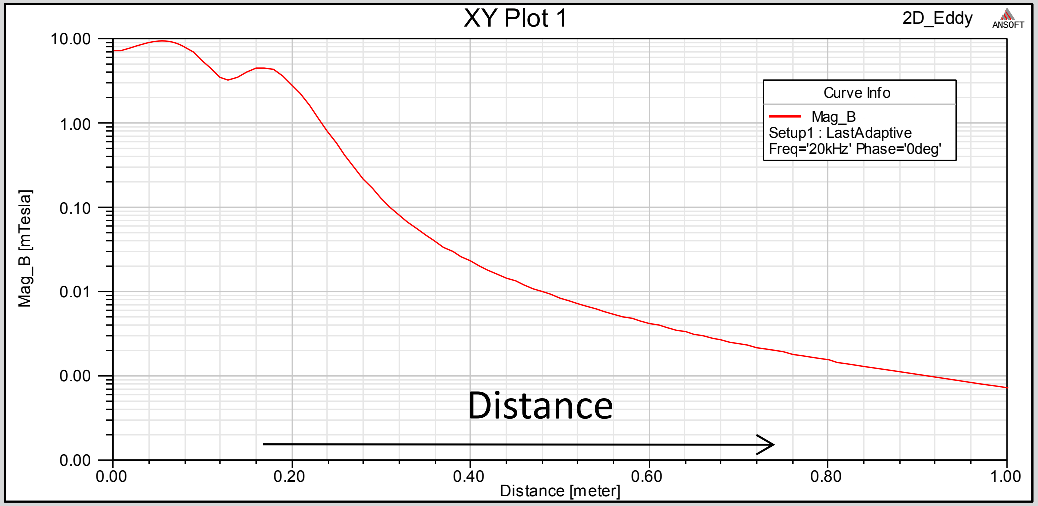
Shield Loss[W]

Scl : 22.9386748099613
Scl : Integrate(Surface(Shield_1st), SurfaceLossDensity)

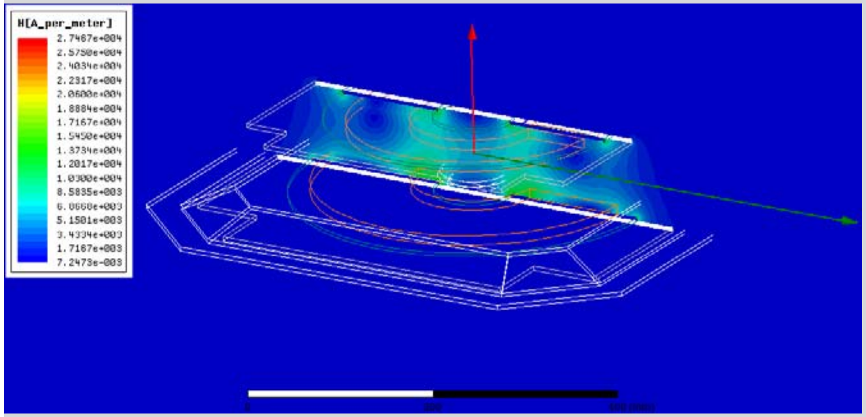
Back to Maxwell: Field Solution Using the Current Amplitude and Phase from Simplorer



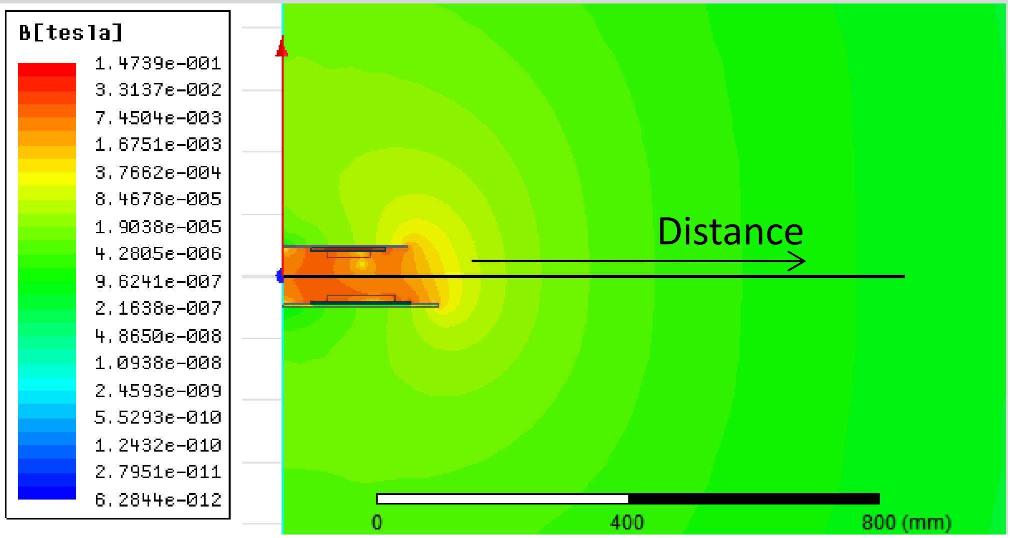




Magnetic Field Density

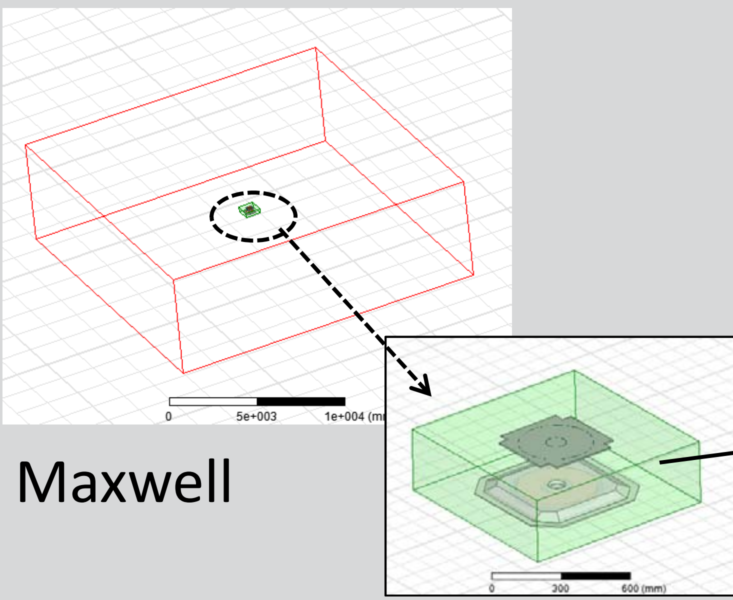


Magnetic Field Intensity

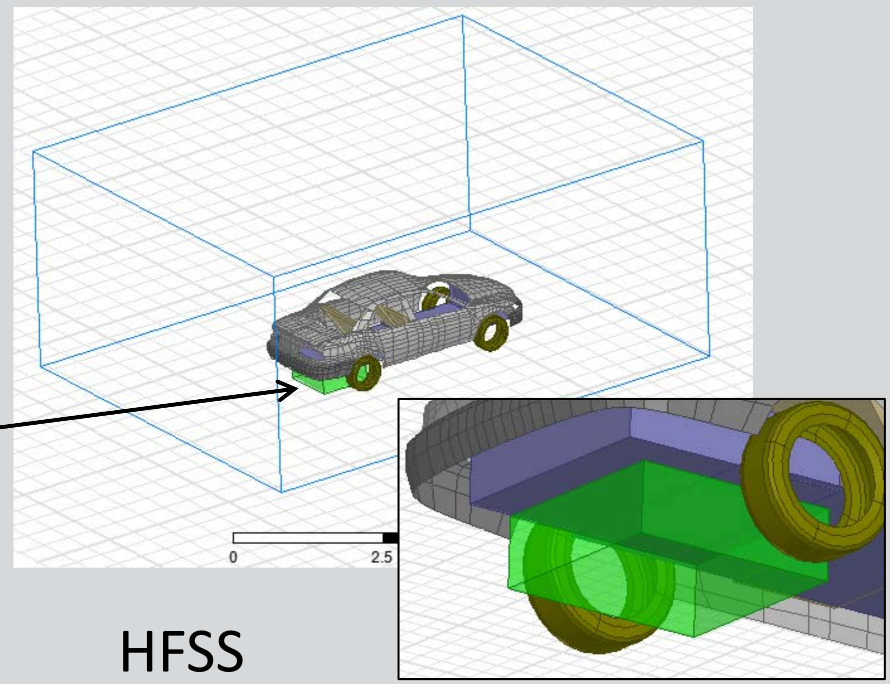


Back to Maxwell and Link to HFSS

- **Maxwell → HFSS Dynamic Link**
  - Magnetic source solved by Maxwell and Link to HFSS field solution
  - Far Field and Large Area electromagnetic solution
  - HFSS can handle a car body object as 2D sheet object



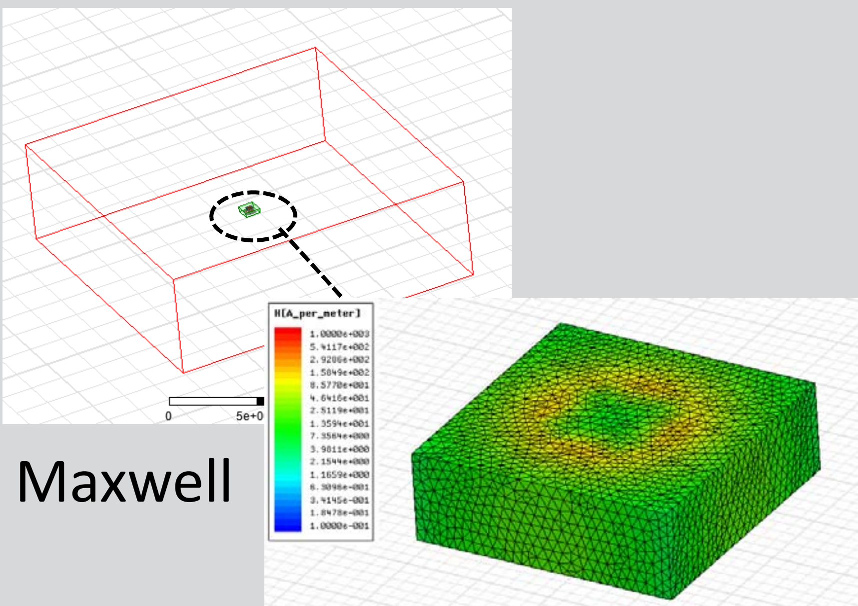
Maxwell



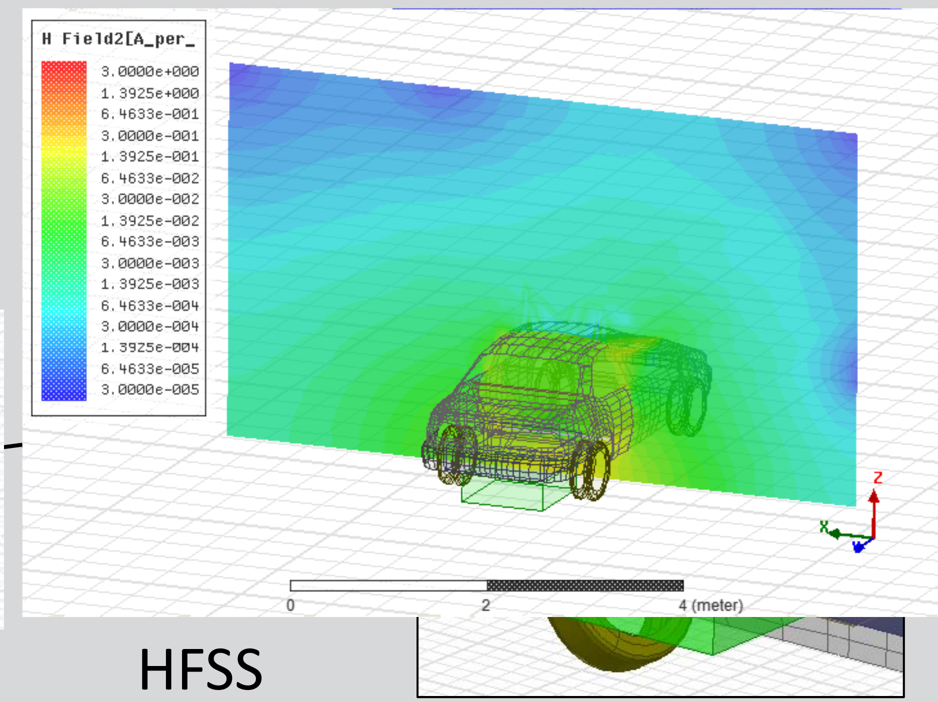
HFSS

Back to Maxwell and Link to HFSS

- **Maxwell → HFSS Dynamic Link**
  - **Magnetic source solved by Maxwell and Link to HFSS field solution**
  - **Far Field and Large Area electromagnetic solution**
  - **HFSS can handle a car body object as 2D sheet object**



Maxwell

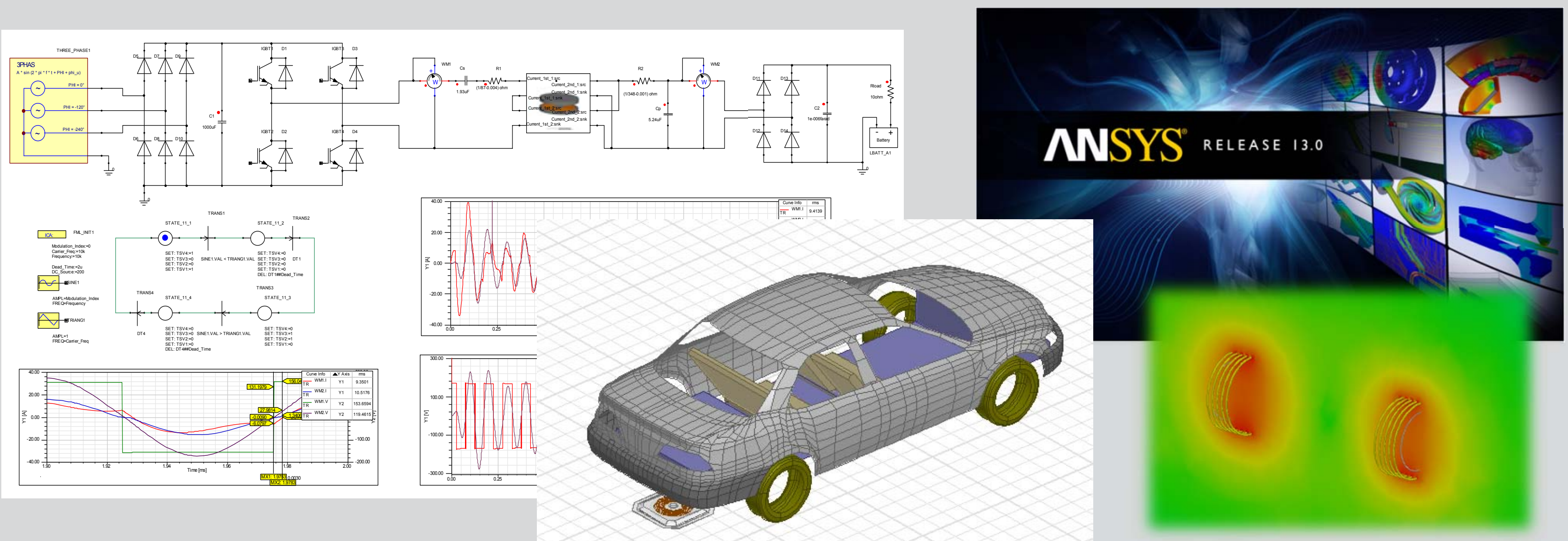


HFSS

ANSYS

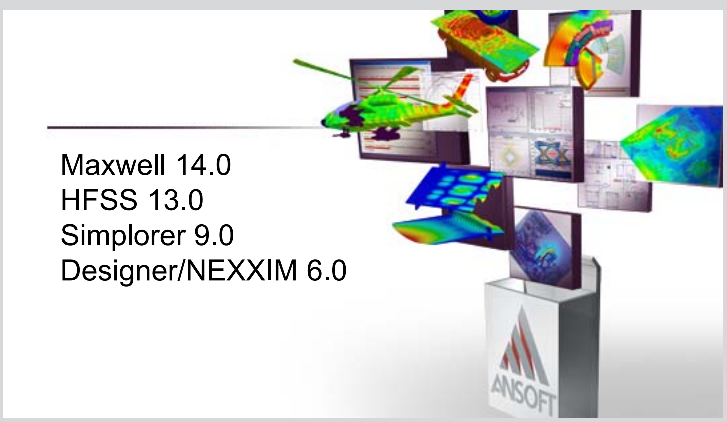
Conclusion

- Wireless power transfer for HEV/EV’s can easily be simulated with ANSYS’ electromagnetic and circuit simulation tools.
- The full solutions requires a system level approach.
- ANSYS’ Products can also support multiphysics simulation, i.e. combined Thermal / Structure / Fluid



Thank you!

Concept of Operations
High-Level Requirements
Detailed Requirements
High-Level Design
Detailed Design
Implementation
Operations & Maintenance
System Verification
Sub-System Verification
Integration & Testing
ANSYS
ENGINEERING THE
SYSTEM
2011 REGIONAL CONFERENCES



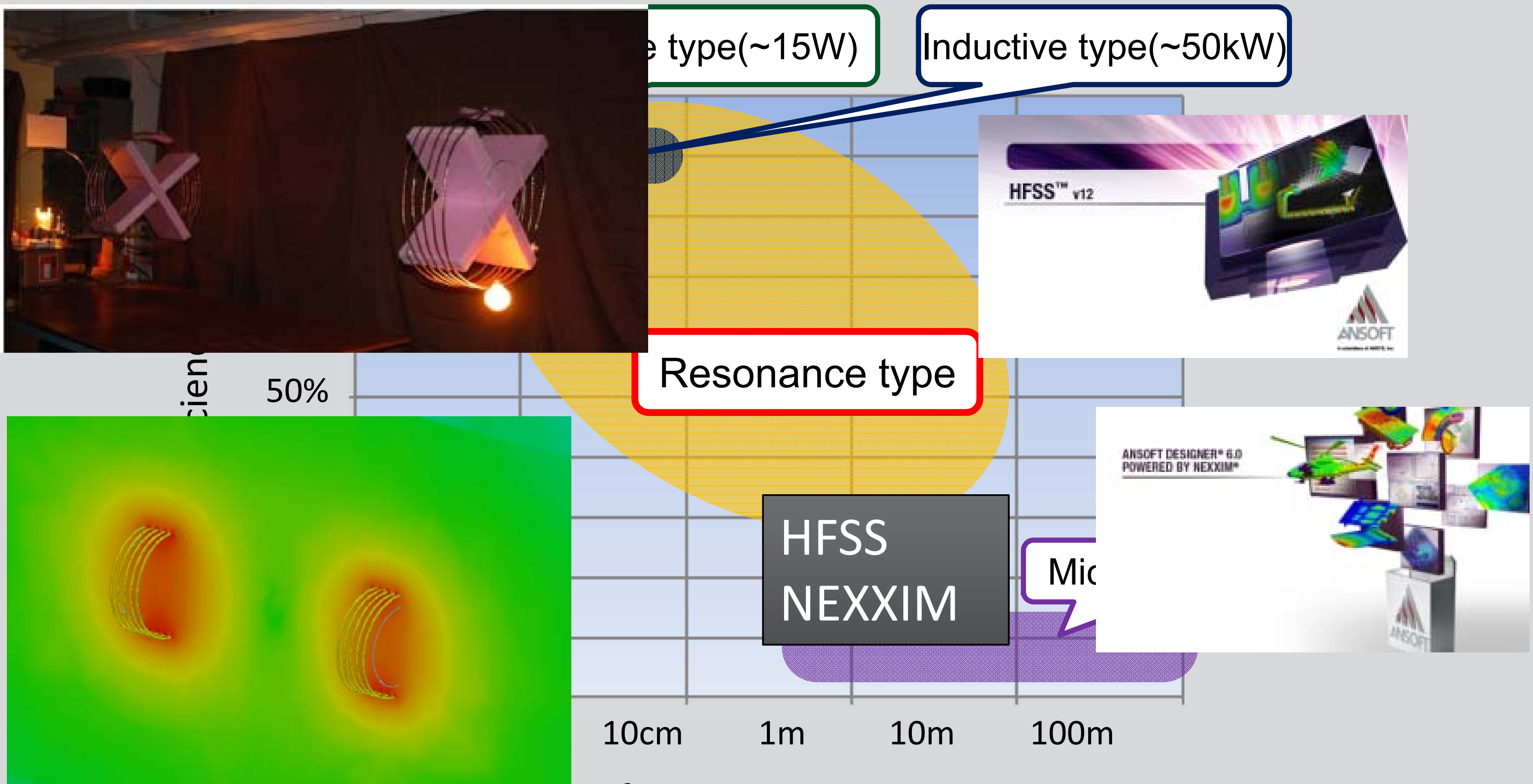
Maxwell 14.0
HFSS 13.0
Simplorer 9.0
Designer/NEXXIM 6.0
ANSOFT

ANSYS
RELEASE 13.0

- **Add the following slides for an in-depth discussion on how HFSS can be used to solve this type of problem.**

Resonance type wireless power supply

- **Antenna coil**

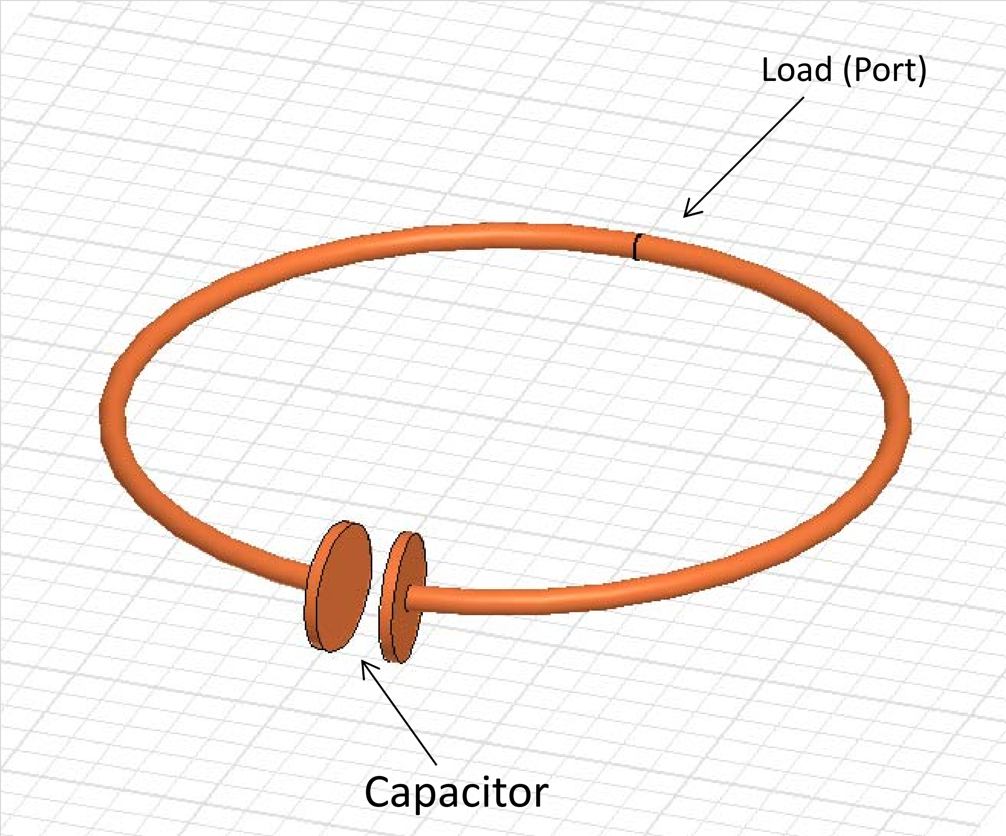


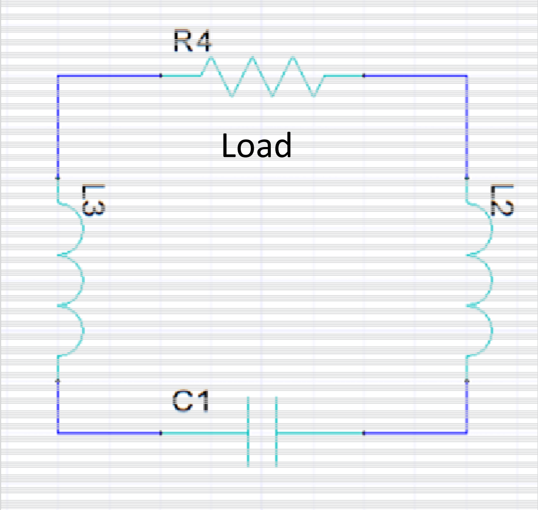
Transfer Distance

Ref: EE Times Japan 2009.10

Model

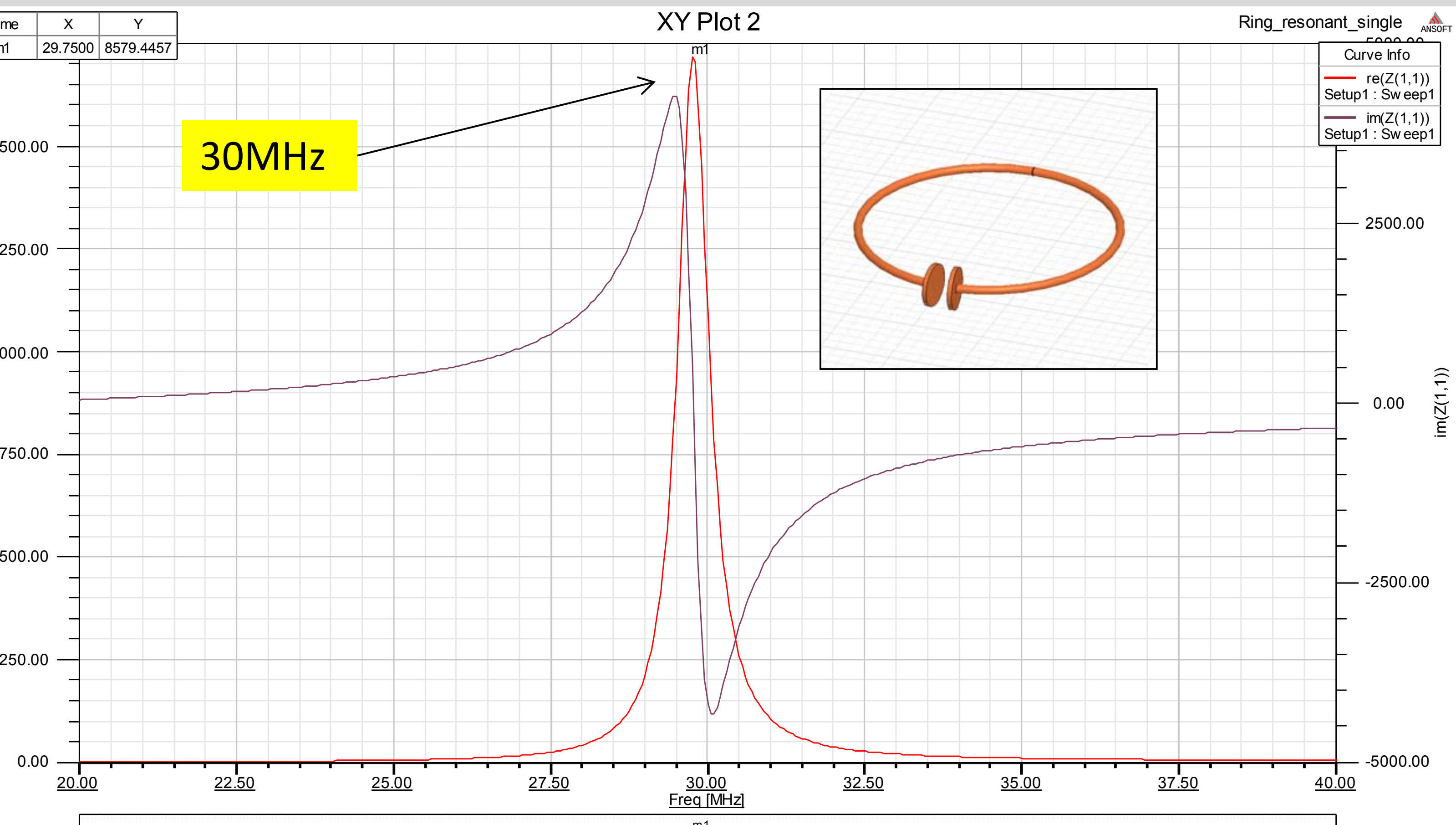
- Theoretically resonance type antenna coil





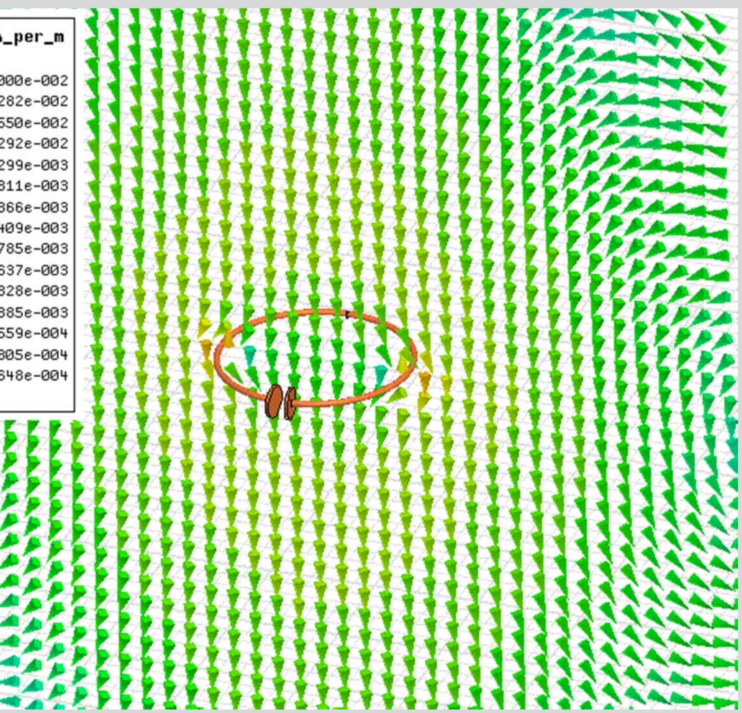
HFSS / Impedance Characteristics

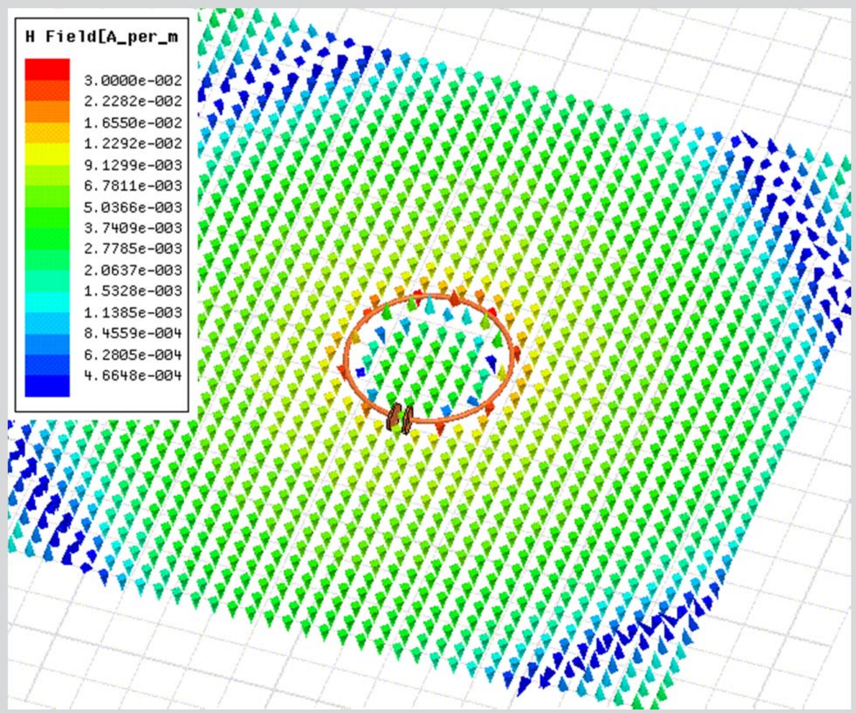
11



HFSS / Magnetic Field

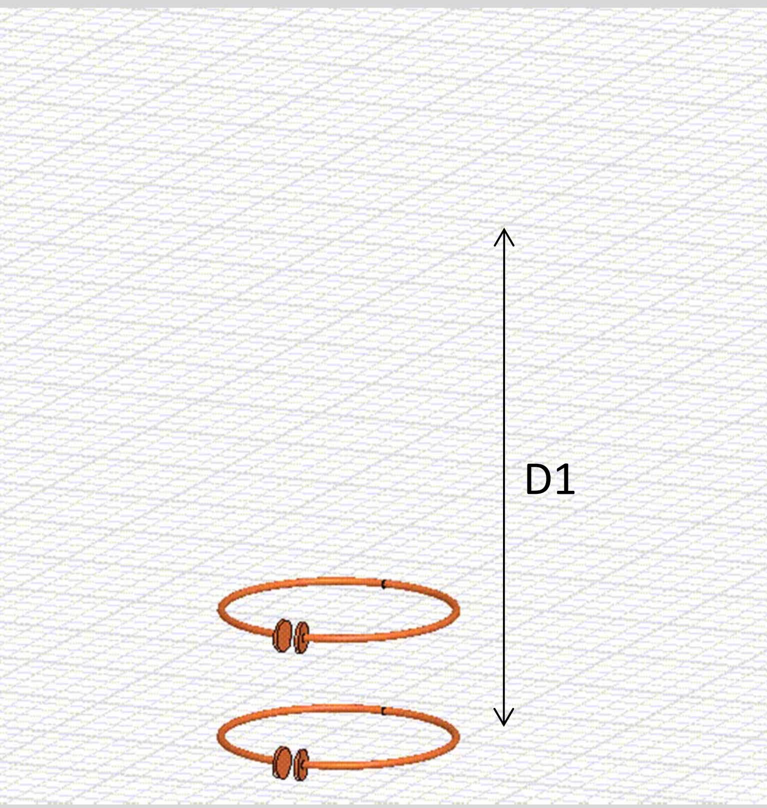
requency : 30MHz

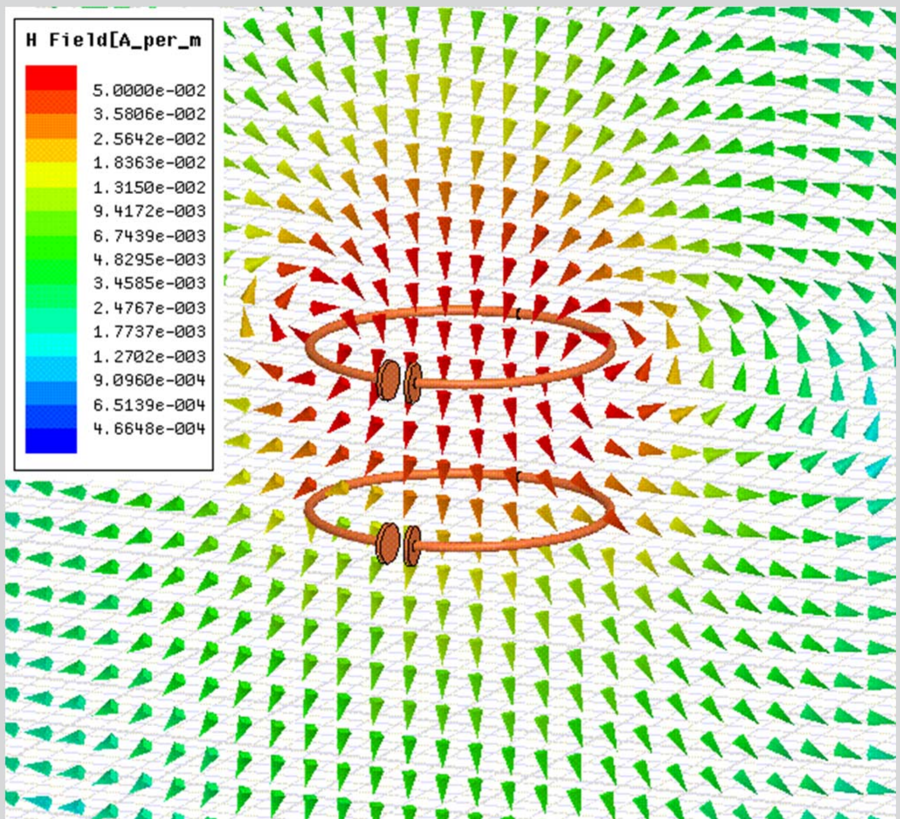




Resonance type Coil Antenna Transfer Model

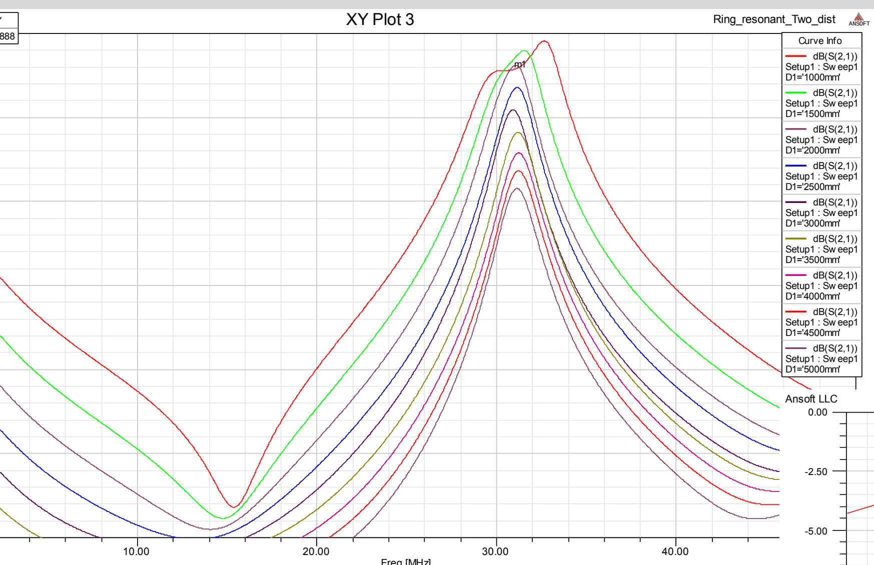
ransfer characteristics between primary and secondary coils y the distance(D1)



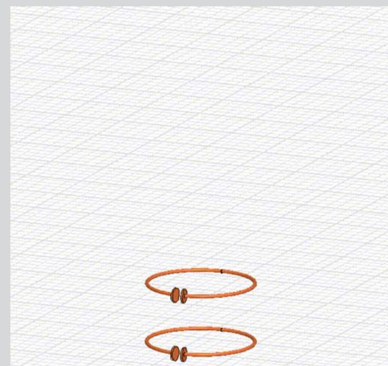


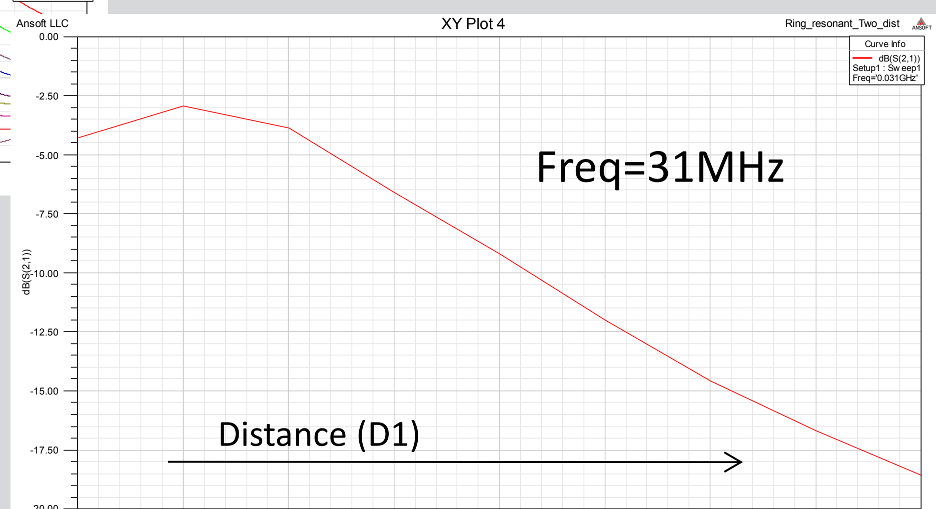
HFSS / Transfer characteristics

1



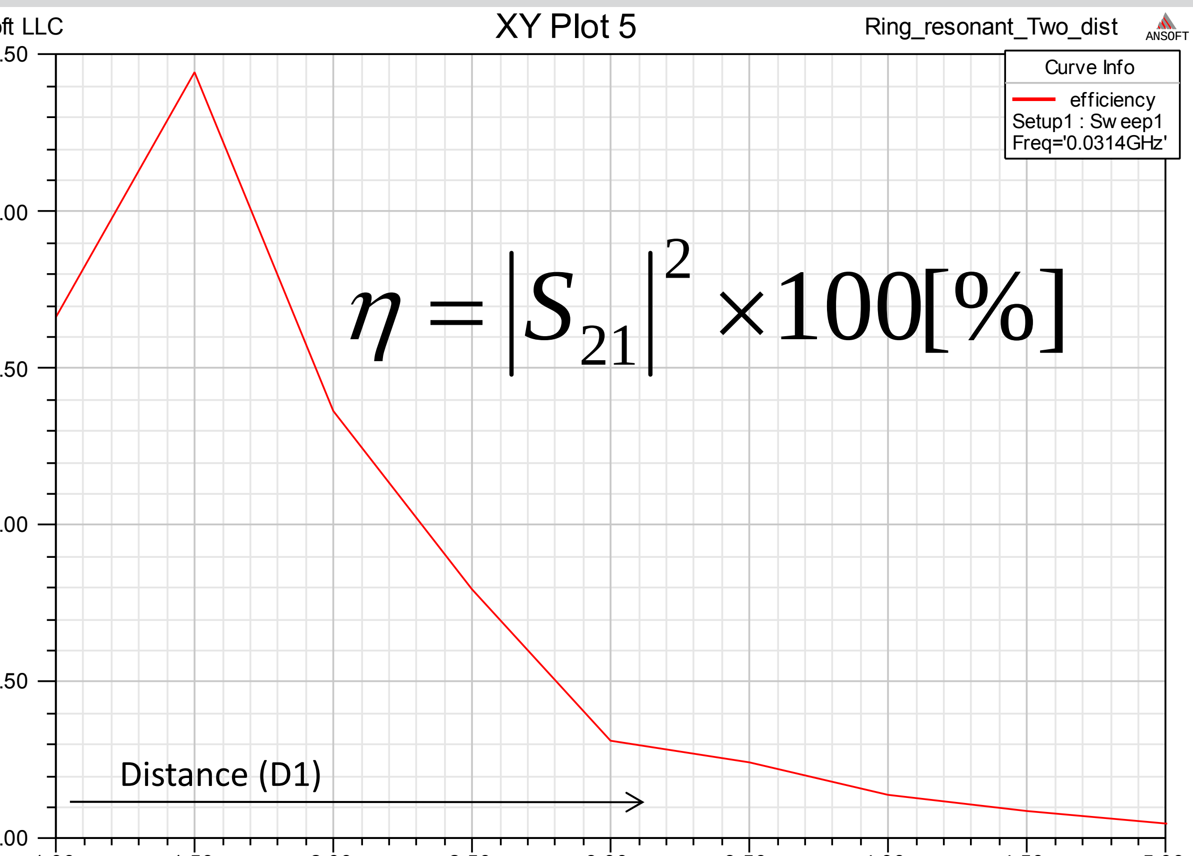
Frequency



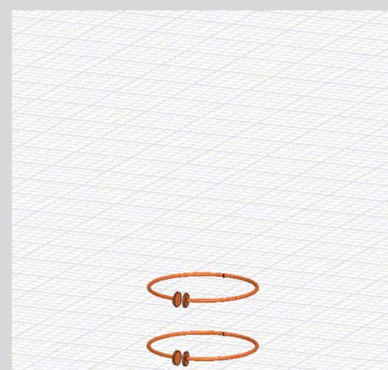


HFSS / Transfer efficiency

Transfer efficiency calculated by S21

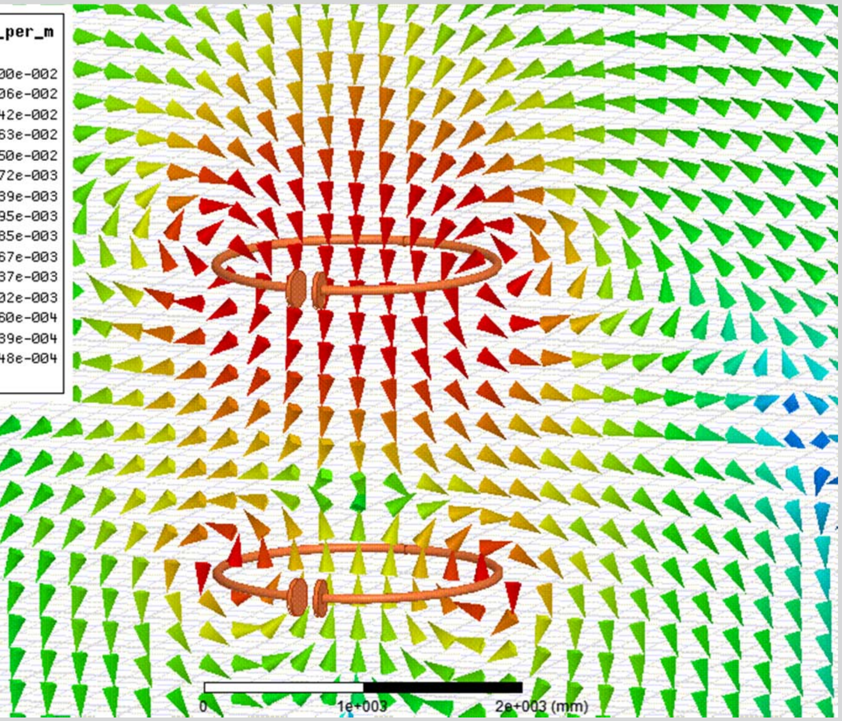


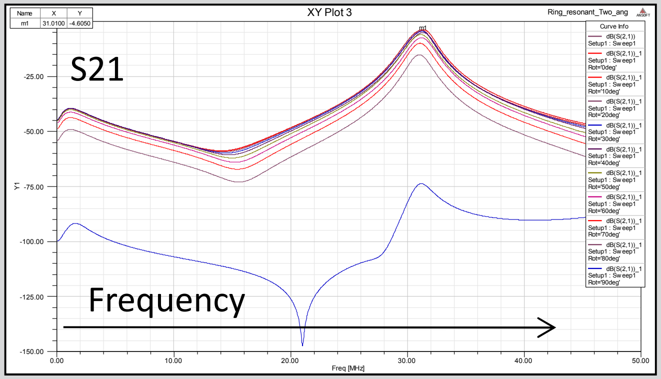
$$\eta = \left|S_{21}\right|^2 \times 100[\%]$$

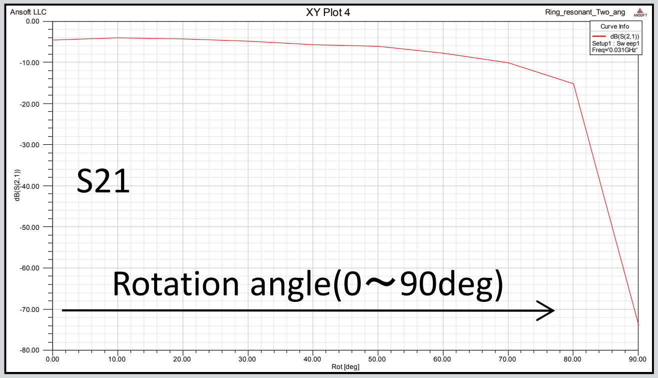


HFSS / Transfer characteristics

otated secondary coil



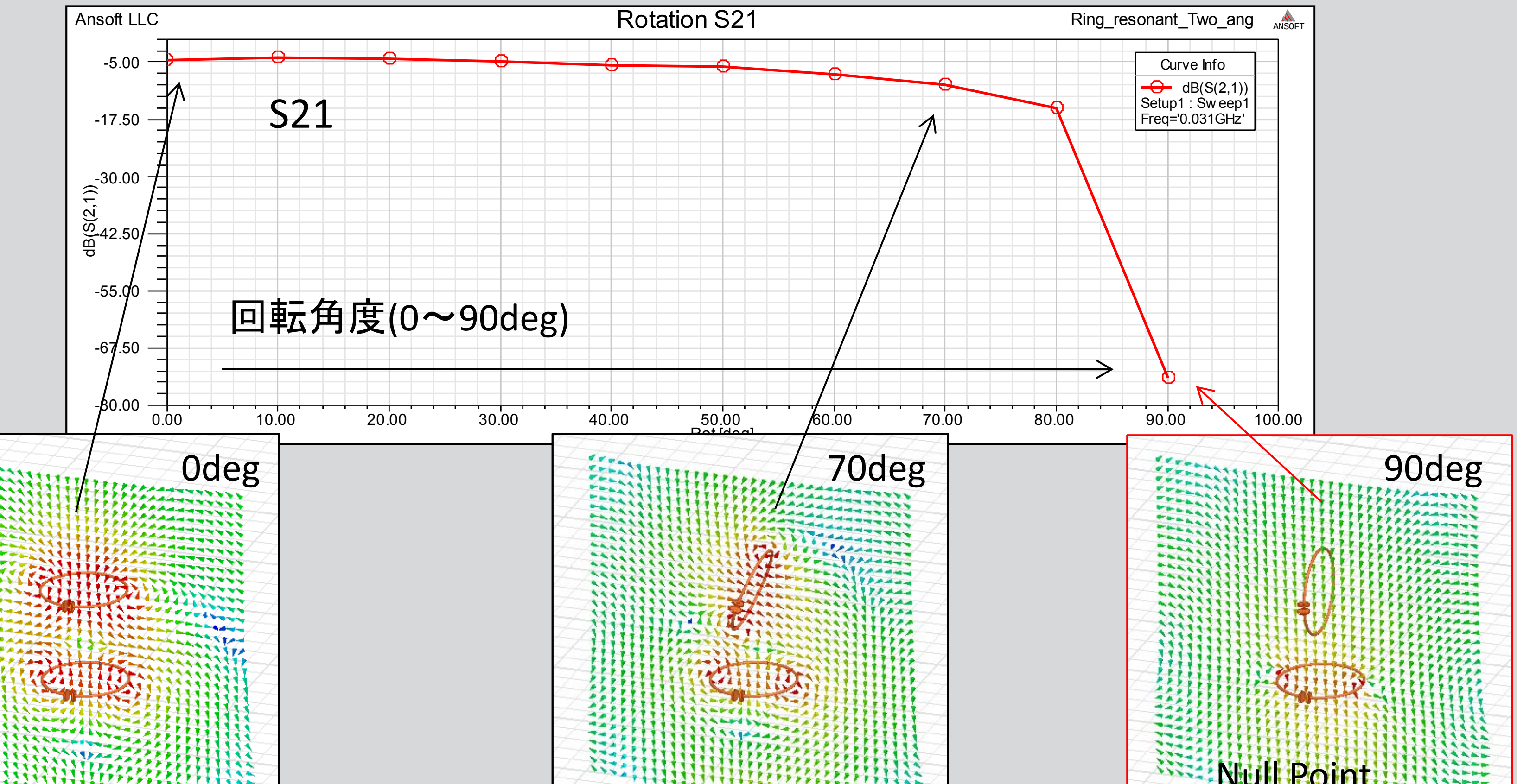




HFSS / Rotated Antenna(Cont.)

otated secondary coil

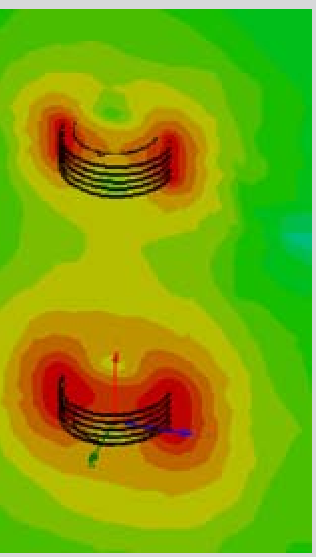
ransfer null point at 90deg

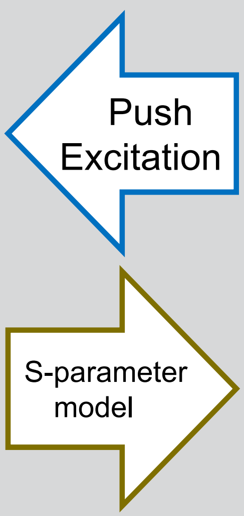


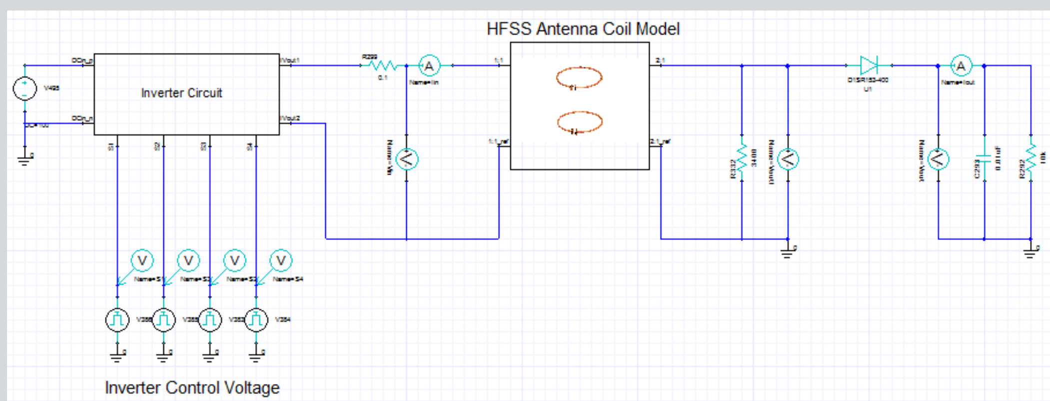
Designer/NEXXIM with HFSS Direct Link

IFSS + Designer/NEXXIM

- HFSS model direct link to Designer
  - S-parameter model by electromagnetic link to circuit simulation
  - Push Excitation : Get excited condition for HFSS by Designer simulation







HFSS

Designer/NEXXIM
circuit

HFSS – Designer/NEXXIM System Simulation