2012 Automotive Simulation World Congress

Wireless Power Transfer Using Maxwell and Simplorer

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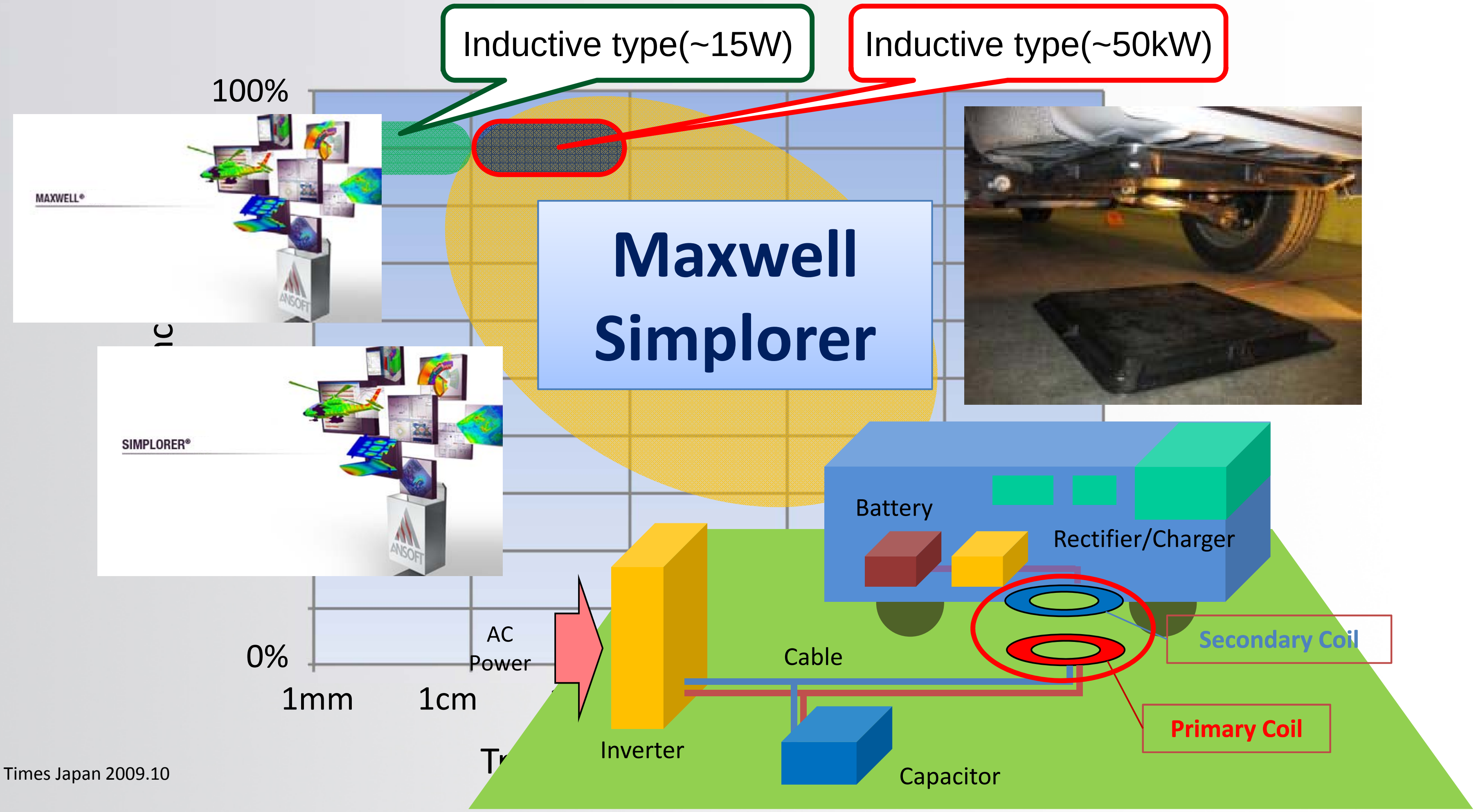
Mark Christini

Takahiro Koga

ANSYS, Inc.

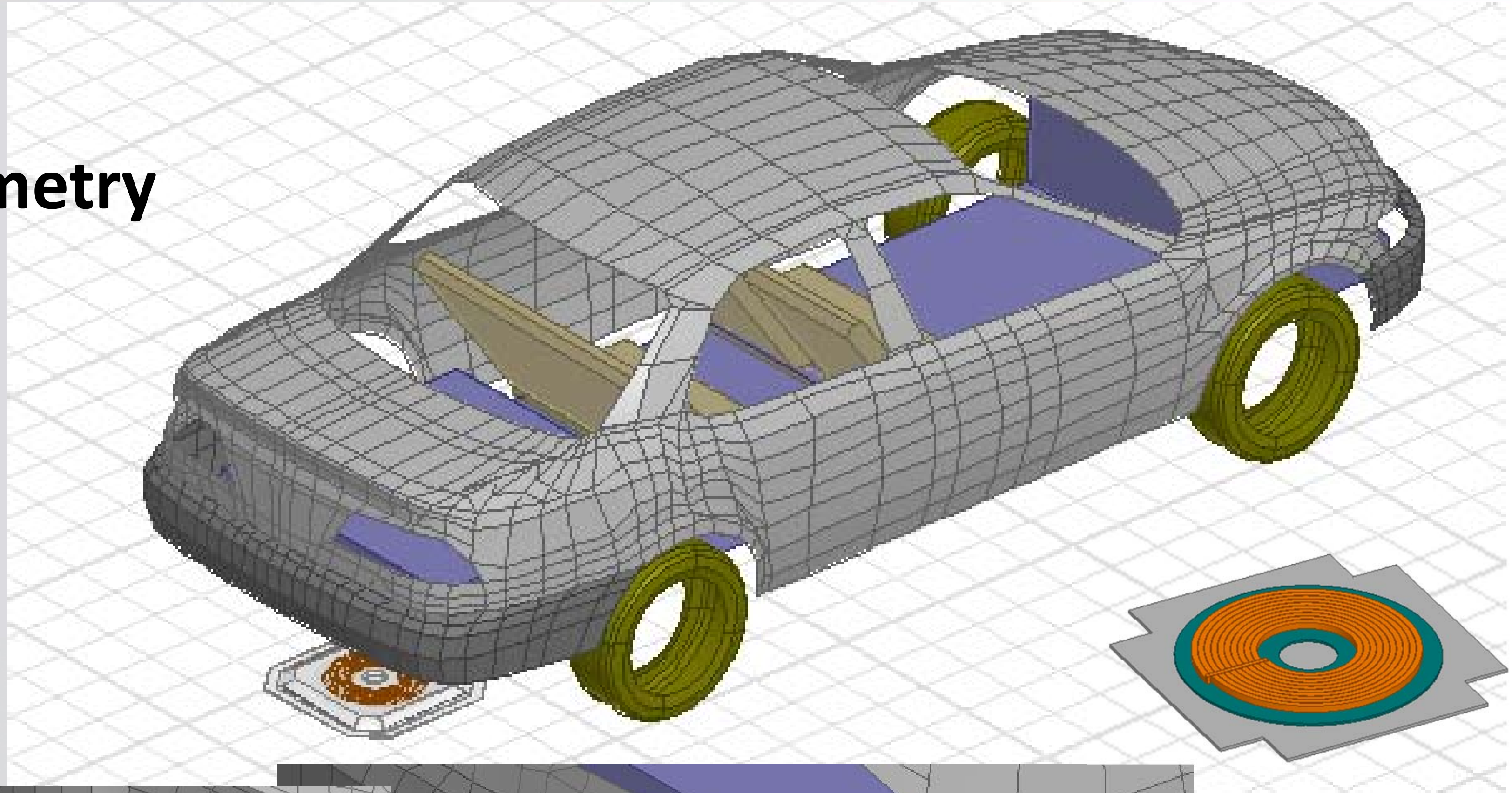
Wireless Power Supply System for EV

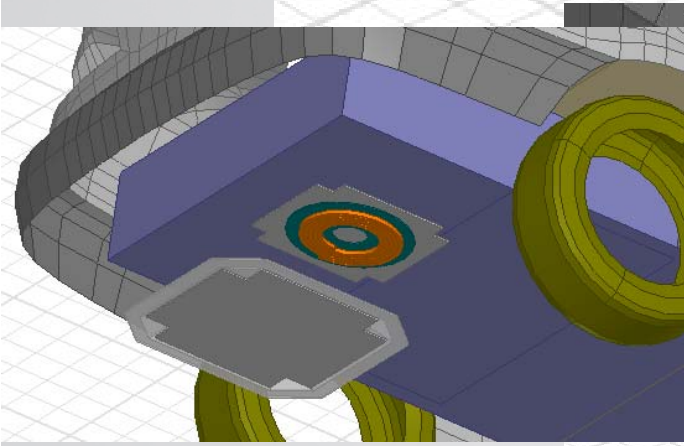
- Inductive type

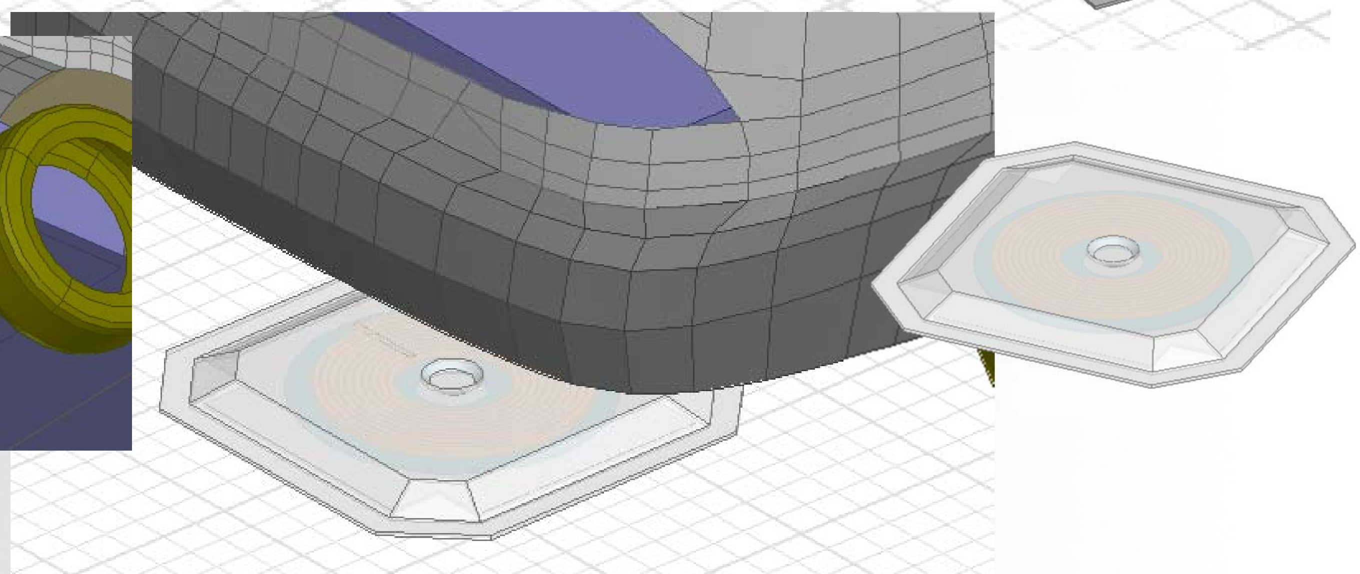


Ref: EE Times Japan 2009.10

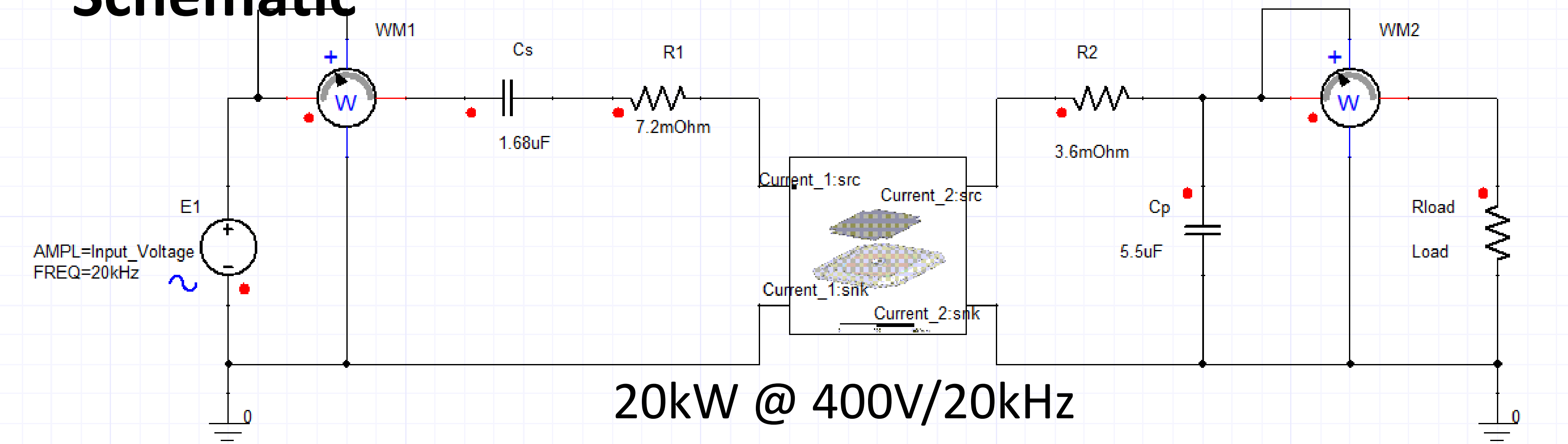
Geometry



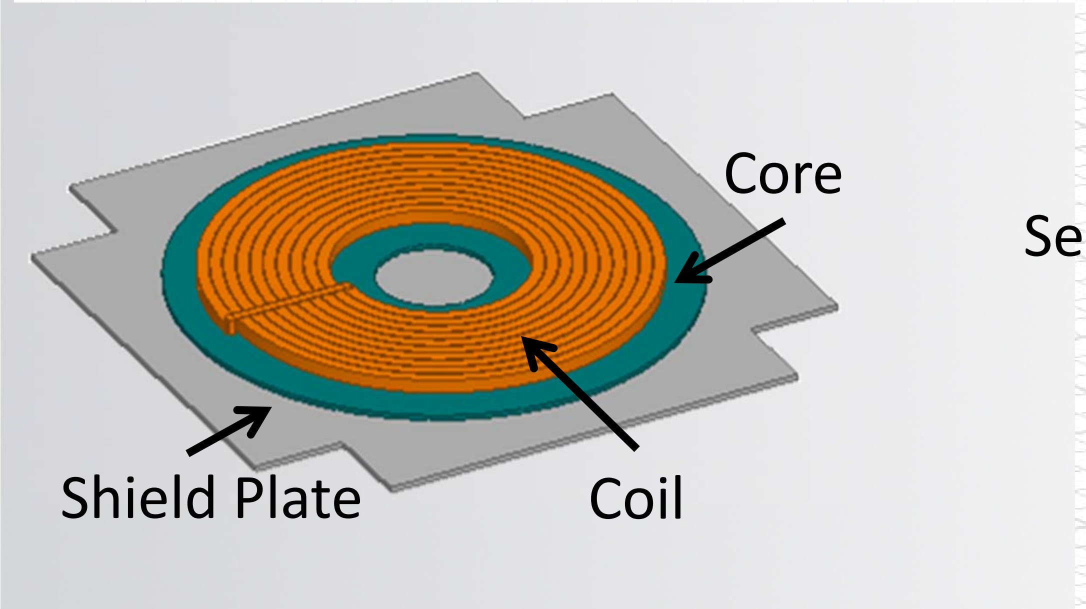


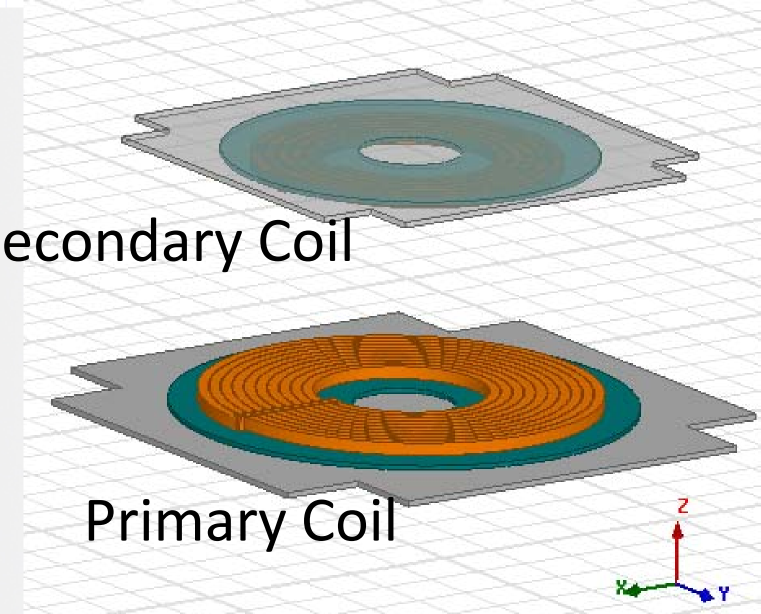


Schematic



20kW @ 400V/20kHz





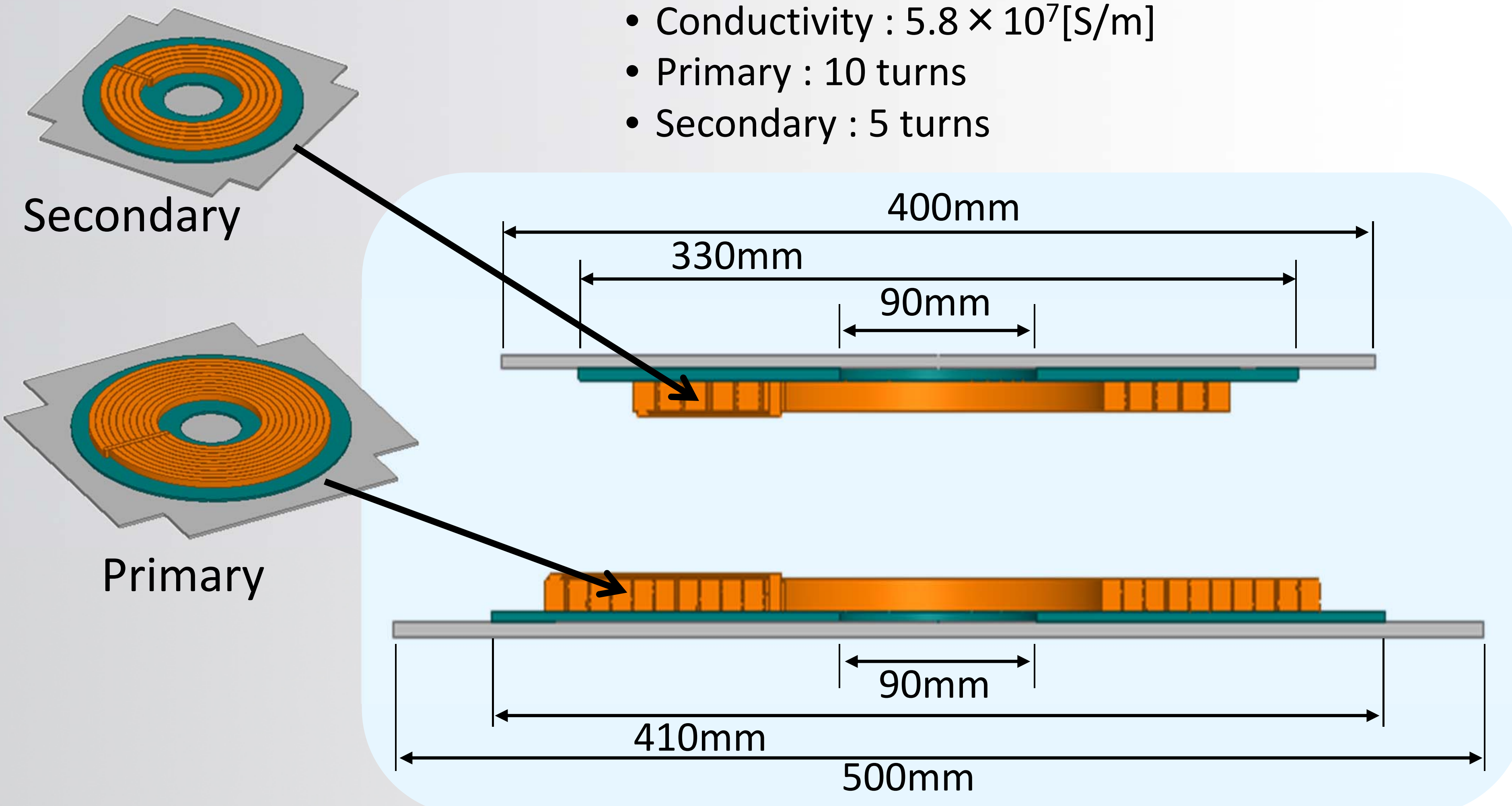
Materials

Magnetic Core

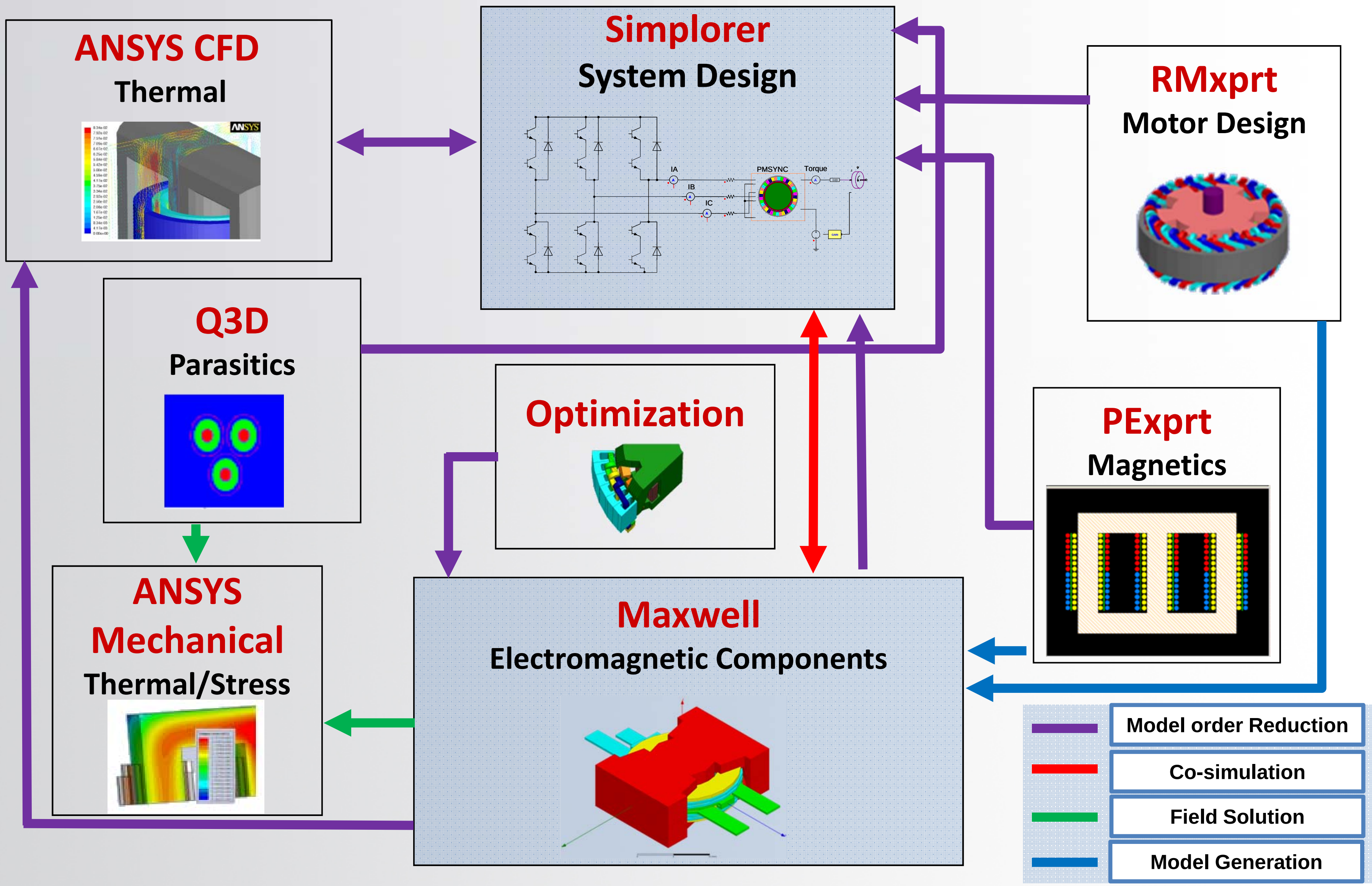
- Material : FDK 6H40 (Bs=0.53T, μi=2400)

Winding Coil

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

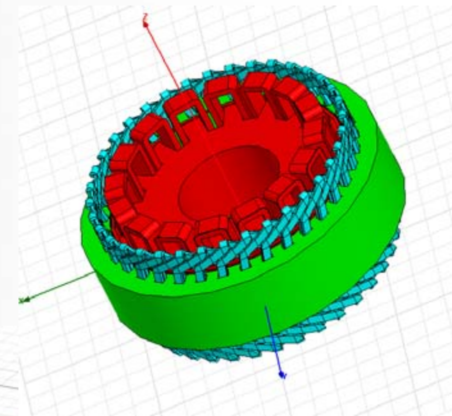


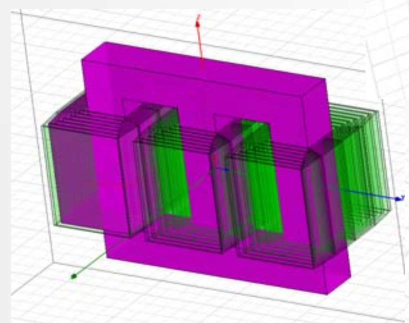
Electromechanical Design Flow

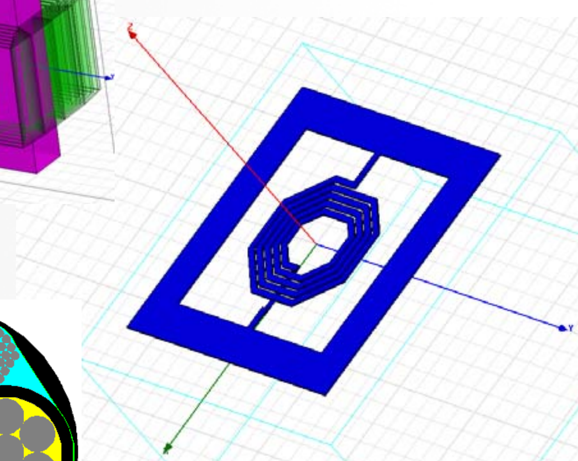


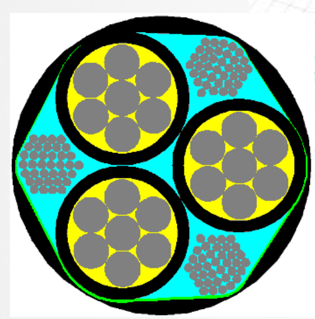
Maxwell - Introduction

- Solves 2-D and 3-D electromagnetic field problems using FEA
- Five Solution Types: Electrostatic, Magnetostatic, Eddy Current, Transient Electric, Transient Magnetic
- Determines R,L,C, forces, torques, losses, saturation, time-induced effects
- Simulation of: Power Magnetics, Inductors, Transformers, Motors, Generators, Actuators, Bus bars
- Co-simulation with Simplorer
- Direct link from PExprt, RMxprt
- Direct link to ANSYS Mechanical





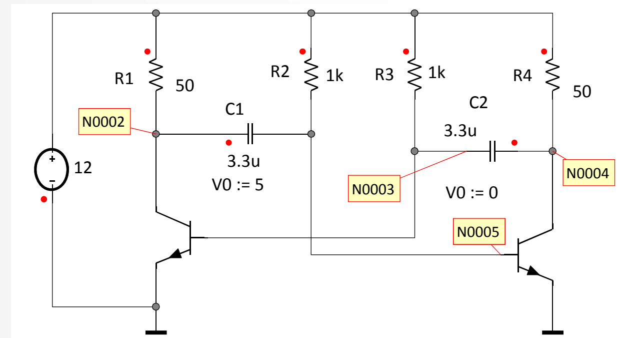




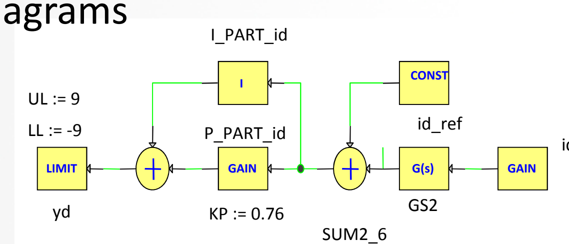
Simplorer - Introduction

- Three Basic Simulation Types:
  - Circuits
  - Block Diagrams
  - State Machines
- Multi-domain simulator for electrical, magnetic, mechanical, fluid, and thermal systems
- Integrated analysis with EM tools (Maxwell, PExprt, Q3D, RMxprt, HFSS) and thermal tools (ANSYS CFD, ANSYS Icepack)
- Co-simulation with Maxwell and Simulink
- Optimization and Statistical analysis
- VHDL-AMS capability

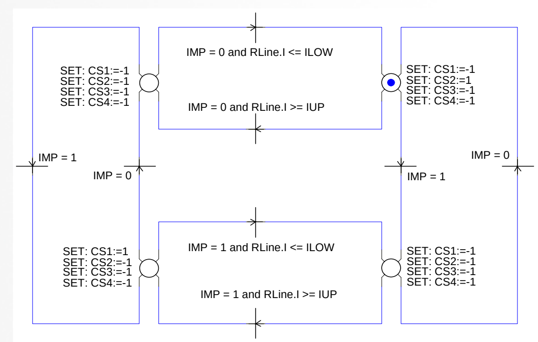
Circuits



Block Diagrams

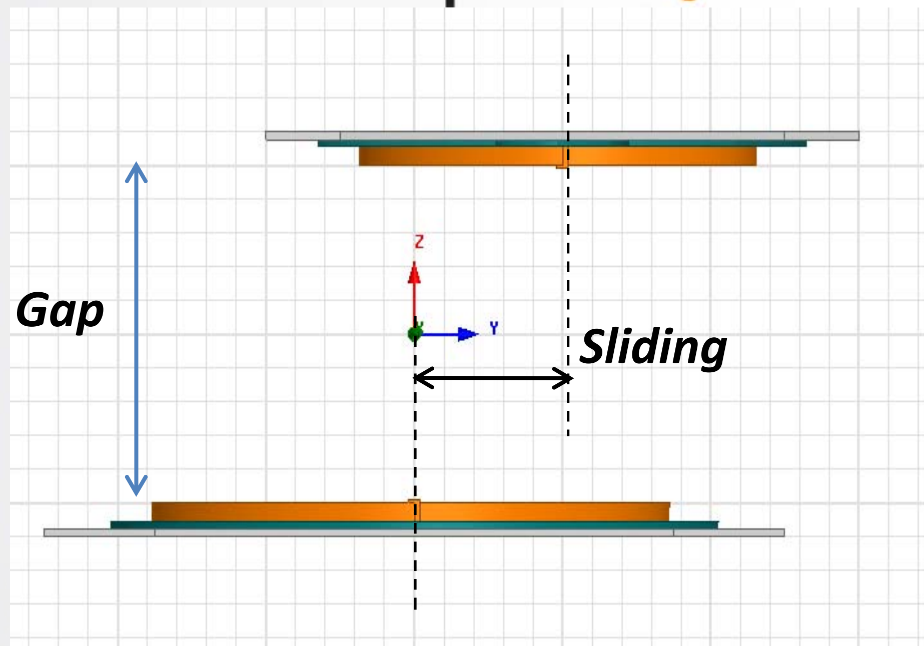


State Machines



Solution Flow Chart

- Maxwell + Simplorer



Maxwell Magnetostatic

Core, Winding

Maxwell Eddy Current

Impedance Model

Maxwell Eddy Current

Fields, Losses

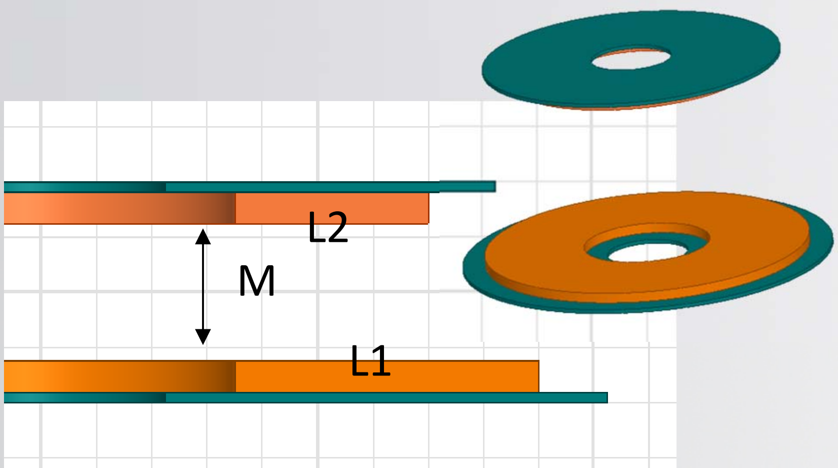
Simplorer

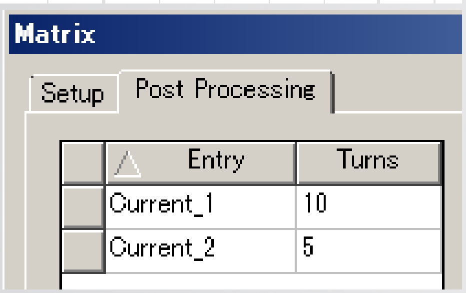
AC / TR

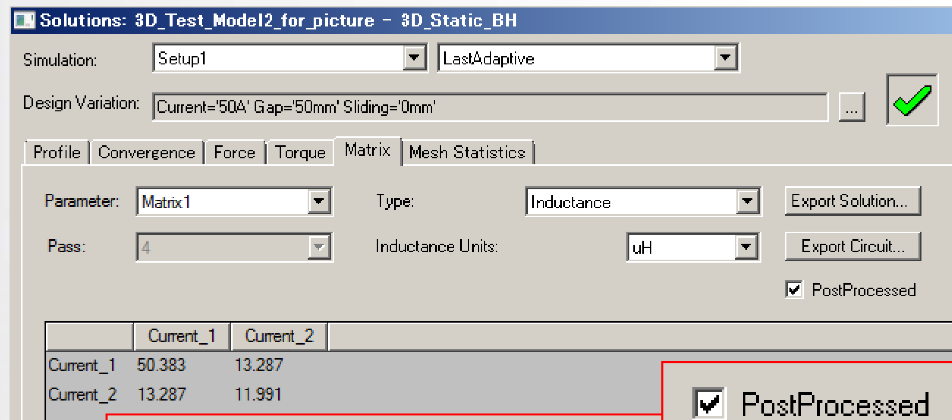
Circuit / Drive / Controller design
Waveform, Efficiency, Power factor, Response

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

	Current_1	Current_2
Current_1	1	0.54056
Current_2	0.54056	1

k=0.54

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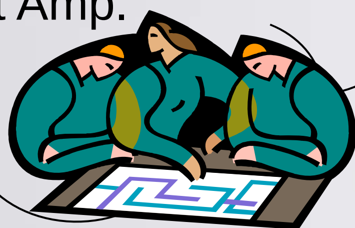
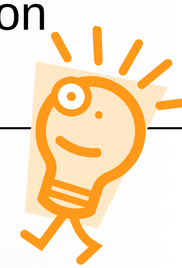
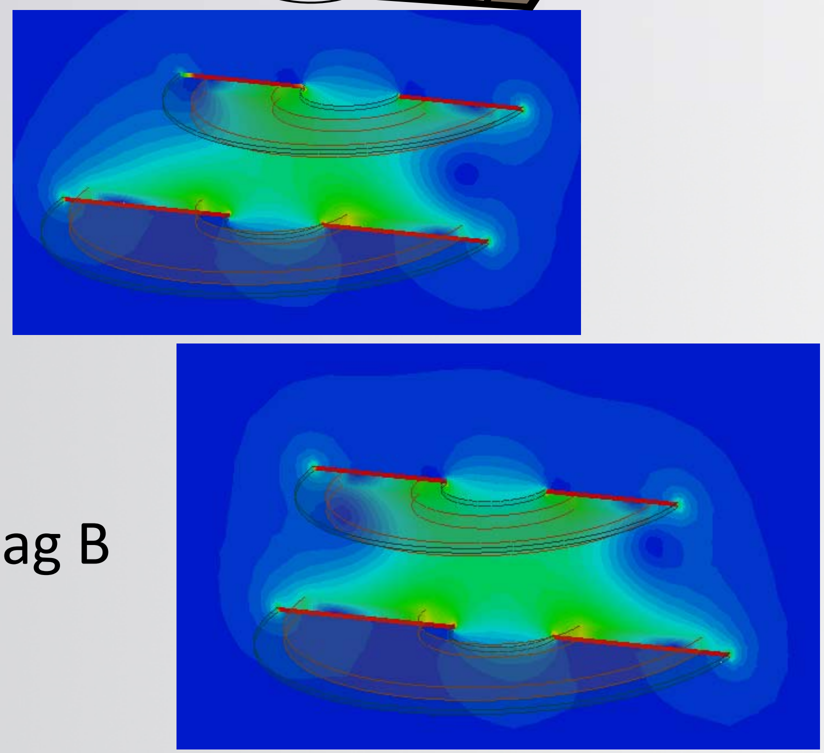
Maxwell / Magnetostatic

Core Shape/Material
Number of turns
Current Amp.
Gap

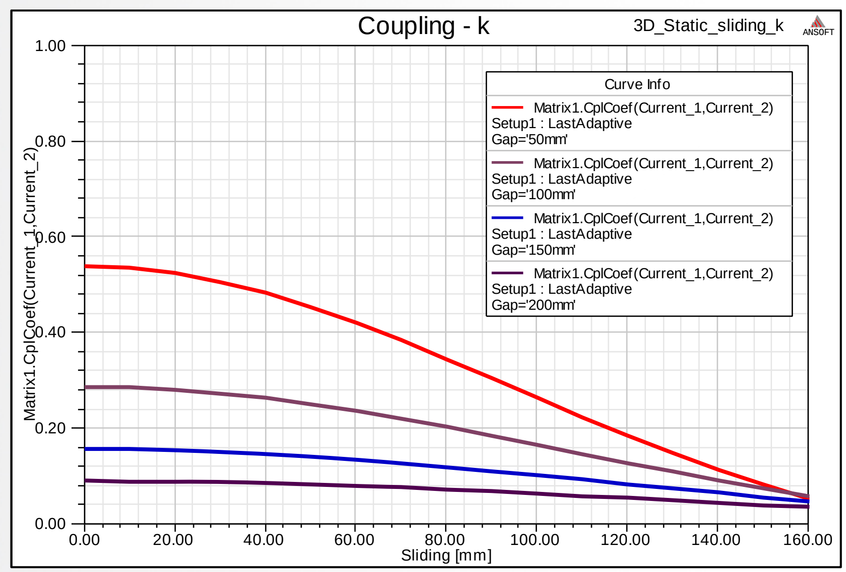


Inductance L, M
Coupling factor k
Field
Core saturation





Mag B

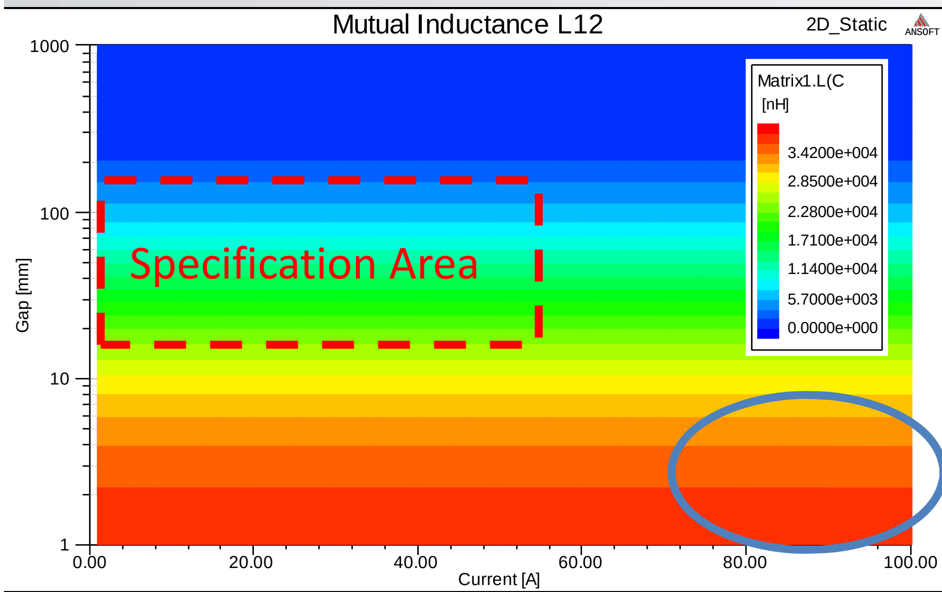


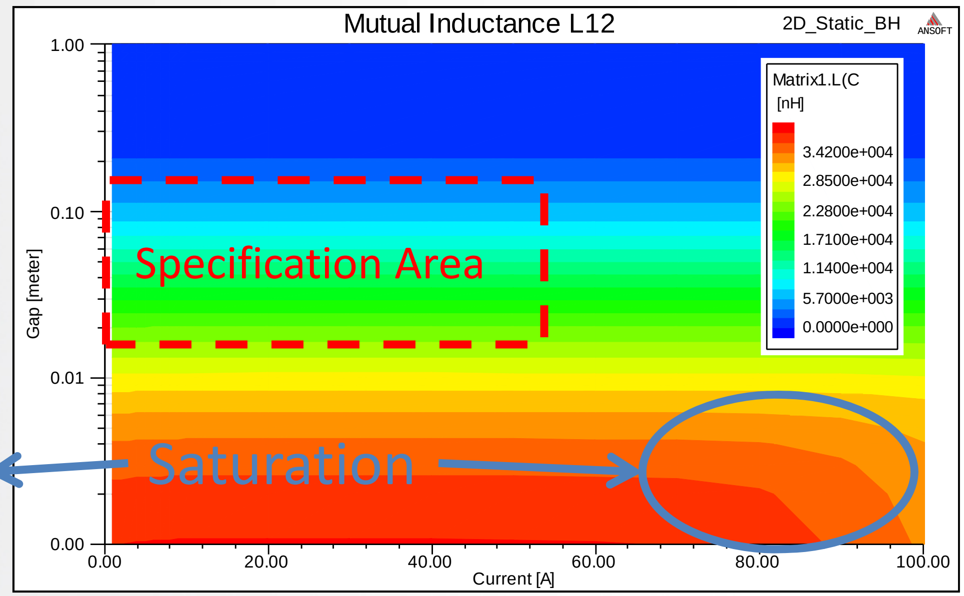
Coupling factor k – sliding gap

Maxwell / Magnetostatic

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

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



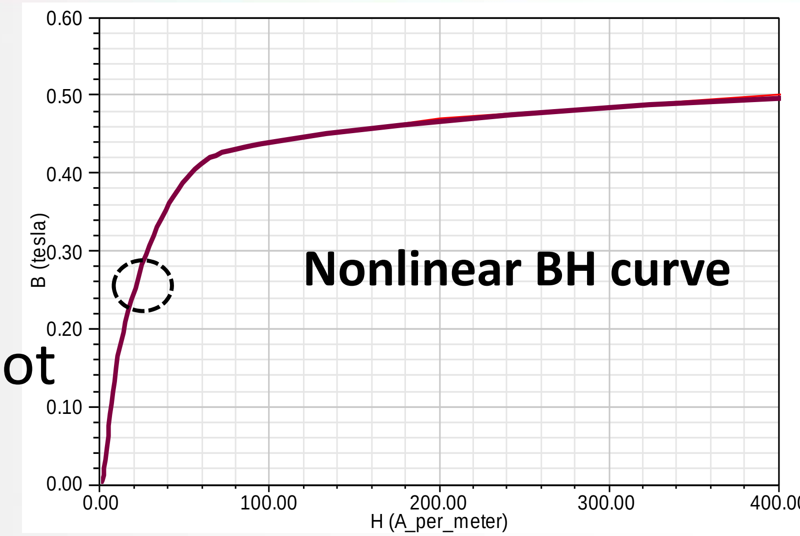


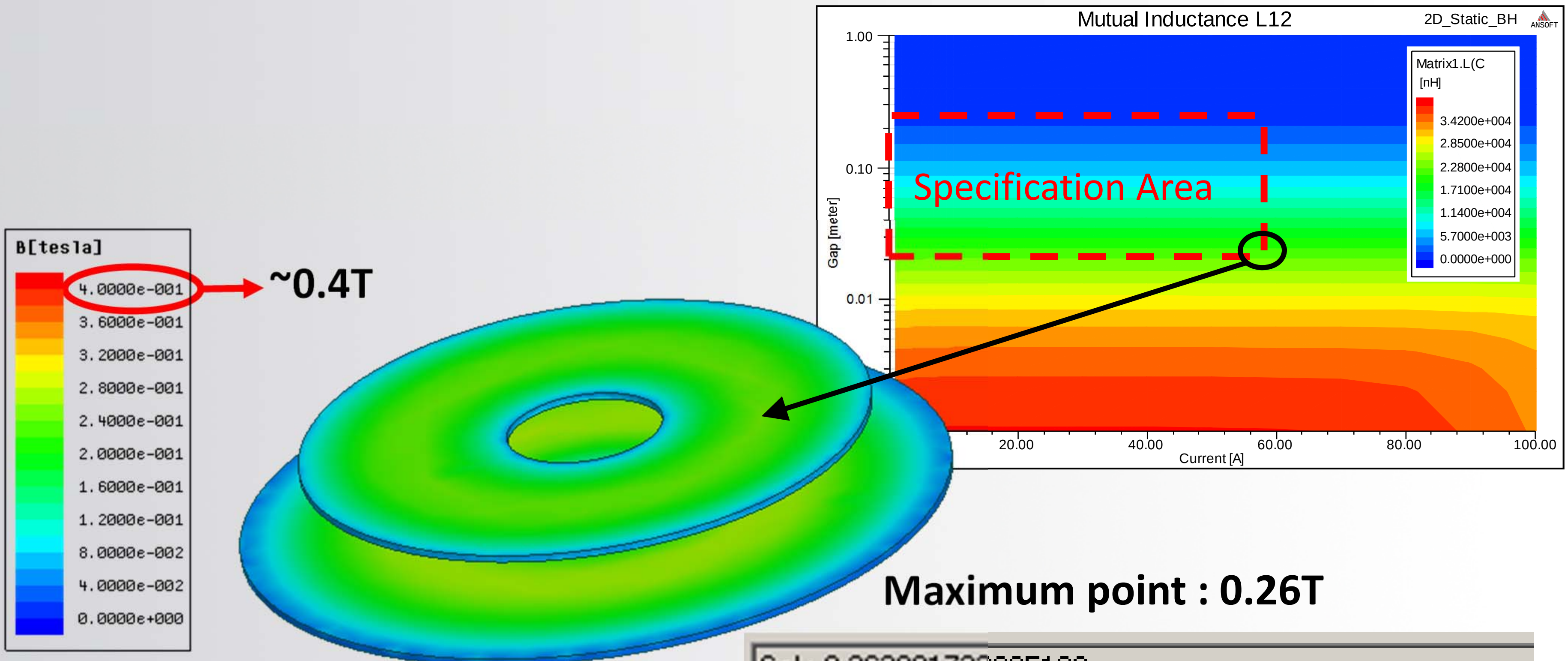
Linear Material
(Initial permeability)

Nonlinear Material
(BH curve)

Maxwell / Magnetostatic

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





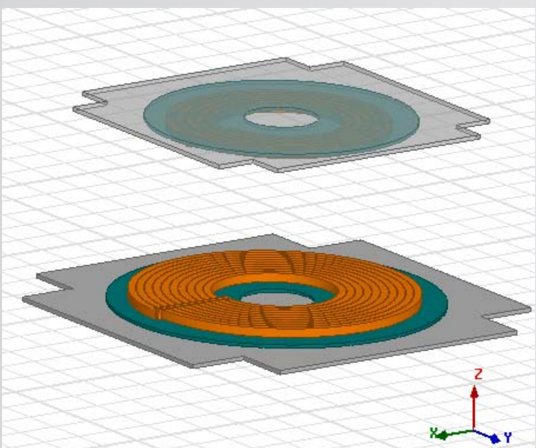
Maximum point : 0.26T

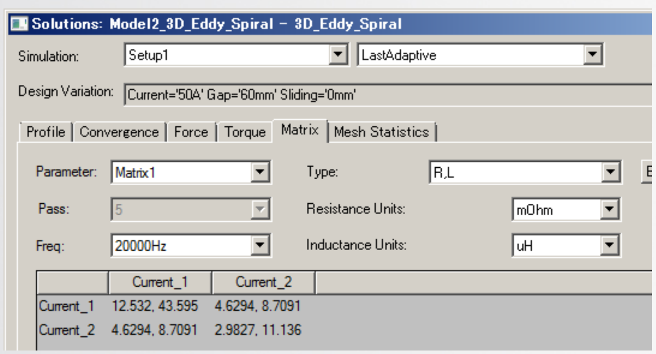
Scl : 0.263981733295126
Scl : Maximum(Volume(Core_1st), Smooth(Mag(<Bx,By,Bz>)))

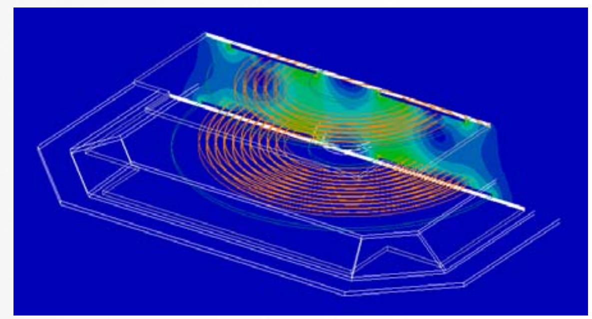
Maxwell / Eddy Current

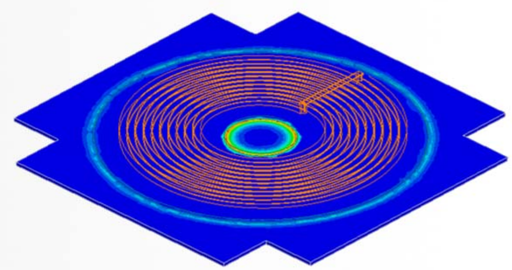
- State Space Modeling for Simplorer
  - Frequency domain impedance(R,L) model for circuit simulation

- AC fields and Losses (after circuit simulation)



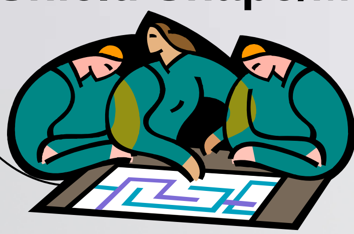




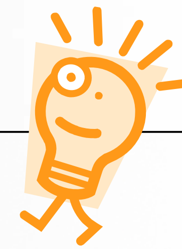


Maxwell / Eddy Current Solver

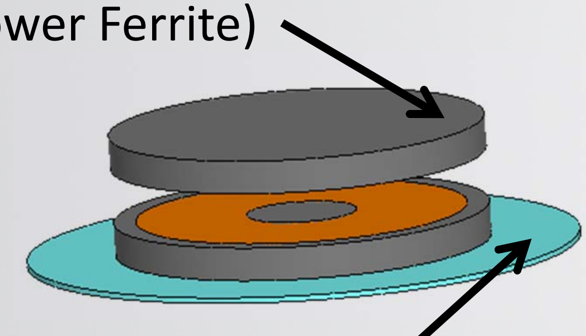
Core Shape/Material
Number of turns
Frequency
Gap
Shield Shape/Material



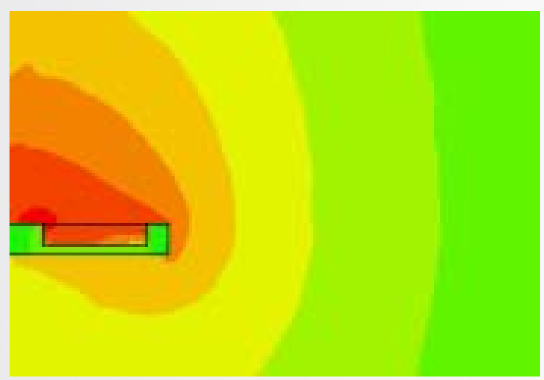
AC Characteristics
Inductance L, M
Coupling factor k
Field
Core Hysteresis
Shield



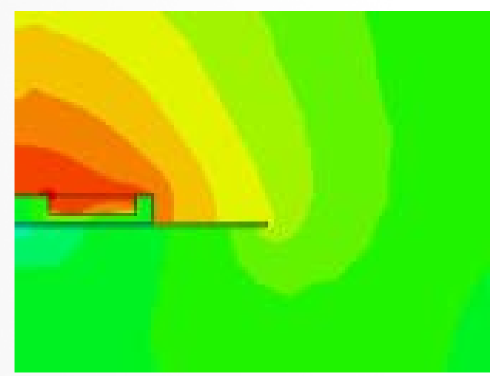
Core(Power Ferrite)



Shield Plate (Aluminum)

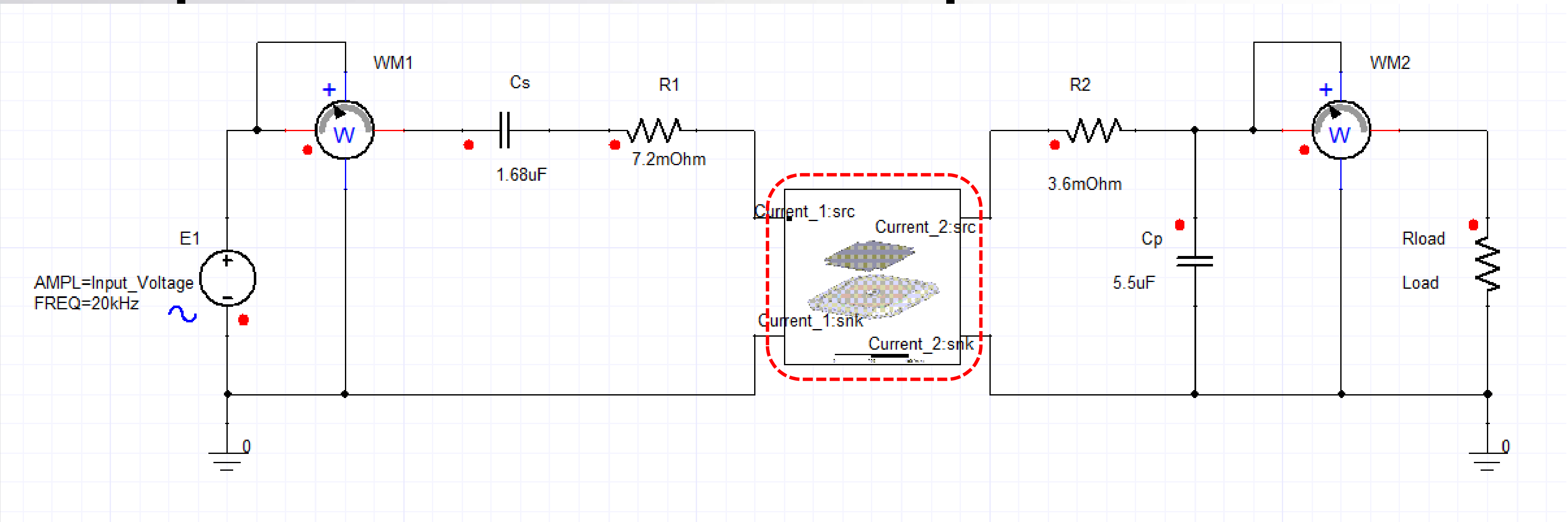


No Shielding

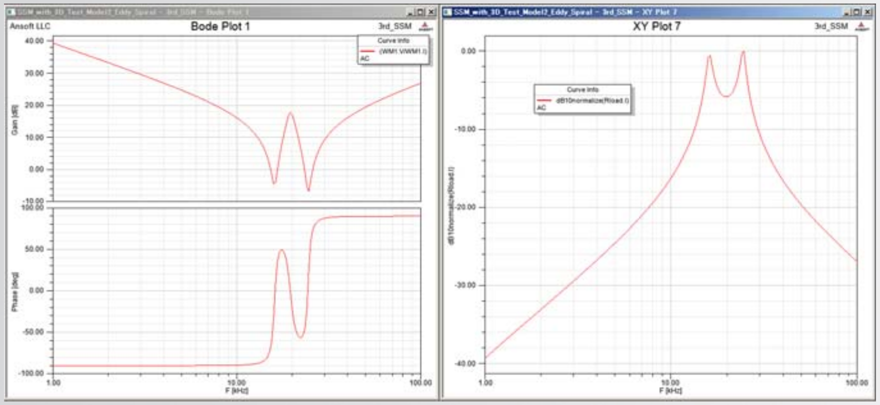


Shielding

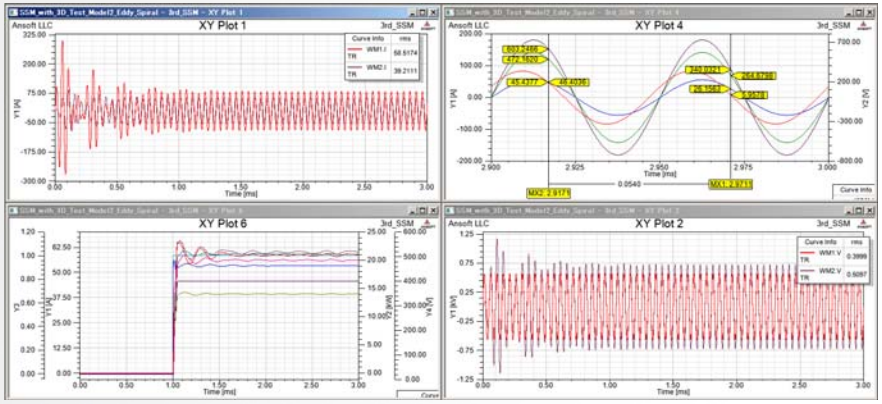
Simplorer with Maxwell State Space Model



AC / Frequency domain

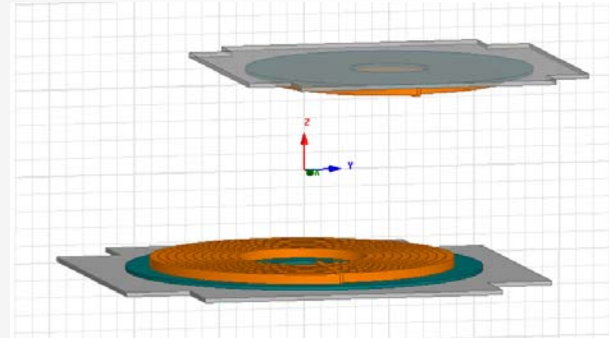


TR / Time domain



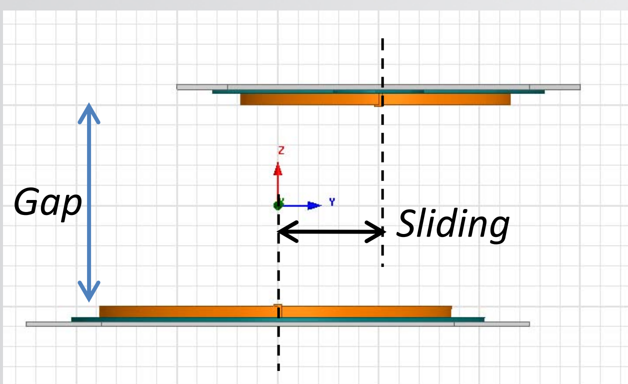
Efficiency Map

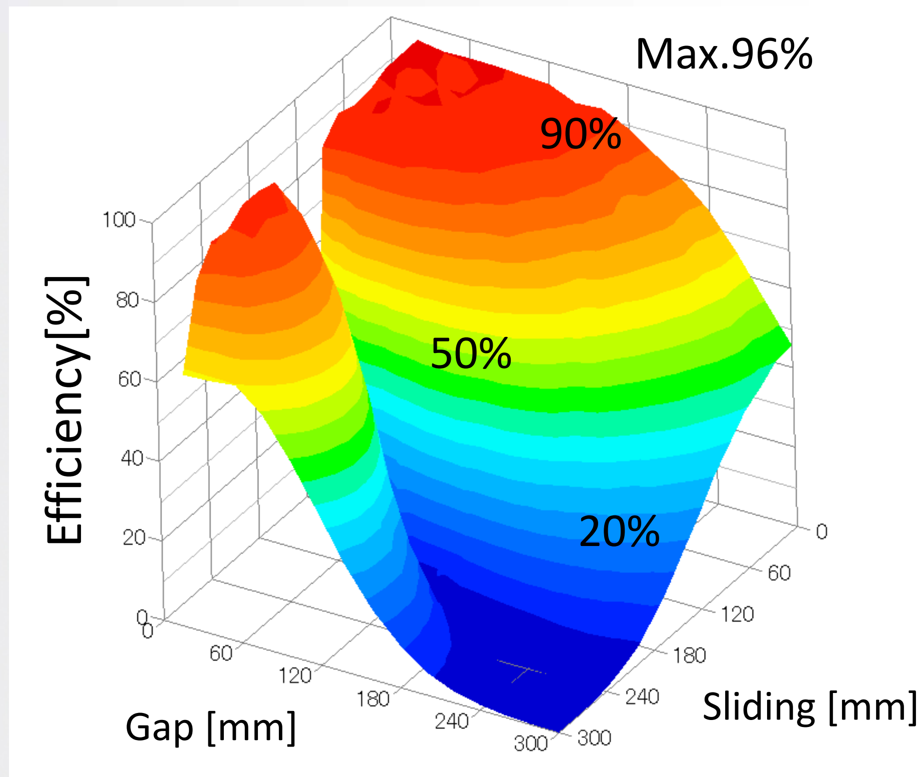
- Output/Input Power
- Tuned capacitance for each conditions
- Blue valley vs sliding indicates poor design (coil too small)



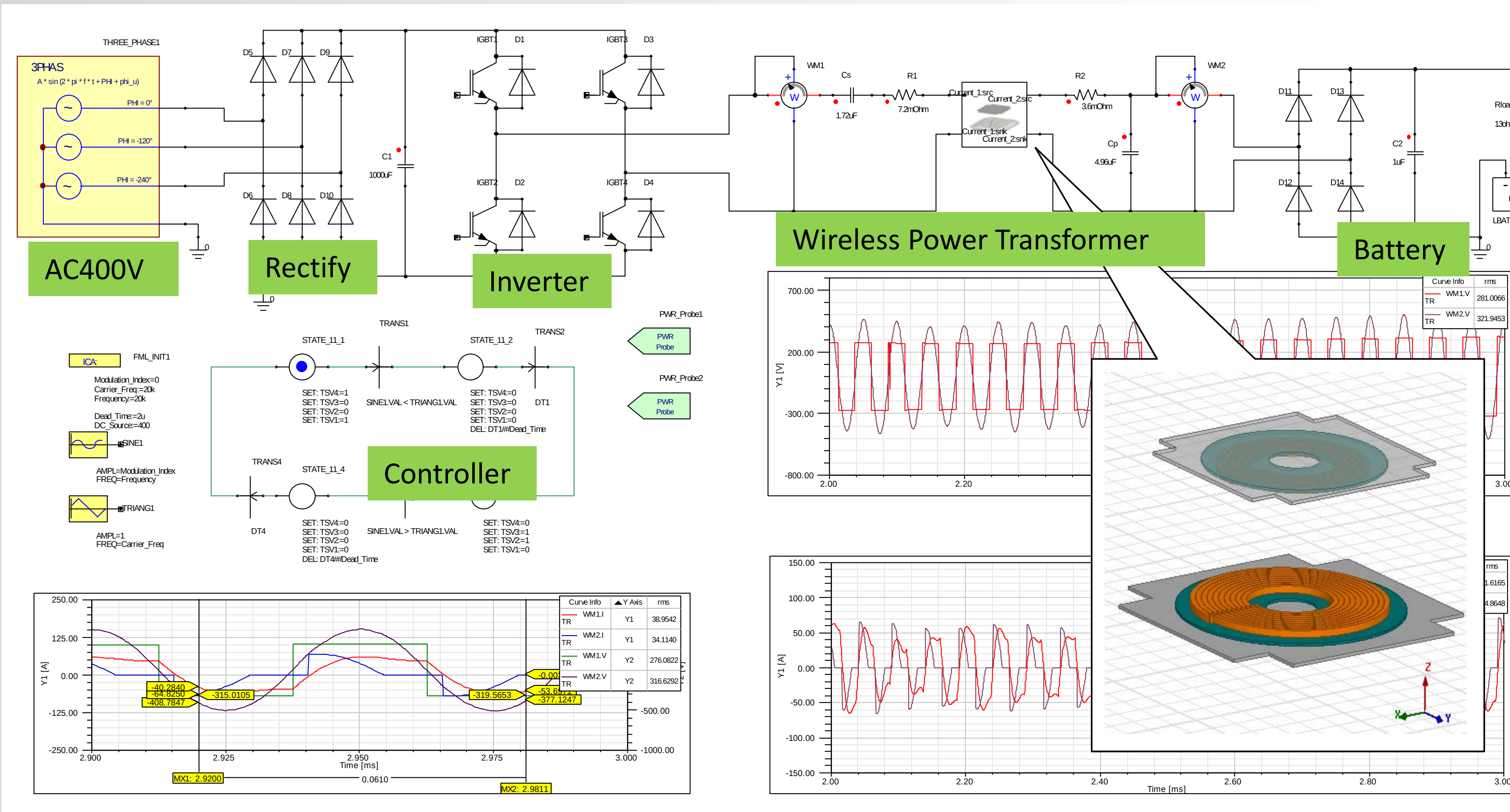
$$P = VI\cos\theta$$

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

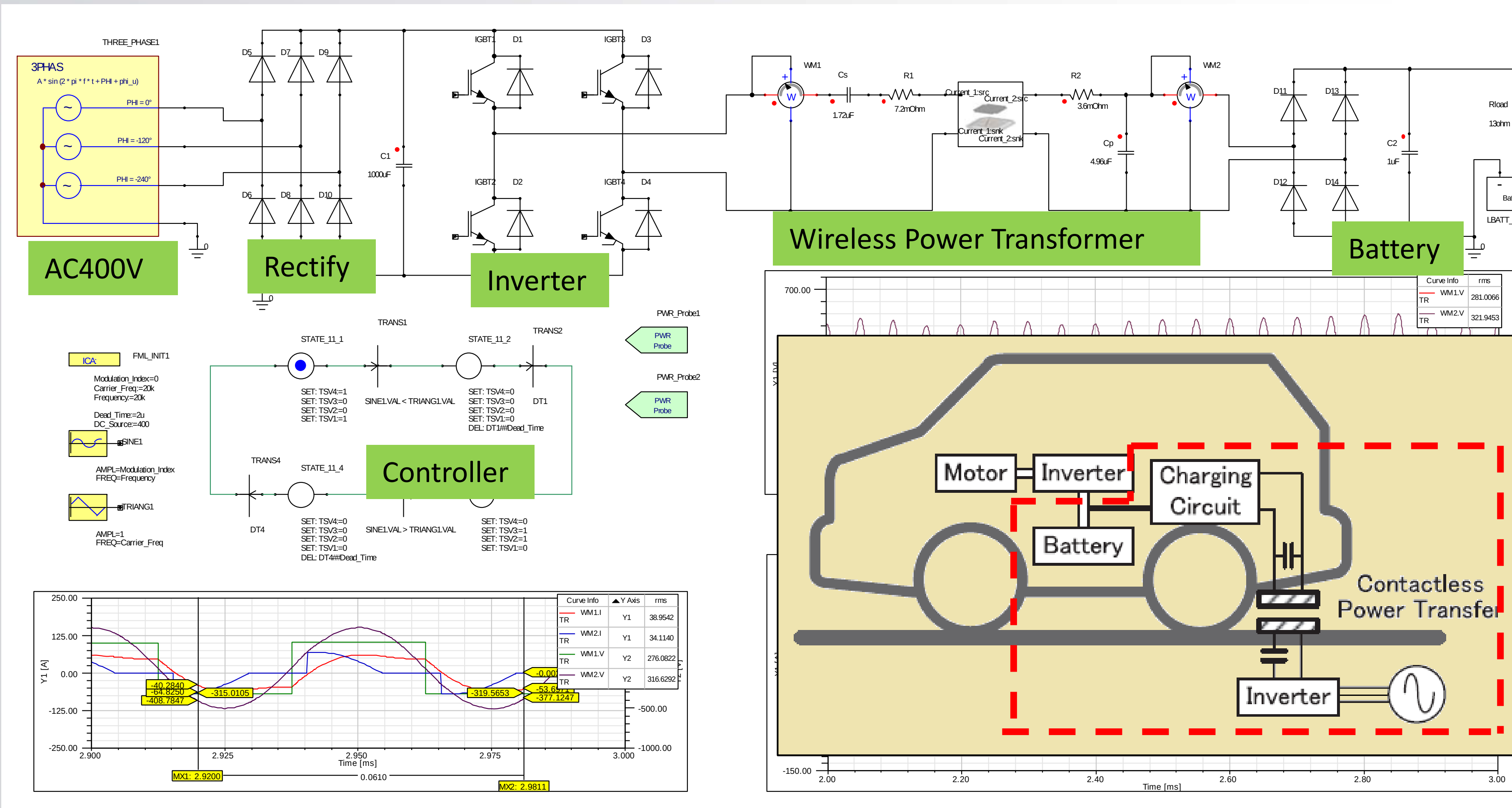




Maxwell – Simplorer System Simulation

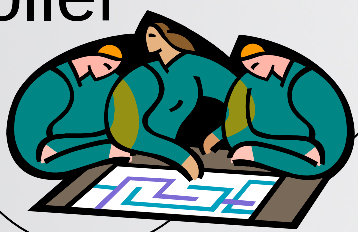


Maxwell – Simplorer System Simulation

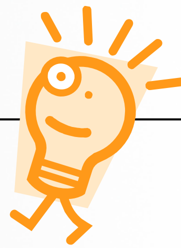


Simplorer: Design Driver Controller in a System Level Simulation

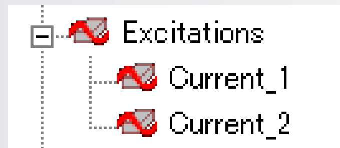
Circuit
Driver
Controller

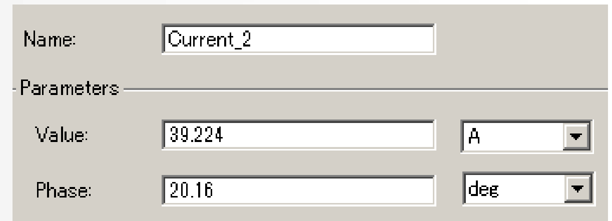


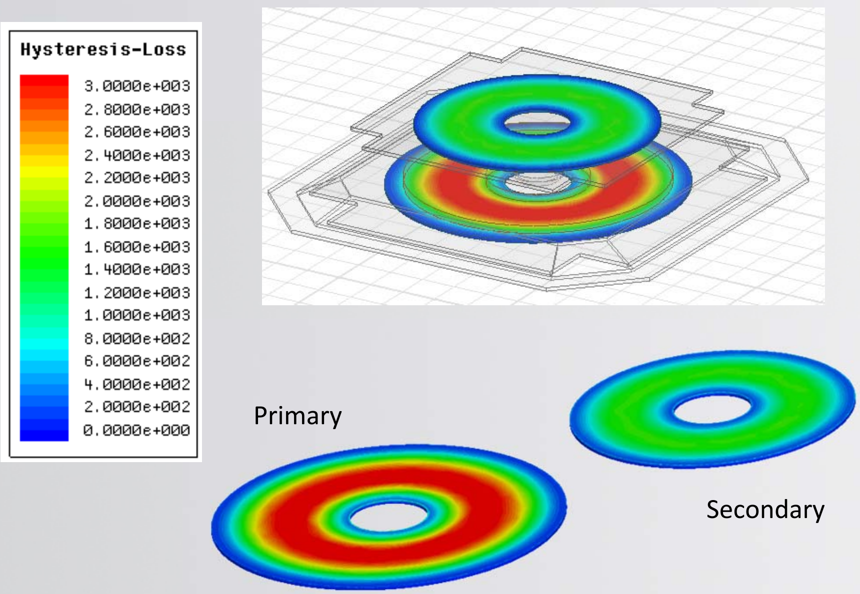
AC/TR Response
Waveform
Efficiency



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



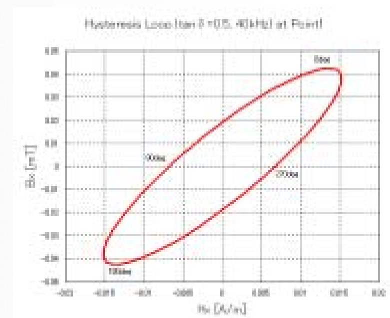




Hysteresis Loss

Considering Magnetic Loss tangent

$$\mu = \mu' - j\mu'' = \mu'(1 - j\tan\delta)$$



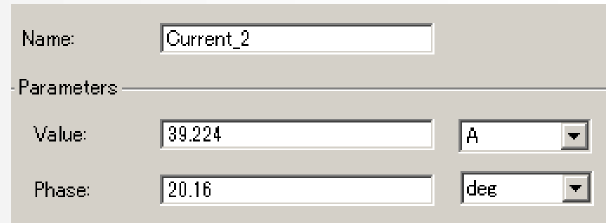
Core Loss — 3D_Eddy

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

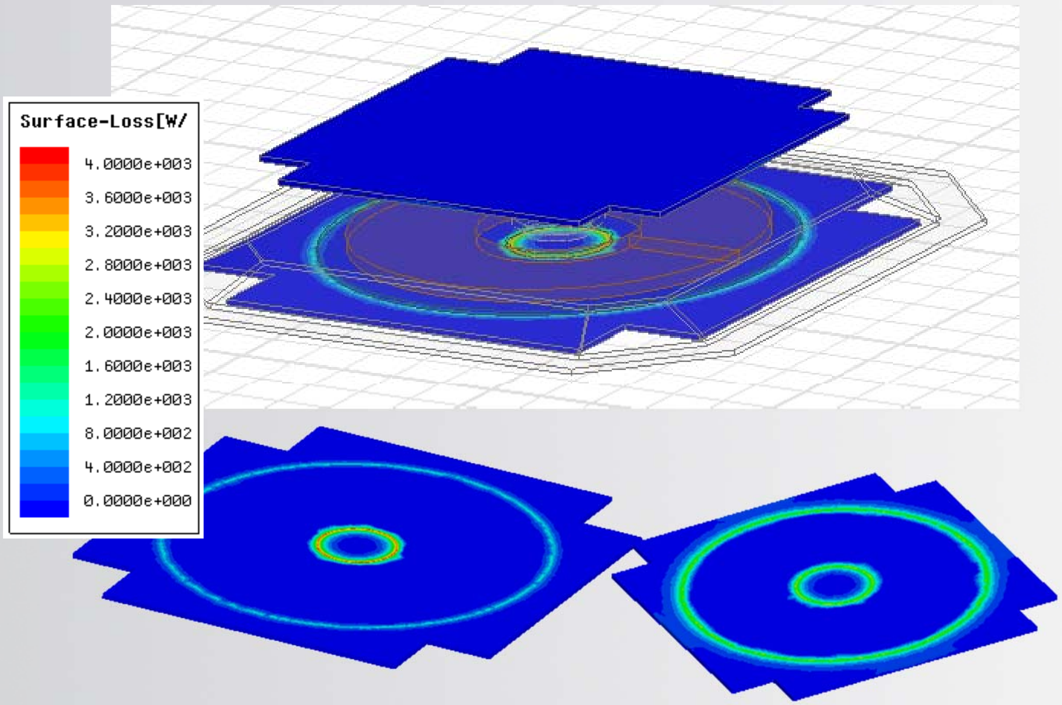
Core loss[W]

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

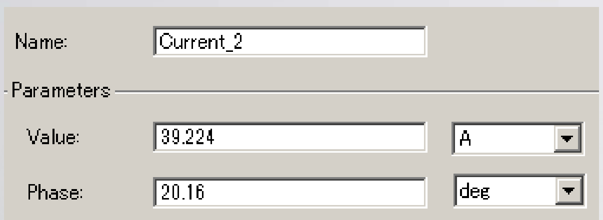
Shield Loss 3D_Eddy ANSOFT

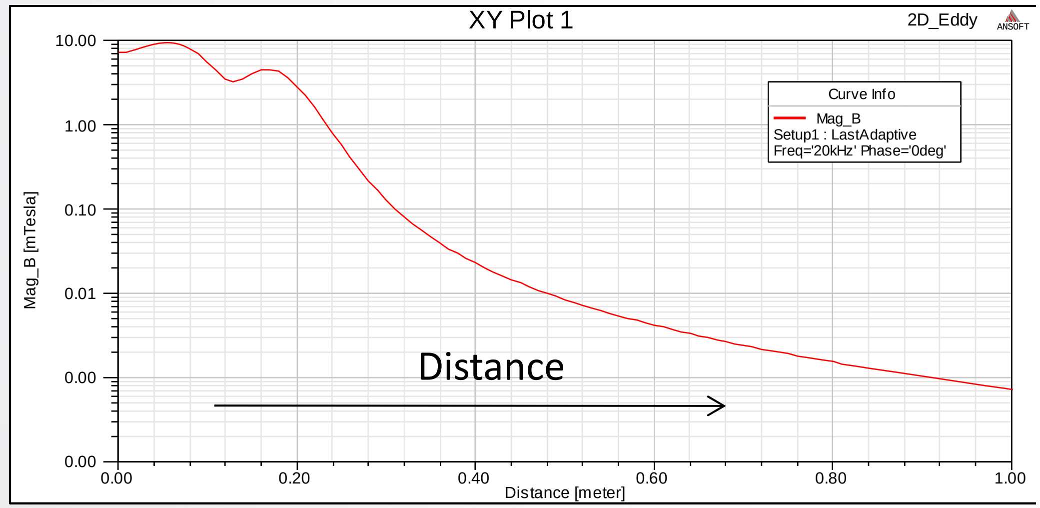
	Freq [kHz]	Shield1st_Loss Setup1 : LastAdaptive Phase='0deg'	Shield2nd_Loss Setup1 : LastAdaptive Phase='0deg'
1	20.000000	22.938675	37.886583

Shield Loss[W]

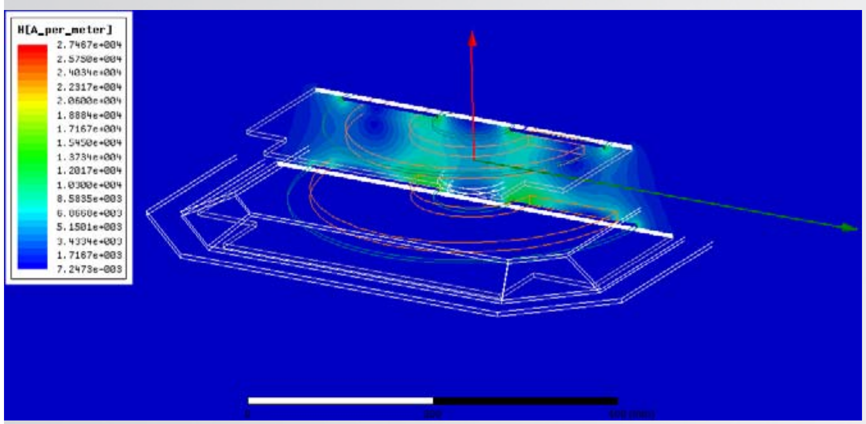
Scl : 22.9386748099613
Scl : Integrate(Surface(Shield_1st), SurfaceLossDensity)

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

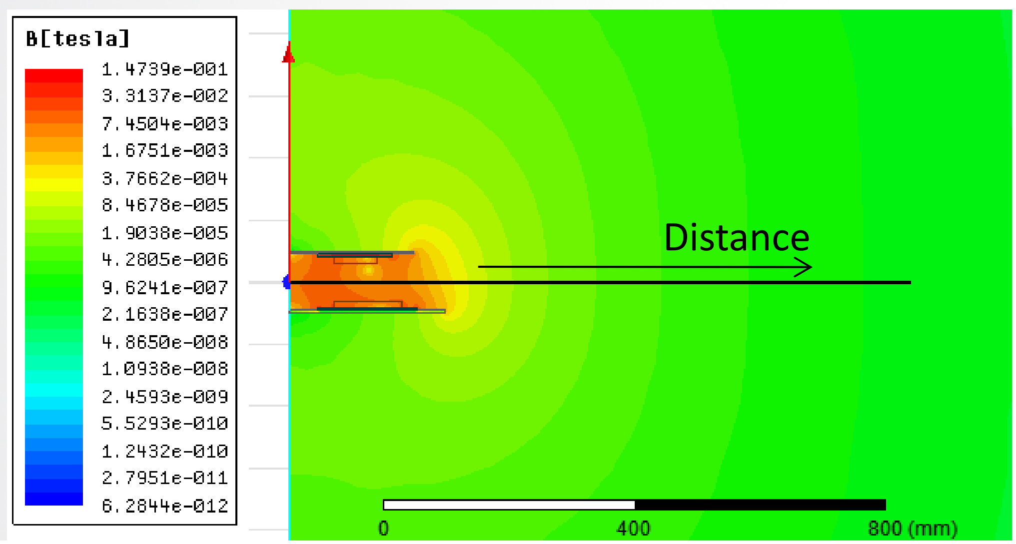




Magnetic Field Density

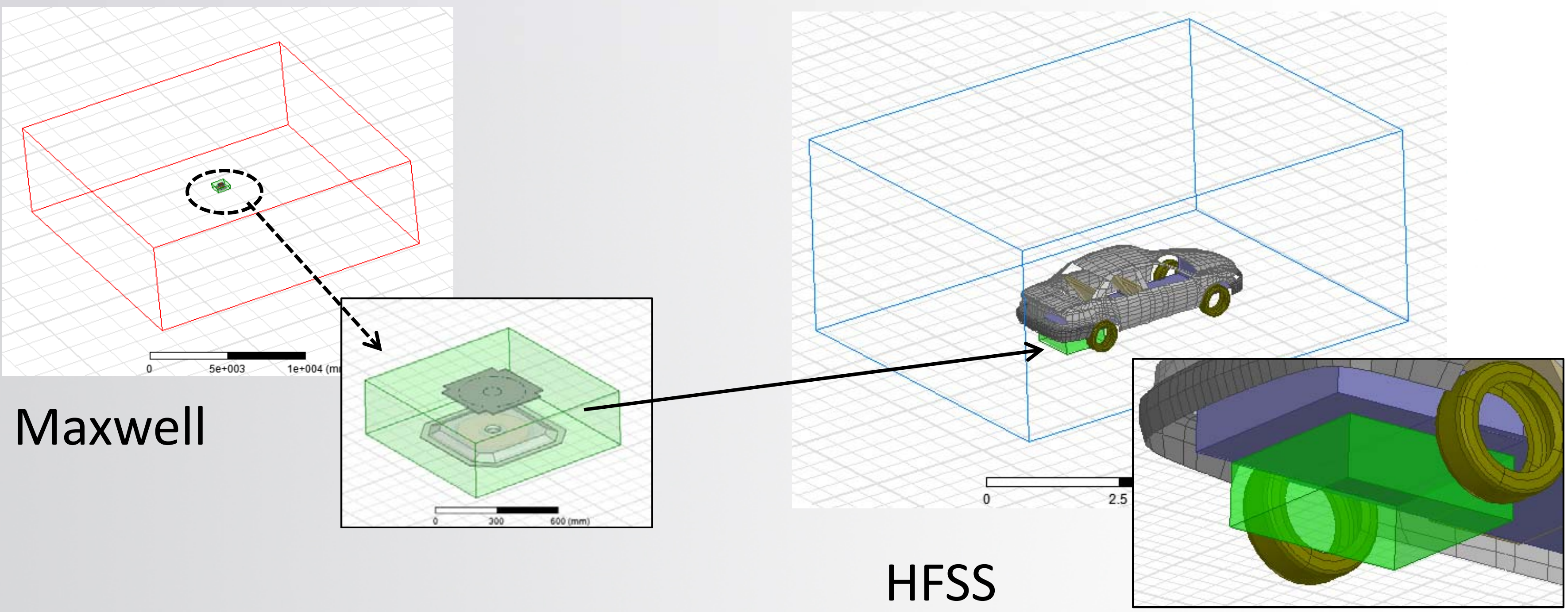


Magnetic Field Intensity



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



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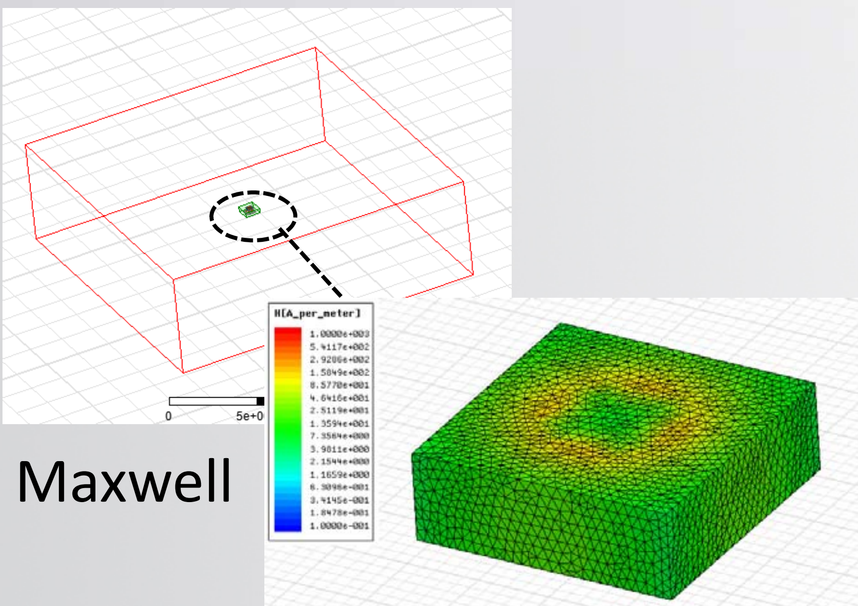
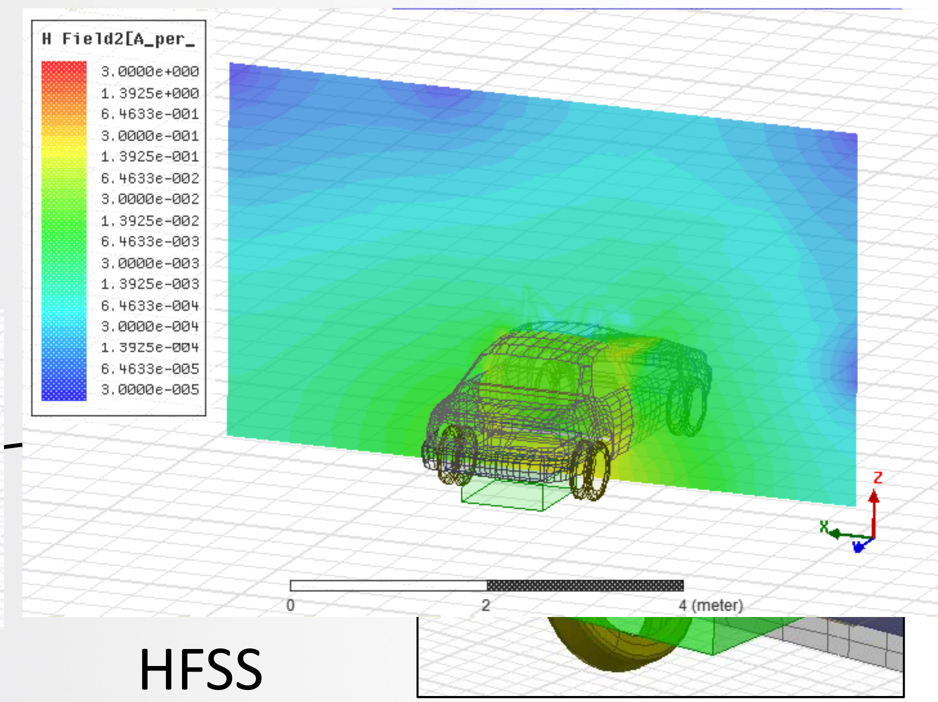


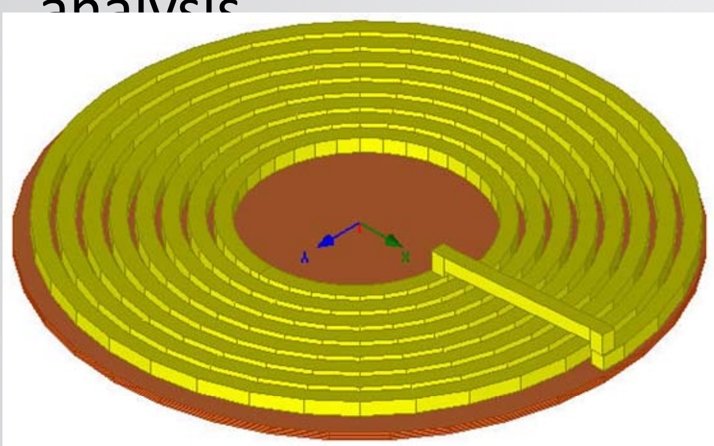
Maxwell

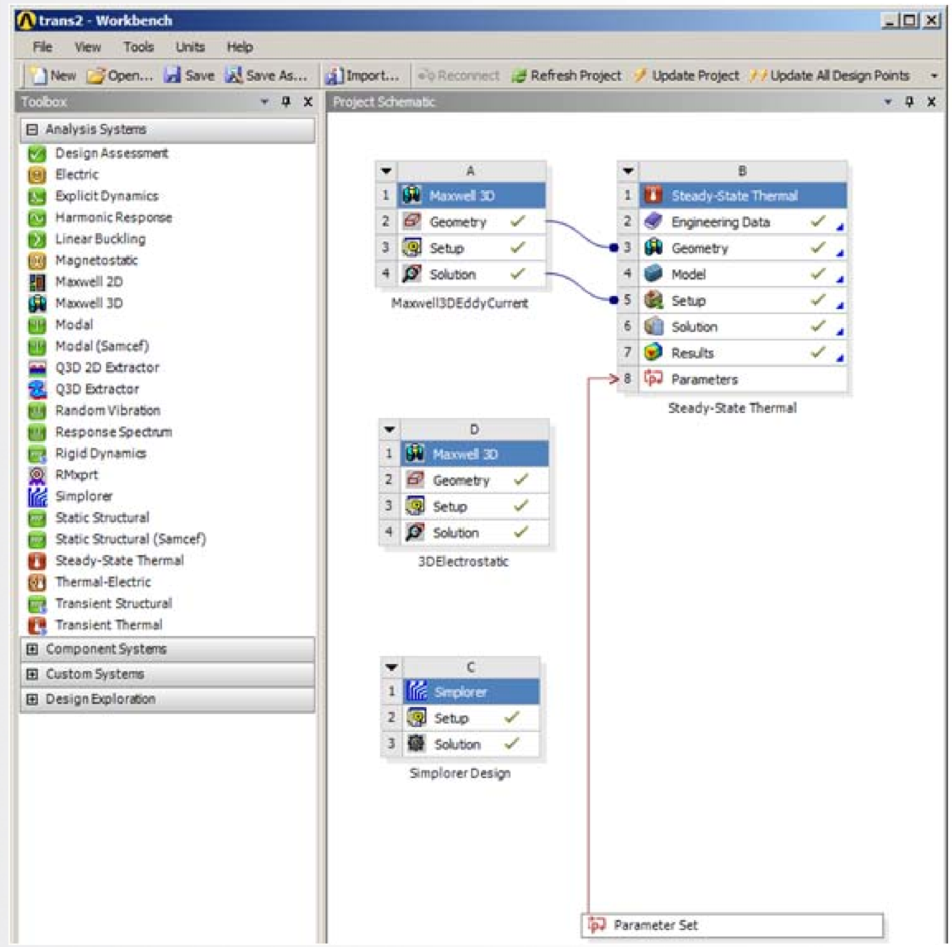


HFSS

Thermal /Stress Analysis using Workbench

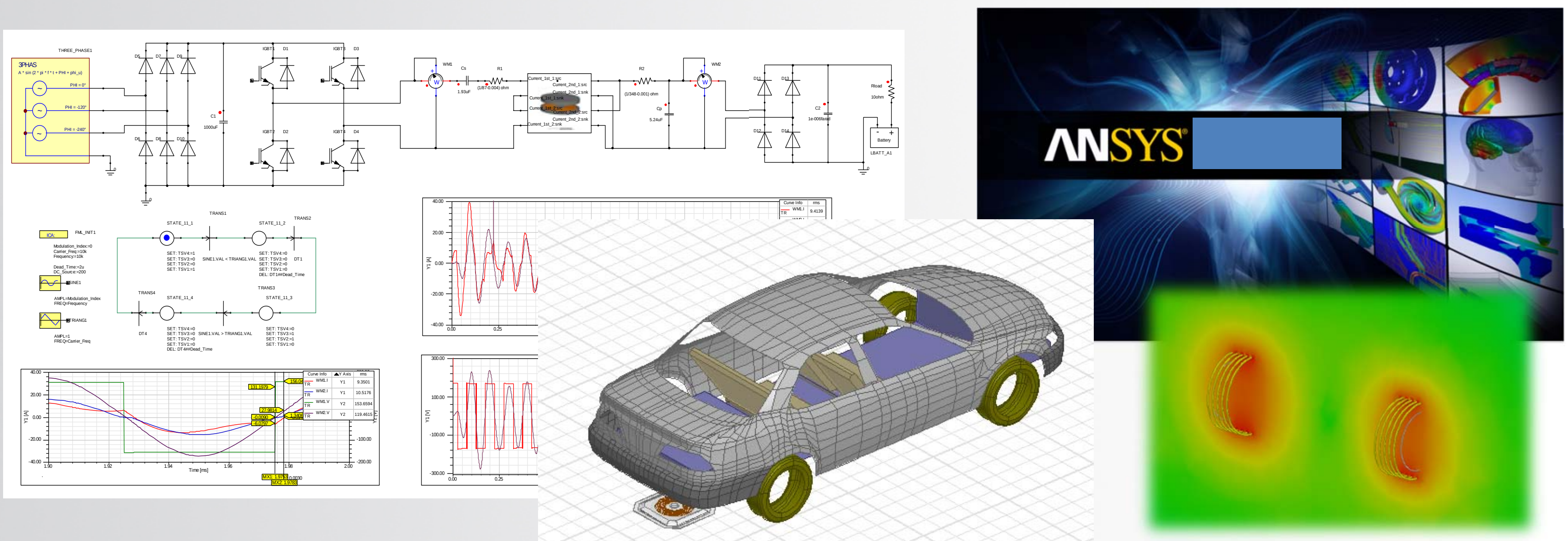
- Maxwell 3D Eddy Current losses can be imported directly to ANSYS steady-state thermal and stress solver for mechanical analysis





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 multi-physics simulation, such as combined Thermal / Structure for mechanical analysis.

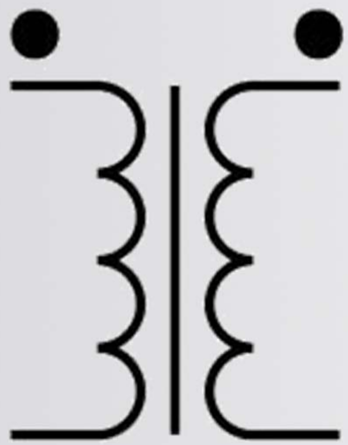


Appendix

Electromagnetic tools

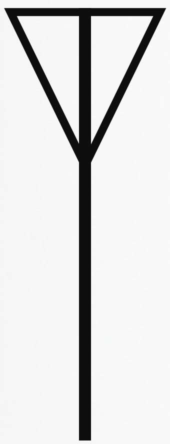
Which is the optimal simulation tool ?

"Low Freq."



Maxwell

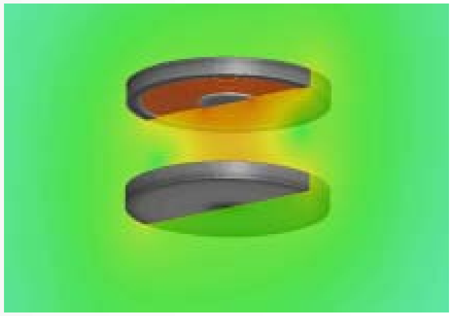
"High Freq."



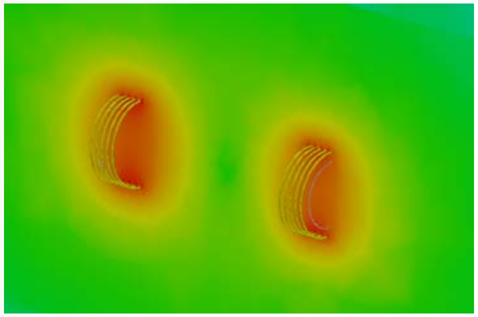
HFSS

Differentiating Features

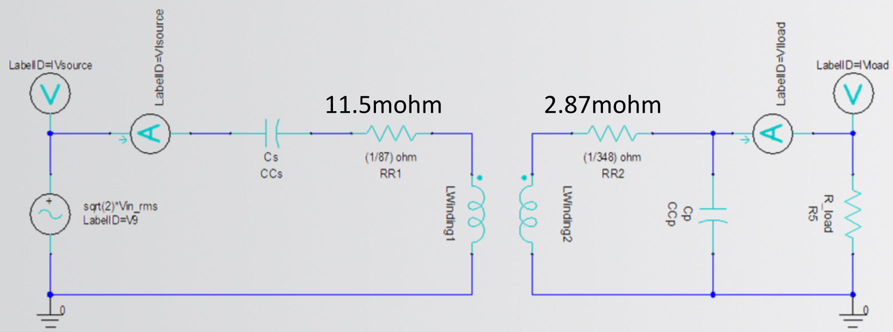
- Maxwell: Low Frequency Field Simulator
  - Separated Solver "Magnetic" and "Electric"
  - Time Transient and Lumped Circuit: L,R,C
  - Linear and Nonlinear Material
  - Application:
    Motor, Transformer/Inductor for power machine, Inductive noise



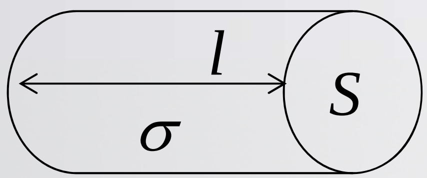
- HFSS: High Frequency Structure Simulator
  - Electromagnetic Full Wave Solver
  - Distributed Circuit: S,Z,Y
  - Linear Material
  - Application:
    Antenna, Transformer/Inductor for signal, Radiation noise



Calculation of Coil Resistance

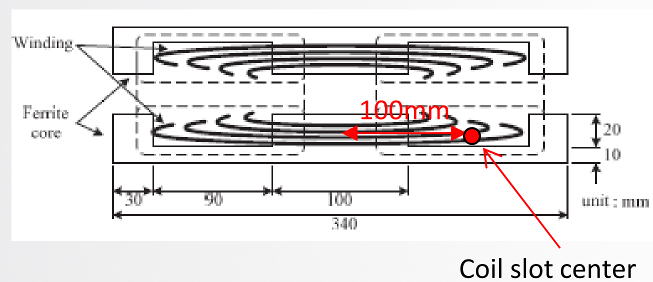


$$R = \frac{l}{\sigma S}$$



Coil

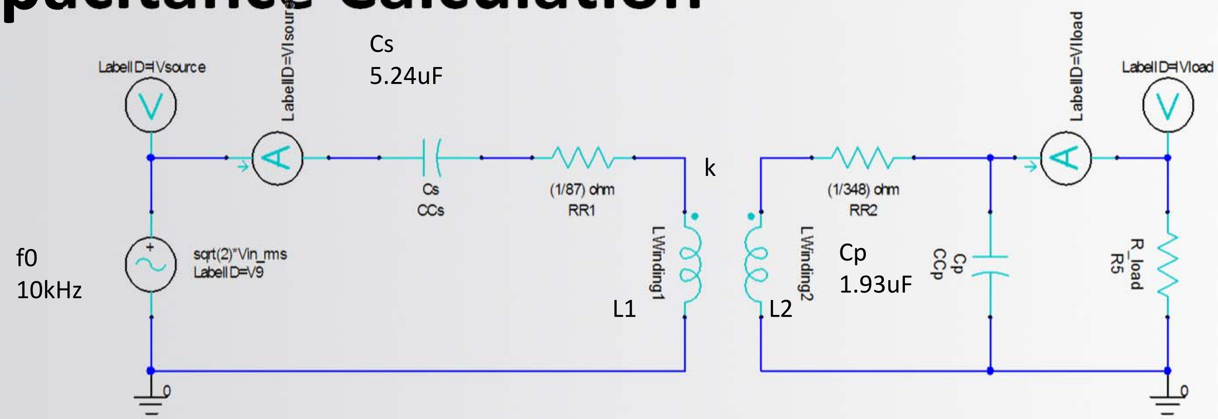
- Litz : 0.25ϕ × 384parallel
- σ : 5.8×10^{7}[S/m]
- Primary : 20 turns
- Secondary : 10 turns x 2parallel



<u>Primary Coil R1:</u>
(2*100*pi*10^-3)/(58000000*(0.25/2)^2*pi*10^-6)*(1/384)*20 = 1/87 ohm = <u>11.5mohm</u>

<u>Secondary Coil R2:</u>
(2*100*pi*10^-3)/(58000000*(0.25/2)^2*pi*10^-6)*(1/384)*10/2 = 1/348 ohm = <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*10000*pi)^2*0.0048166) = 5.24*10^-6 F = 5.24uF

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

Cs:
1 /((2*10000*pi)^2*(1-0.5668^2)*0.0019267) = 1.93*10^-6 F = 1.93uF

Key partner in Design Process Innovation

Wireless power supply implementation for electric vehicles batteries charging

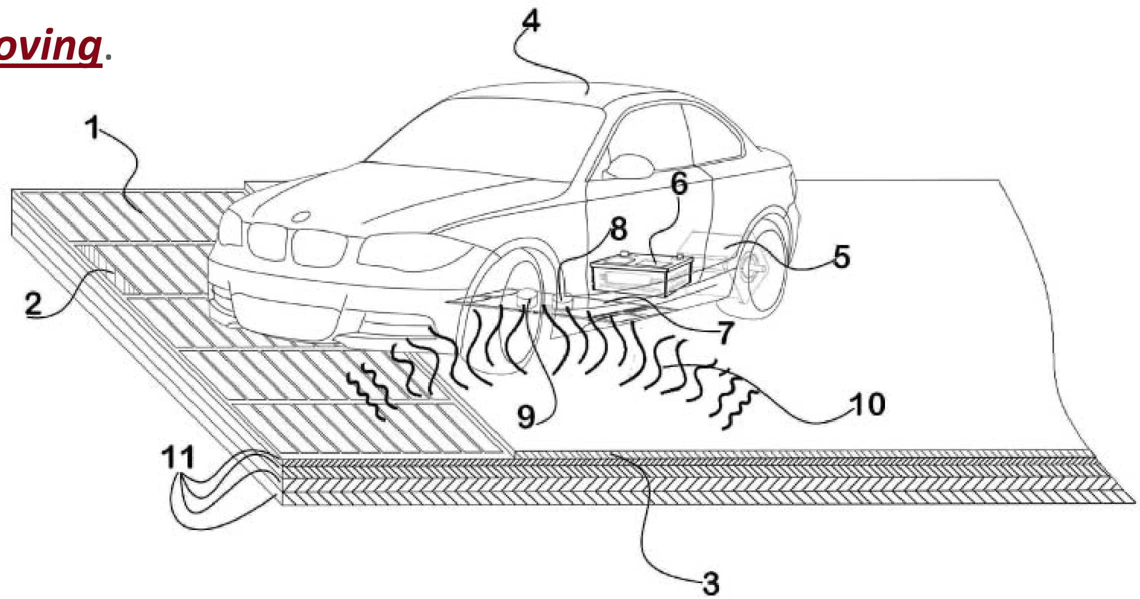
Ing. Andrea Serra, Ph.D.
Dott. Giovanni Falcitelli,
Ing. Emiliano D'Alessandro

Alfredo Sonnante, Vision CEO

VISION®

- Vision is a young consulting company specialized in design, management, promotion and distribution of industrial systems and innovative technology infrastructures.
- It proposes and provides technologies and innovative services for enterprises, public institutions and private users, through research programs with international partners and pilot actions.
- In the automotive research framework, Vision promotes the E-way® project, that is the result of a collaboration between Vision and the Italian Region of Puglia. The latter approved a measure of financial relief for the start-up of innovative micro-enterprises (Regional Regulation Nr. 25 of 11.21.2008) .
- Vision mission is to innovate actual vehicles power chain, through power supply systems based on WPT (Wireless Power Transfer).

E-way® system consists of ***an electromagnetic carpet*** with emitters that can ***transfer power*** to a collector placed under the car floor in order to ***charge its batteries WHILE the vehicle is moving***.



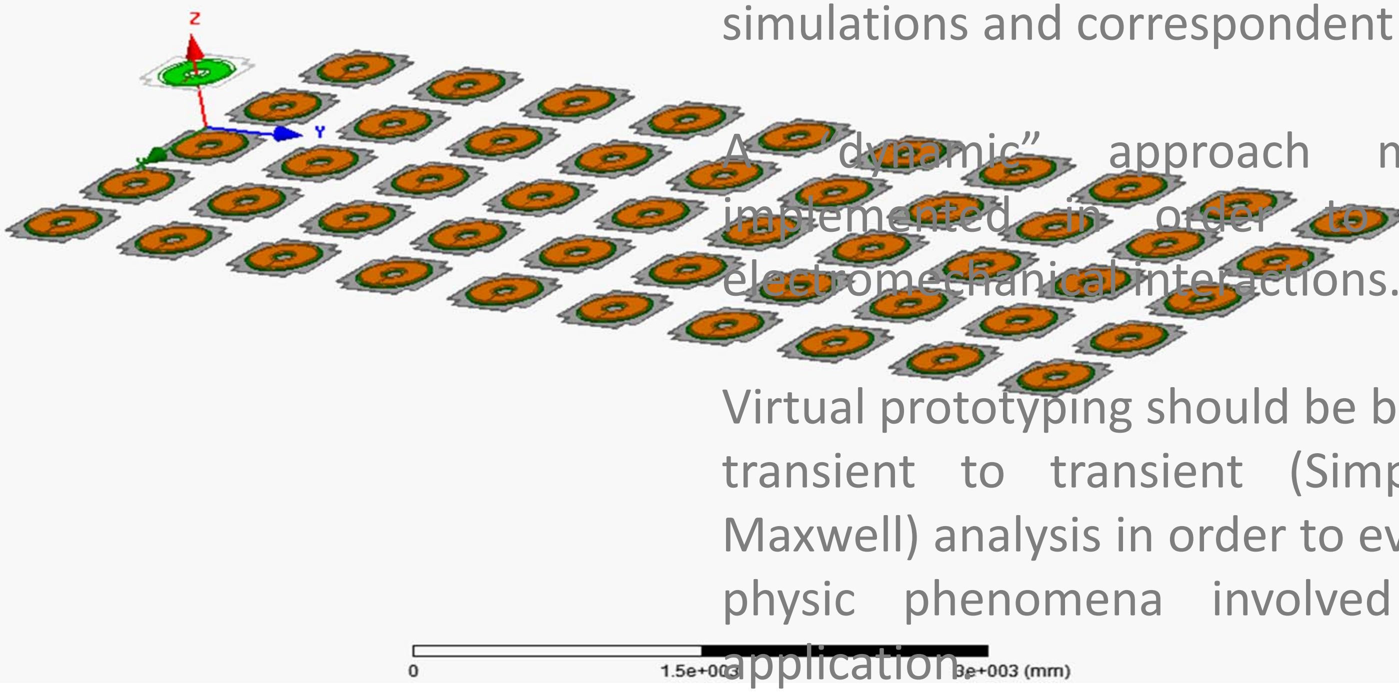
2) Emitters carpet

3) Asphalt layer

5) Car collector

6) Car batteries

Eway®: physical aspects



A more complex model needs to be defined and more parameters can affect simulations and correspondent results.

A "dynamic" approach must be implemented in order to consider electromechanical interactions.

Virtual prototyping should be based on a transient to transient (Simplorer to Maxwell) analysis in order to evaluate all physic phenomena involved in this application.

Eway®: physical aspects

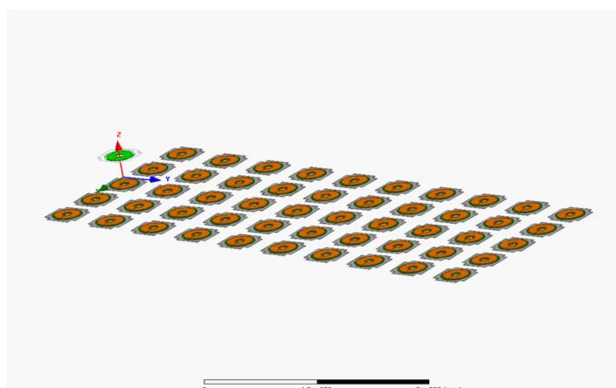
Current densities can be induced on the collector coil as a consequence of the following separated and independent effects:

Motionless coupling

Alternate source currents in the emitters generate a ***time variant magnetic flux*** that concatenates with the collector (even if the latter does not move).

Motion coupling

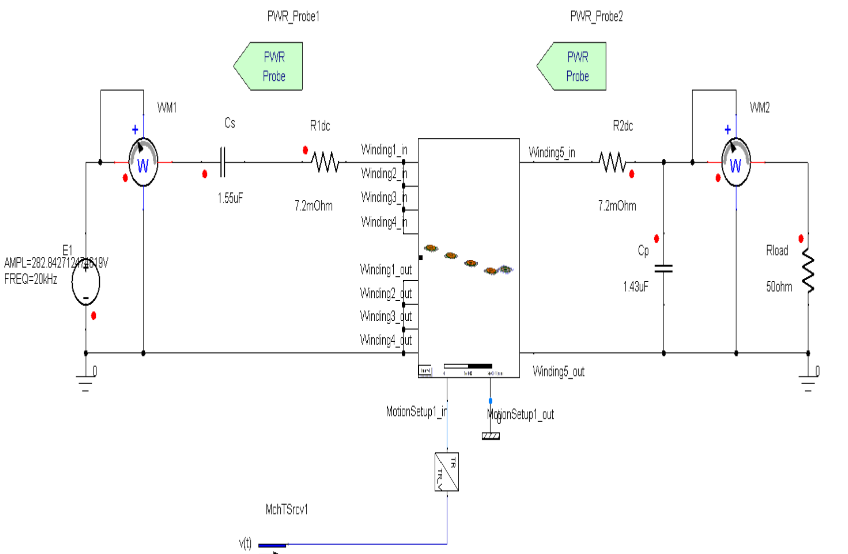
The relative motion between the emitter and the collector concatenates a ***space variant magnetic flux*** and generates the correspondent f.e.m.



Eway®: numerical approach

In order to take in account ***both the time and space variations*** (AC and motion), the numerical analysis should theoretically be carried on through a transient to ***transient with motion*** simulation (Simplorer+Maxwell with motion).

However, in this case, the time stepping for the analysis ***should be fine enough to follow the much higher frequency periodicity*** of the alternate current.



A possible Simplorer scheme for a transient to transient with motion analysis

Eway®: numerical approach

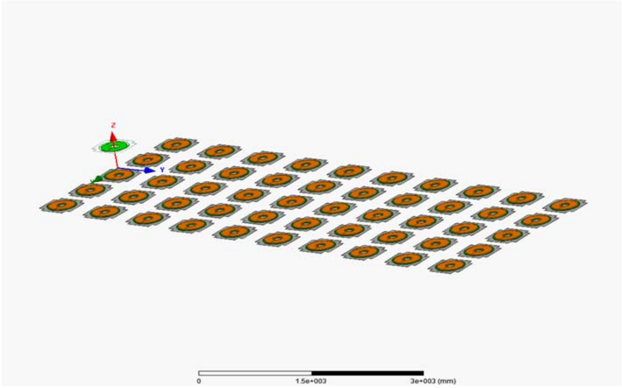
A typical vehicle cruise speed, that is the relative speed between the emitter and the collector carpet, is around 90km/h (25m/sec). This means that ***the induced current frequency is around 25Hz/d_e*** (where d_e is the distance between two consecutive collector rows of the carpet).

If

- emitters and collectors ***have similar size***
- emitters ***are adjacent*** in the carpet
- emitters' alternate current are ***more than 100Hz***

The frequency of the current induced by flux time variations and of the currents induced by flux space variations ***are quite different***.

Physic phenomena are frequency decoupled and can be analyzed through different numerical approaches.

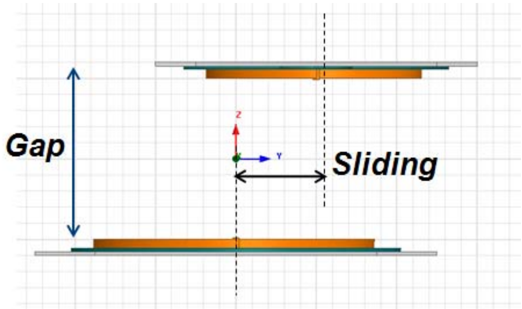


Eway®: numerical approach

Motionless coupling

A parametric, as a function of different position of the collector with respect to the carpet, transient analysis will be performed to evaluate the main stationary system performances.

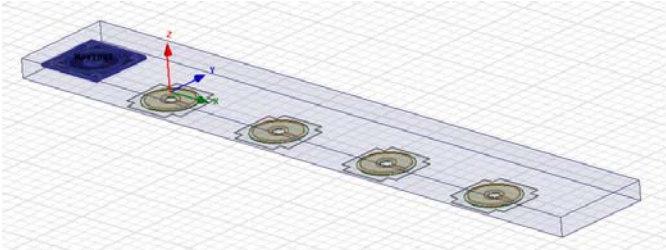
Transient (Simplorer) to transient without motion (Maxwell) system control.



Motion coupling

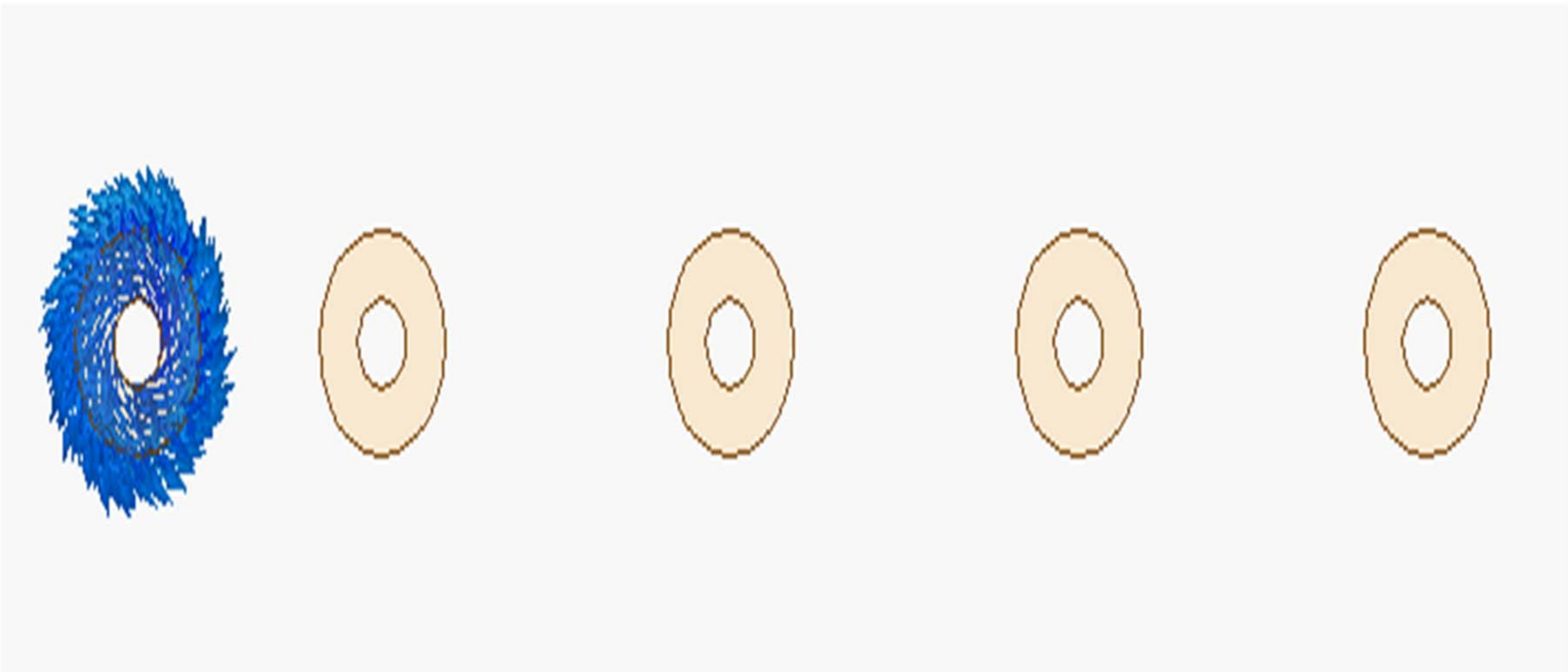
A velocity driven mechanical transient analysis will be performed to evaluate the main dynamic system performances.

Transient (Simplorer) to transient with motion (Maxwell) system control.



Eway®: sample results

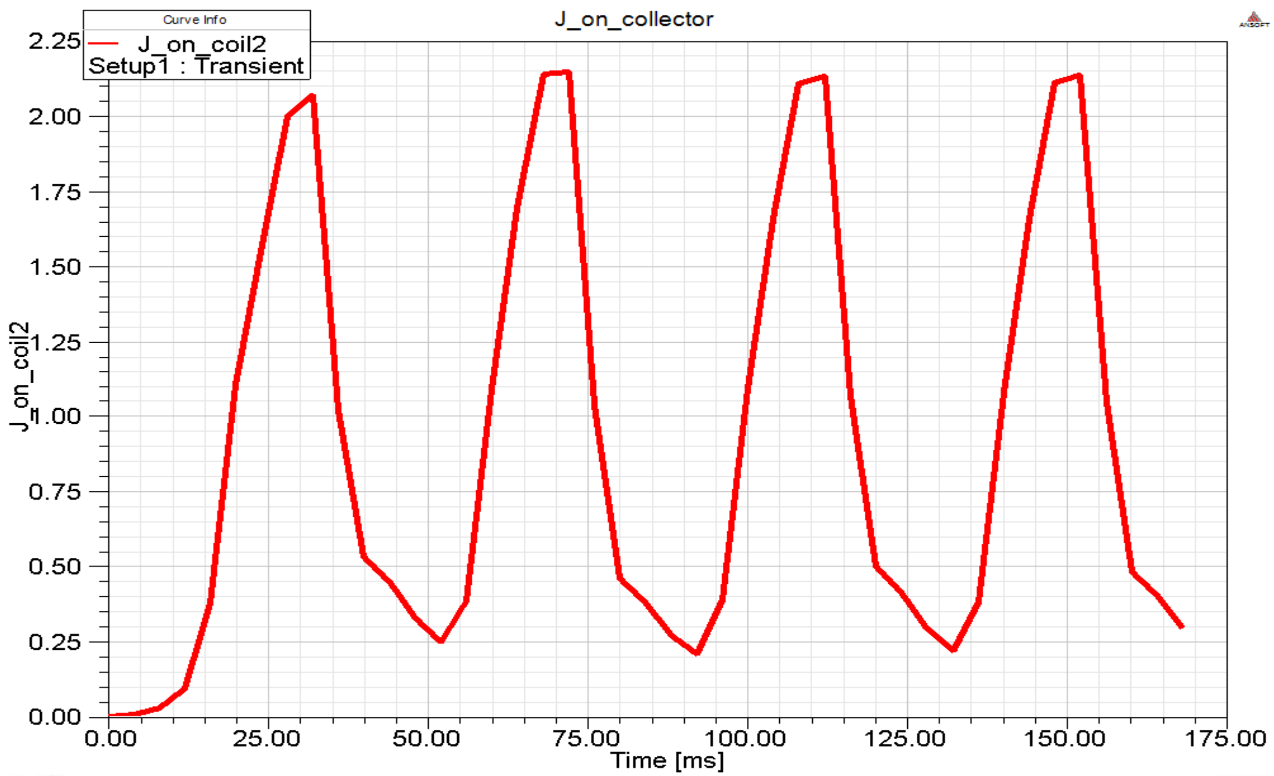
Sample of the induced currents on a collector that moves at 90km/h over an “one row carpet” of emitters placed at one meter distance each other.
Current amplitudes increase as soon as they cross one of the emitters’ section.



Eway®: sample results

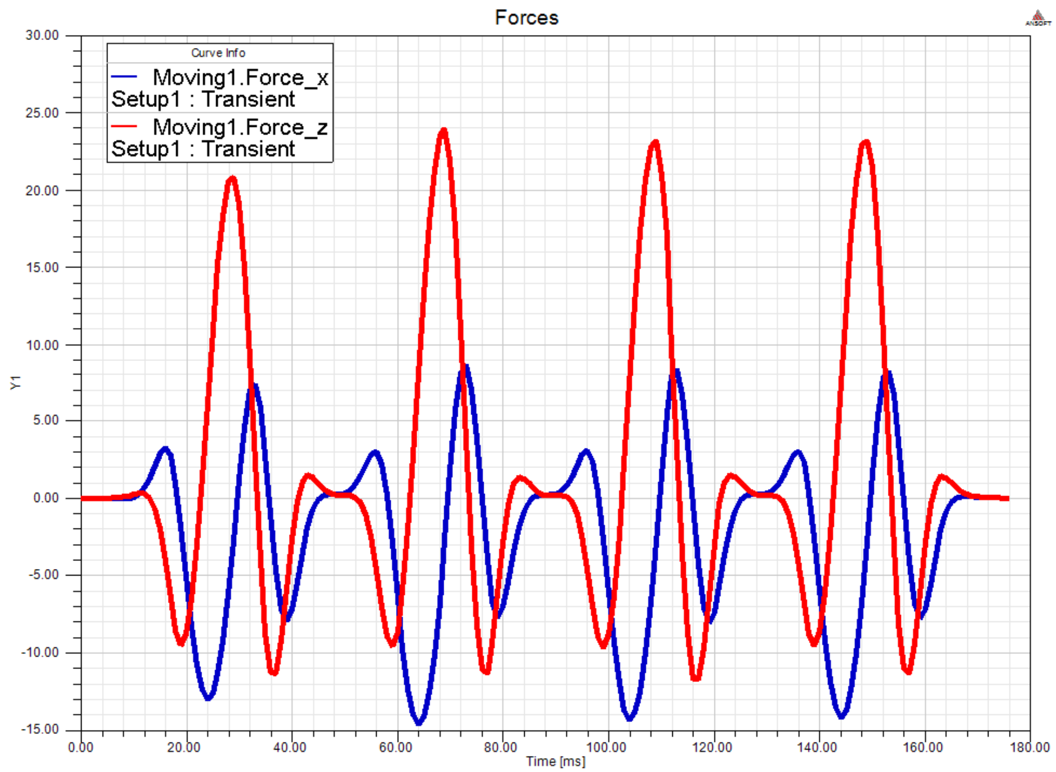
Sample of the induced currents on the collector that moves at 90km/h over an “one row carpet” of emitters placed at one meter distance each other.

Current amplitudes increase as soon as they cross one of the emitters’ section.



Eway®: sample results

Sample of the induced forces on the collector that moves at 90km/h (toward the x direction of the coordinate system) over an "one row carpet" of emitters placed at one meter distance each other.
Current amplitudes increase as soon as they cross one of the emitters' section.



Forces along the x direction are mainly resistive and they oppose to the motion. The correspondent power is dissipated and cannot be collected.
Forces along the z direction do not generate mechanical work but they suggest that some energy can be collected toward batteries. This behavior reflects the alternator working principle, where the primary winding is represented by the planar carpet and the secondary winding is represented by the collector.