PEEC-Based Modeling of EMI Filters Including Parasitics and Geometrical Arrangement of Filter-Elements

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With increasing switching frequency and higher power density of converter systems, electromagnetic interference (EMI) problems introduce additional design constraints that should be considered in the earliest system design stages. To comply with EMC standards, the conducted and radiated emission levels generated by power electronic systems have to be controlled, necessitating the use of EMI filter circuits. Thus, EMI filter components have to be examined in detail, including their high-frequency behaviour in combination with PCB placement and parasitic couplings. An optimised arrangement of filter components is required to fulfil EMI specifications with minimum constructional effort. In order to speed up EMI filter design, nowadays mostly based on a trial-and-error process, virtual prototyping and accurate electromagnetic simulators are required.

The Partial Element Equivalent Circuit (PEEC) method is a well-suited approach for the numerical simulation of EM field problems in electrical circuits such as EMI filters, power converters, PCBs, etc. The PEEC method has the ability to model typical power electronic structures with lower 3D-mesh requirements than Finite Element Method (FEM)-based approaches, speeding up the modelling process and insuring acceptable accuracy at the same time. The conventional PEEC approach has to be extended for EM modelling in the presence of magnetic materials in order to establish a full 3D PEEC modelling environment. Therefore, the coupled PEEC and Boundary Integral Method (BIM) approach was developed to address the EM modelling problem of magnetic toroidal cores which are frequently used in EMI filters. The developed PEEC-BIM coupled method was verified by inductor impedance and near EM-field measurements. Good agreement between measurement and the PEEC-based simulation results is achieved for a wide frequency range.

It is shown that the presented PEEC method can give a comprehensive understanding of EM behaviour of EMI filter inductors and capacitors, taking their geometrical and material properties into account. Furthermore, it enables the modelling of full EMI filter structures including both parasitic and effects originating from the mutual coupling and the interconnection of filter elements. The simulation results are verified by experimental measurements of different single-phase EMI filters (Fig. 1).

The final goal is to develop a fast 3D CAD PEEC-based virtual prototyping platform (Gecko-EMC) which enables the prediction of the electromagnetic behaviour of power electronic converter systems with high accuracy.

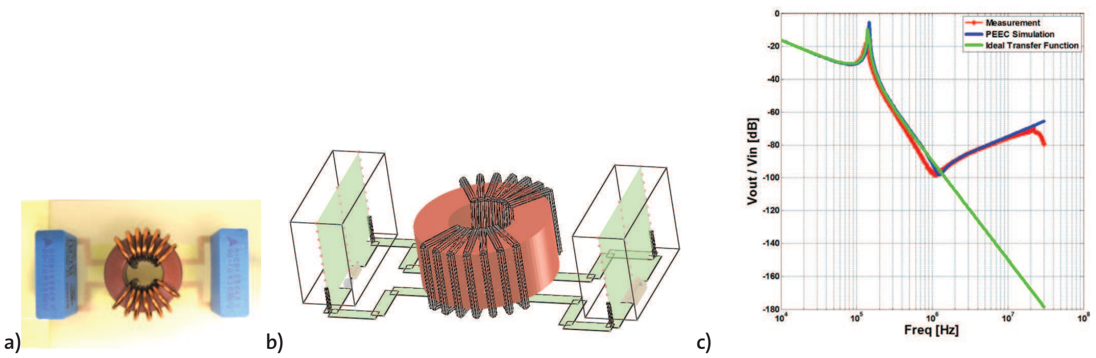

Fig. 1. a) C-L-C filter structure. **b)** Gecko-EMC model of the C-L-C filter structure. **c)** Measurements vs. PEEC simulation of EMI filter transfer function.

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Main Objectives

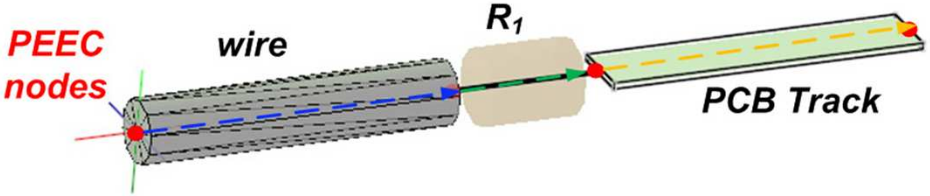
- Increasing Switching Frequency, Reduced Size of Power Converter Systems → EMC requirements → EMI Filter design
- 3D EM Simulation of Passive EMI Filter Components (R, L, C) and of their Mutual Coupling
  - *EM simulation of EMI filter components (frequency domain)*
  - *EM simulation of interconnections, ground planes and shields*
  - *EM simulation of EMI filter circuits including parastics, mutual coupling effects AND 3D geometrical arrangements of EMI filter components*
- Partial Element Equivalent Circuit (PEEC)-based Virtual Prototyping Platform: Gecko EMC

PEEC-Based Modeling Approach

- **Coupling EM Problems and Electrical Circuits**

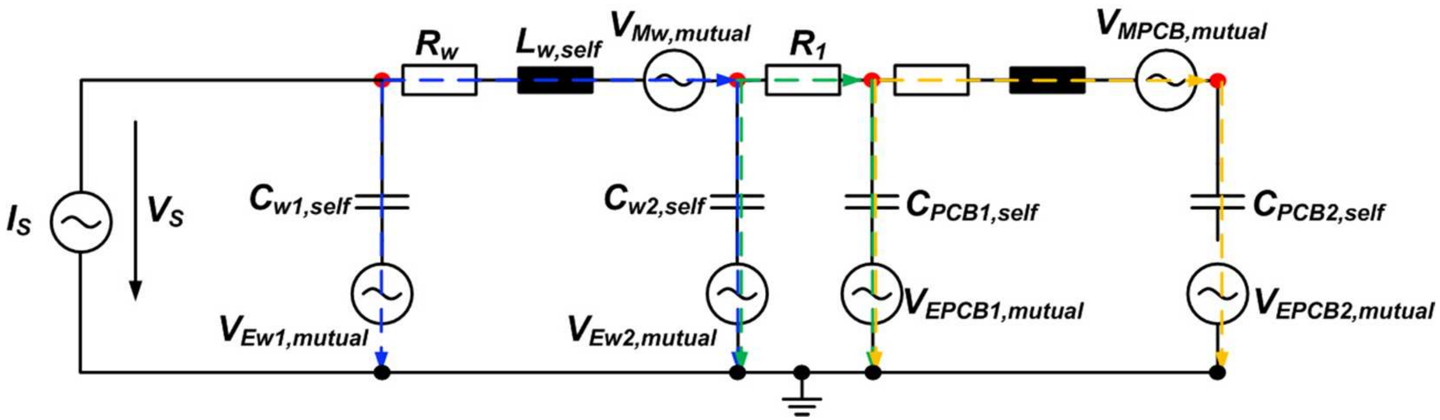
Circuit Element: resistor R_1

PEEC cells: wire, PCB Track



$$V_k = R_k I_k + \sum_{i=1}^{N_J} L_{ik} \frac{dI_i}{dt} + \sum_{i=1}^{N_S} P_{ik} Q_i$$

$$\begin{bmatrix} \mathbf{A} & -(\mathbf{R} + j\omega \mathbf{L}) \\ (j\omega \mathbf{P}^{-1} + \mathbf{Y_L}) & \mathbf{A}^T \end{bmatrix} \begin{bmatrix} \mathbf{V} \\ \mathbf{I} \end{bmatrix} = \begin{bmatrix} \mathbf{V_S} \\ \mathbf{I_S} \end{bmatrix}$$



PEEC-Boundary Integral Method (BIM)

- Presence of Magnetic Material : Magnetization M
- Homogenization/Linearization of Magnetic Cores : $\mathbf{M}=(\mu_r-1)\mathbf{H}$
- Magnetic Surface Modelling : Boundary Integral Method (BIM)
    - *Boundary condition for H_t must be satisfied at magnetic surface S_m with normal vector n_{rm} : PEEC-BIM coupled method*
    - *Fictitious Magnetic Surface Current Approach: K_m*

$$\mathbf{A_M}(\mathbf{r})=\frac{\mu_0}{4\pi}\int_{V_m}\frac{\nabla_{\mathbf{r_m}}\times\mathbf{M}(\mathbf{r_m})}{|\mathbf{r}-\mathbf{r_m}|}dV_m+\frac{\mu_0}{4\pi}\oint_{S_m}\frac{\mathbf{M}(\mathbf{r_m})\times\mathbf{n}(\mathbf{r_m})}{|\mathbf{r}-\mathbf{r_m}|}dS_m$$

$$\mathbf{J_m}(\mathbf{r_m})=\nabla_{\mathbf{r_m}}\times\mathbf{M}(\mathbf{r_m})$$

$$\mathbf{K_m}(\mathbf{r_m})=\mathbf{M}(\mathbf{r_m})\times\mathbf{n}(\mathbf{r_m})$$

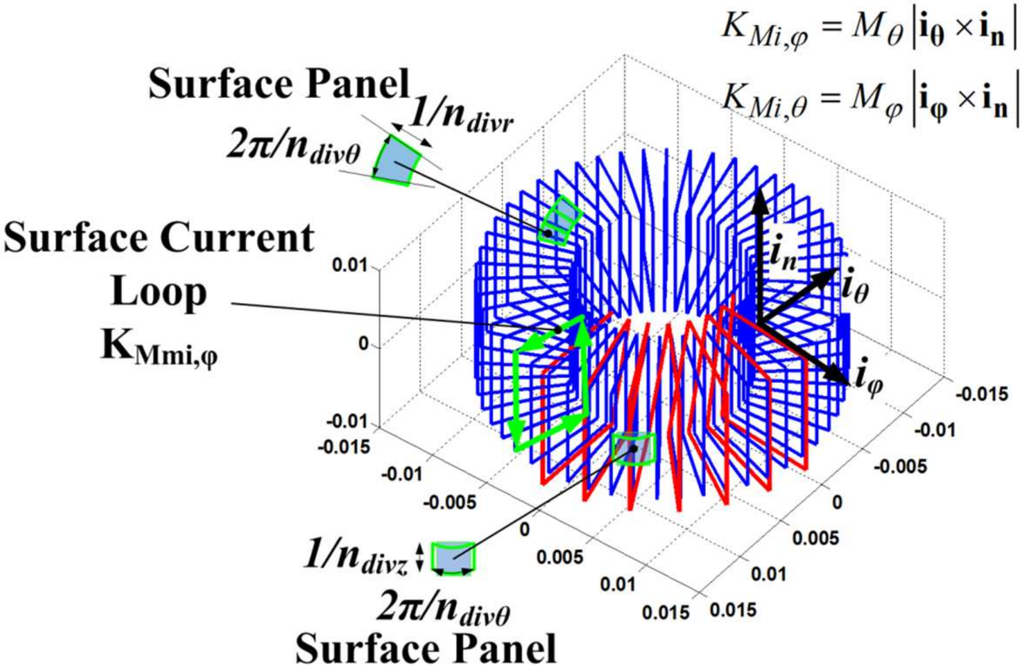
$$V_k=R_kI_k+\sum_{i=1}^{N_J}L_{ik}\frac{dI_i}{dt}+\sum_{i=1}^{N_S}P_{ik}Q_i+\boxed{\sum_{mi=1}^{N_M}L_{Kmi,k}\frac{dK_{mi}}{dt}}$$

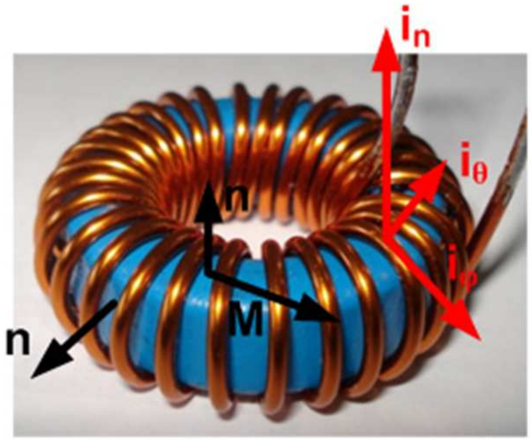
$$\mathbf{B}=\nabla\times\mathbf{A_M}$$

$$[\mathbf{H_{tot}}(\mathbf{r}_m^{air})-\mathbf{H_{tot}}(\mathbf{r}_m^{core})]\times\mathbf{n}(\mathbf{r_m})=0 \longrightarrow \begin{bmatrix}\mathbf{A} & -(\mathbf{R}+j\varpi\mathbf{L}) & j\varpi\mathbf{L_M}\\ (j\varpi\mathbf{P}^{-1}+\mathbf{Y_L}) & \mathbf{A}^T & \mathbf{0}\\ \mathbf{0} & \lambda_{\mathbf{MI}} & \alpha_{\mathbf{MM}}\end{bmatrix}\begin{bmatrix}\mathbf{V}\\ \mathbf{I}\\ \mathbf{K_M}\end{bmatrix}=\begin{bmatrix}\mathbf{V_S}\\ \mathbf{I_S}\\ \mathbf{0}\end{bmatrix}$$

PEEC-BIM Modeling of Magnetic Core

- **Example: Toroidal Inductor**

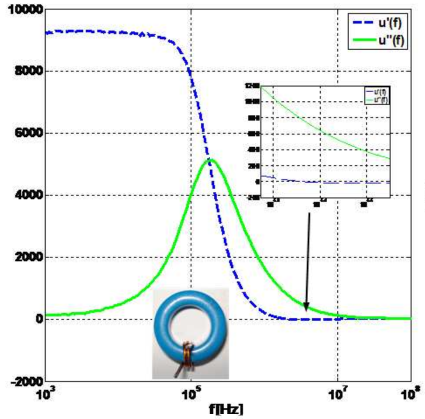




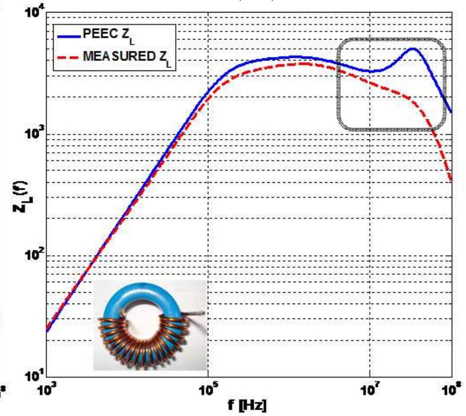
PEEC-BIM Modeling of EMI Filter Inductors (1)

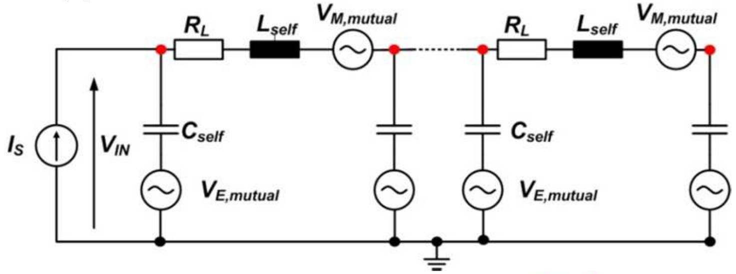
- **Input parameters**
  - *Magnetic core properties:*
    - Nanocrystalline: VITROPERM 500F
    - Nanophy (ArcelorMittal)
    - Ferrite
    - Iron-powder core material
  - *Permeability curves*
    - Datasheets
    - Measurements
  - *Winding properties*
- **Impedance : $Z_L = V_{IN}/I_S$**
- **Stray (leakage) field**
  - *Post-processing: H-field*

$\mu(f)=\mu_{re}(f)-j\mu_{im}(f)$



$Z_L\ (f\ )= R_L + j\ X_L$





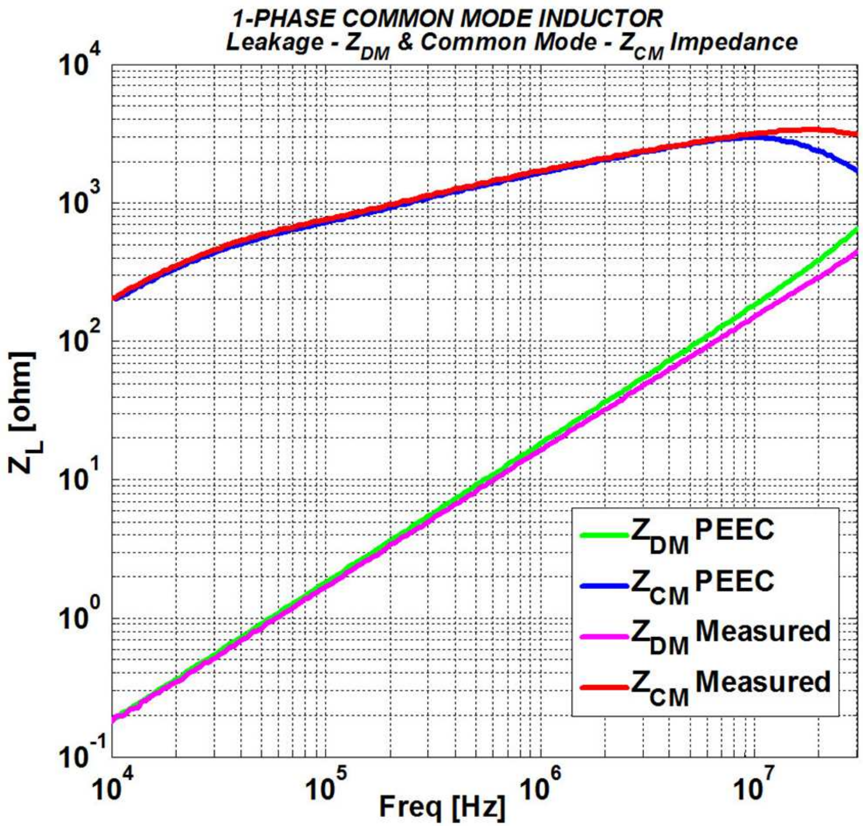
PEEC model of N-Turns Winding Magnetic Inductor

PEEC-BIM Modeling of EMI Filter Inductors (2)

- Common Mode (CM) / Differential Mode (DM) Inductors

DM Inductor: Micrometals T94-26 Iron Powder Core, 21 turns, ϕ_w=1.5mm

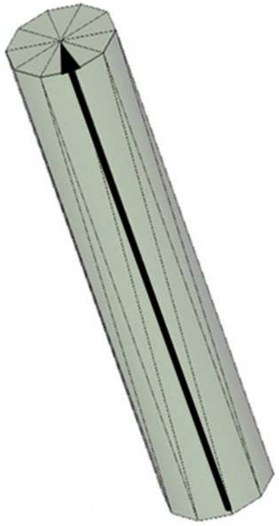
CM Inductor: Air/ VAC Vitroperm 500F Nanocrystalline Core, 2x7 turns, ϕ_w=1.5mm

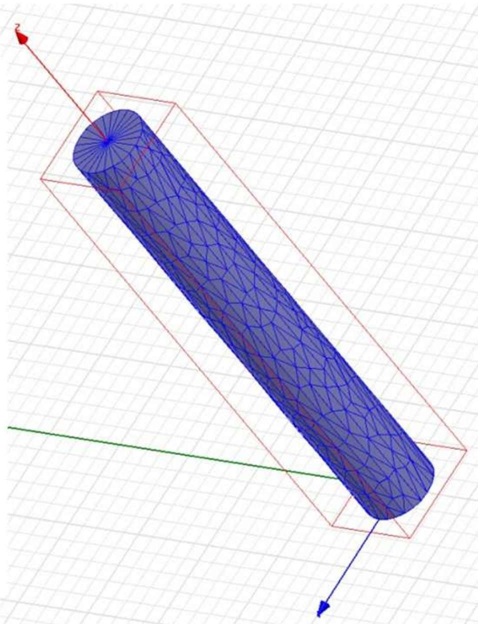


PEEC-BIM vs. FEM (Maxwell 3D)

- Example: Wire

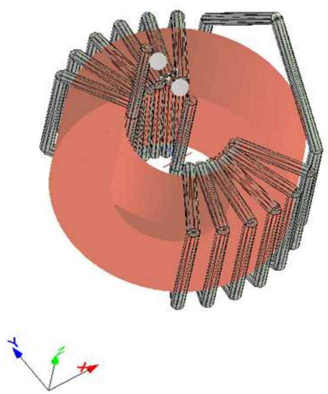
PEEC (Gecko EMC) FEM (Maxwell 3D)

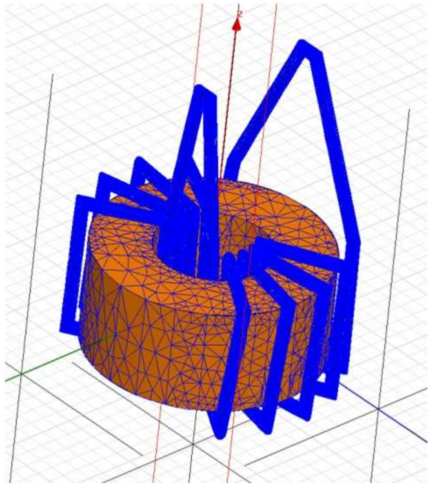




- Example: Single-Phase EMI Filter Inductor
  - *Gecko EMC: approx. 4 min*
  - *Maxwell3D: approx. 20 min*

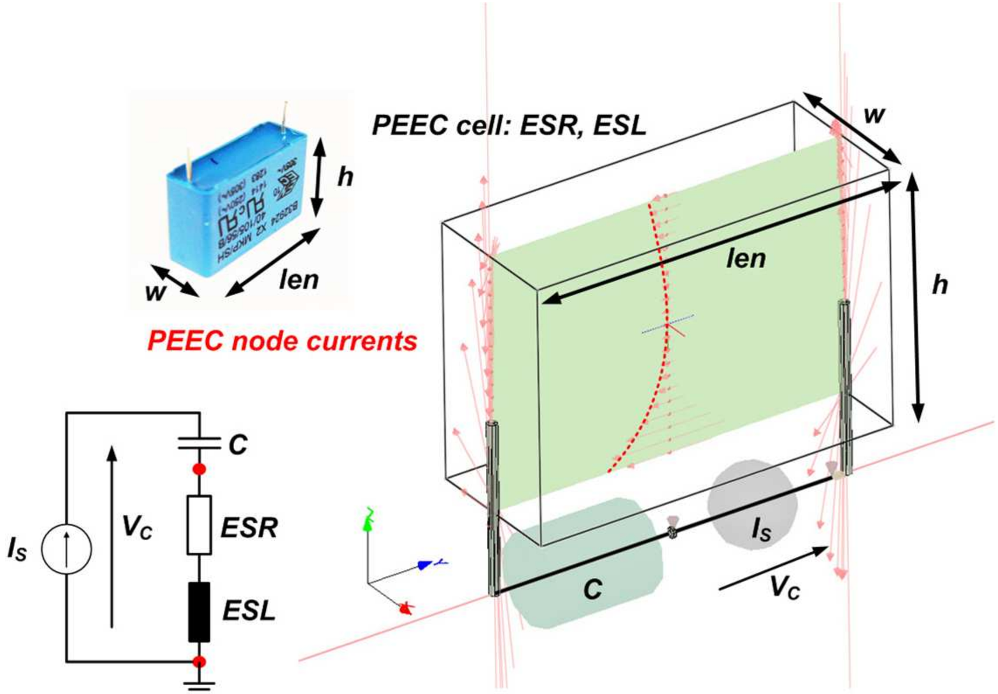
PEEC (Gecko EMC) FEM (Maxwell 3D)





PEEC Modeling of EMI Filter Capacitors

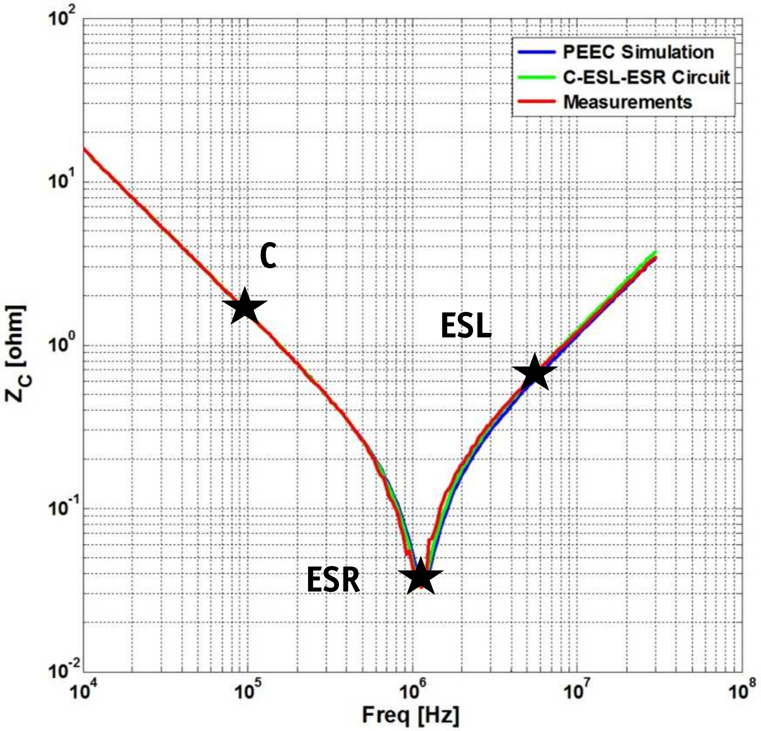
- **X/Y Foil Capacitors – 3D Model**
  - *ESL, ESR determine geometrical/conductivity properties of PEEC cell and length of connectors*
  - *Current distribution within PEEC cell*
- $Z_C = V_C / I_S$



Ref [5, 6, 8]

PEEC Modeling of EMI Filter Capacitors

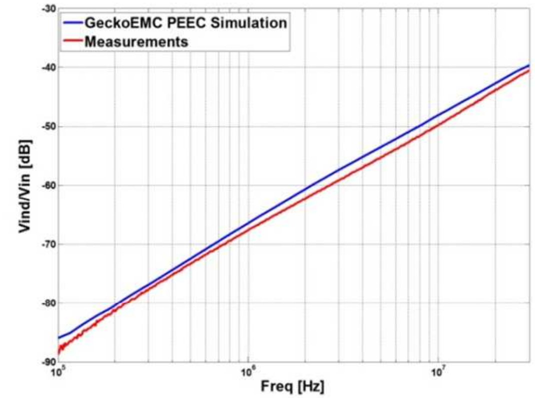
- **X/Y Foil Capacitors – Impedance**
  - *ESL, ESR determine geometrical/conductivity properties of PEEC cell and length of connectors*
  - *Current distribution within PEEC cell*
- $Z_C = V_C / I_S$

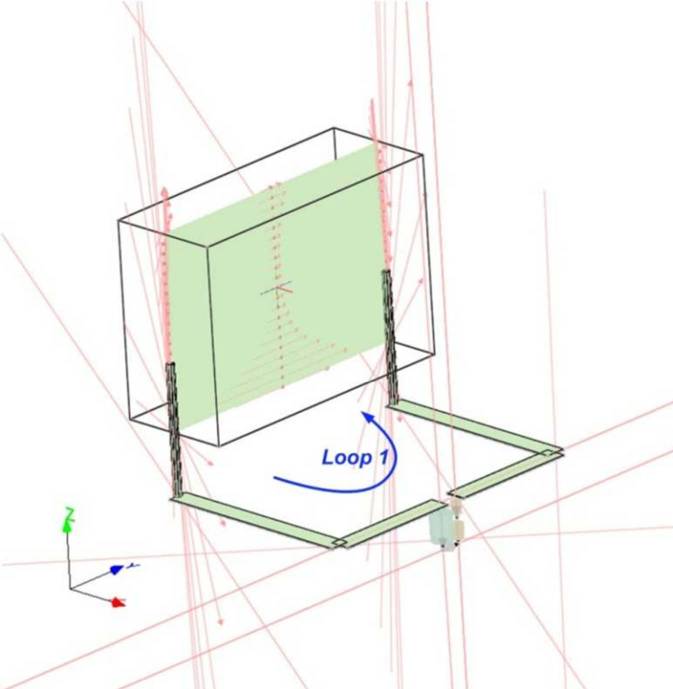


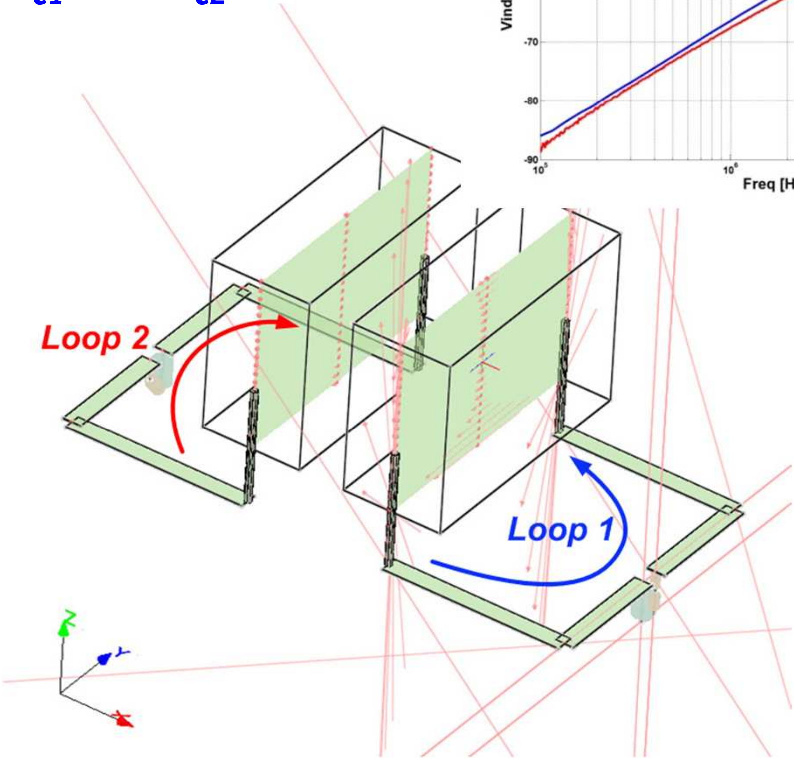
Ref [5, 6, 8]

PEEC Modeling of EMI Filter Capacitors

- **Mutual Coupling:**
  - *Loop 1 : PCB Tracks – ESL_{C1}*
  - *Loop 1, 2 : PCB Tracks – ESL_{C1} – ESL_{C2}*

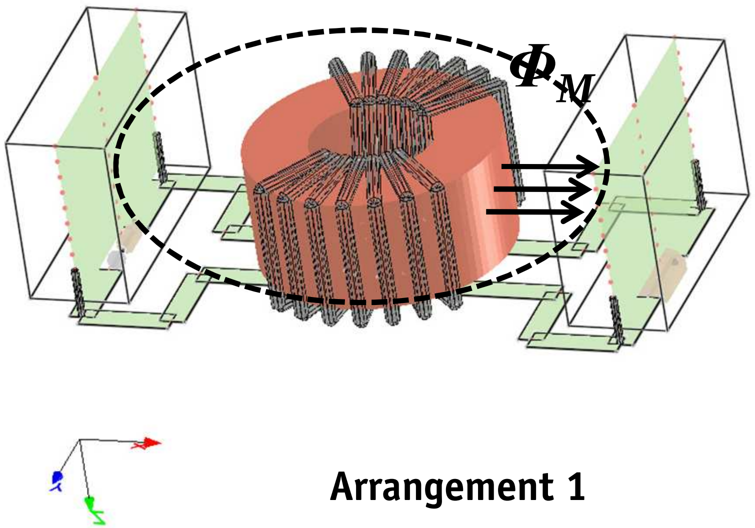




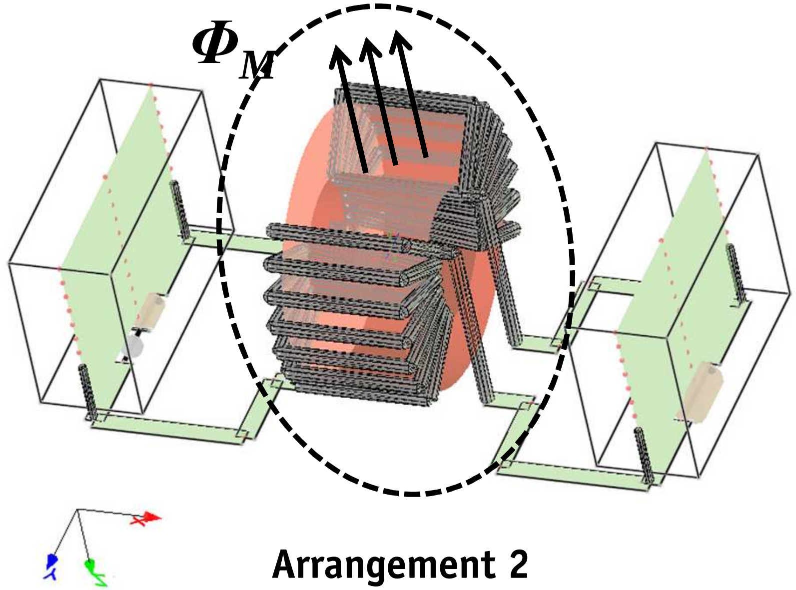


PEEC-based Modeling of EMI Filter

- **Single-Phase Single-Stage C-L-C Filter Structure:**
  - *Inductors/Capacitors/PCB Tracks Modelling*
  - *EMI Filter Components Arrangements on PCB*
  - *Multilevel Prediction (taking into account different effects)*

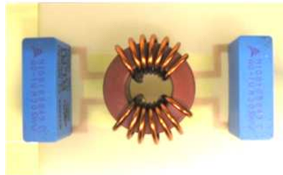


Arrangement 1

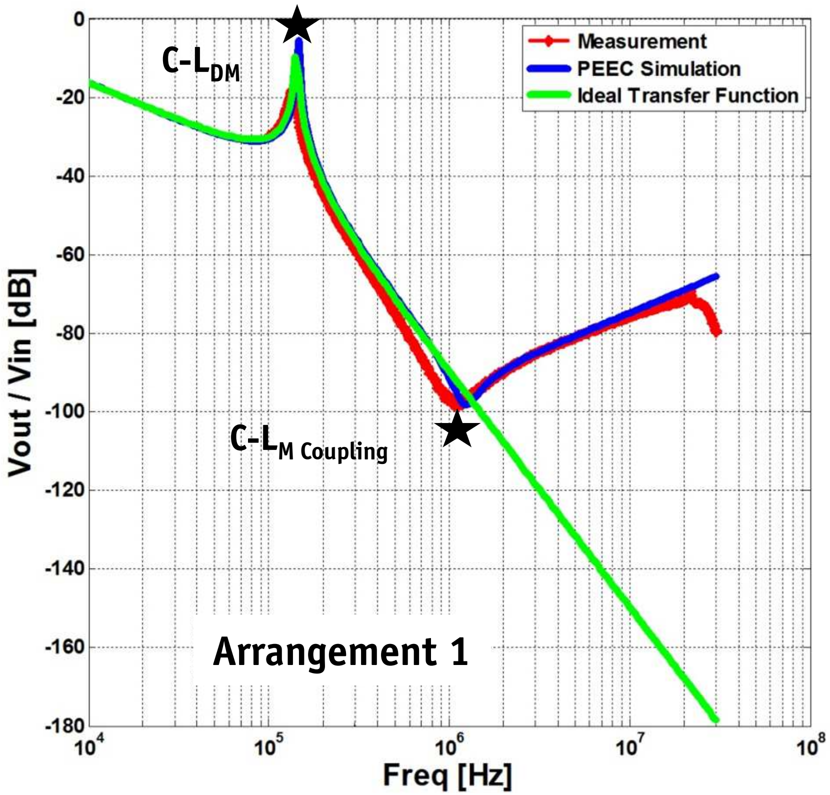


Arrangement 2

PEEC-based Modeling of EMI Filter

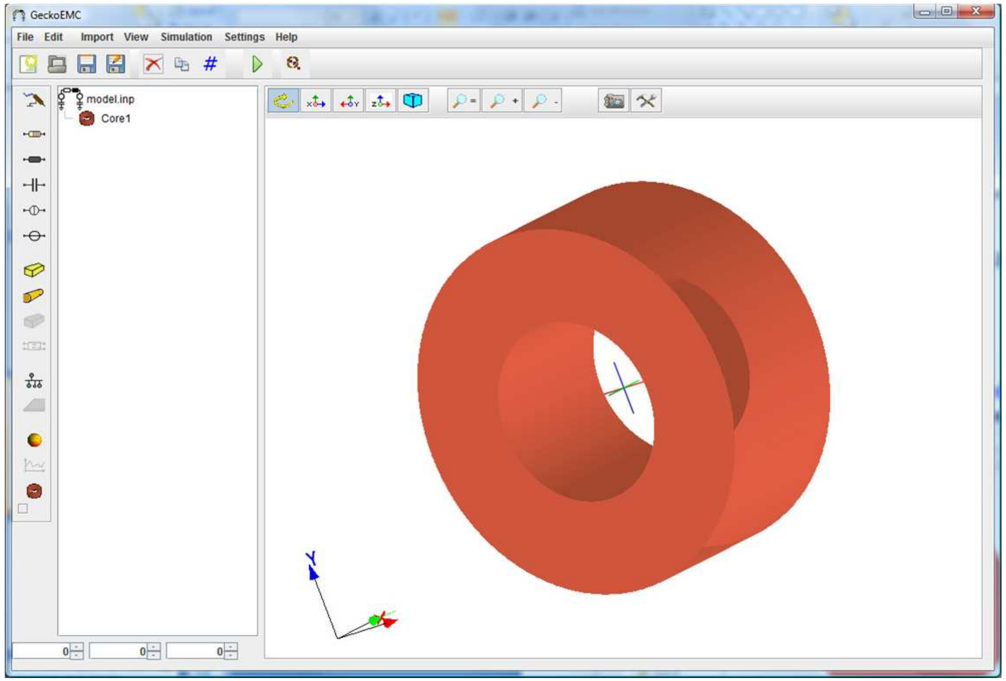


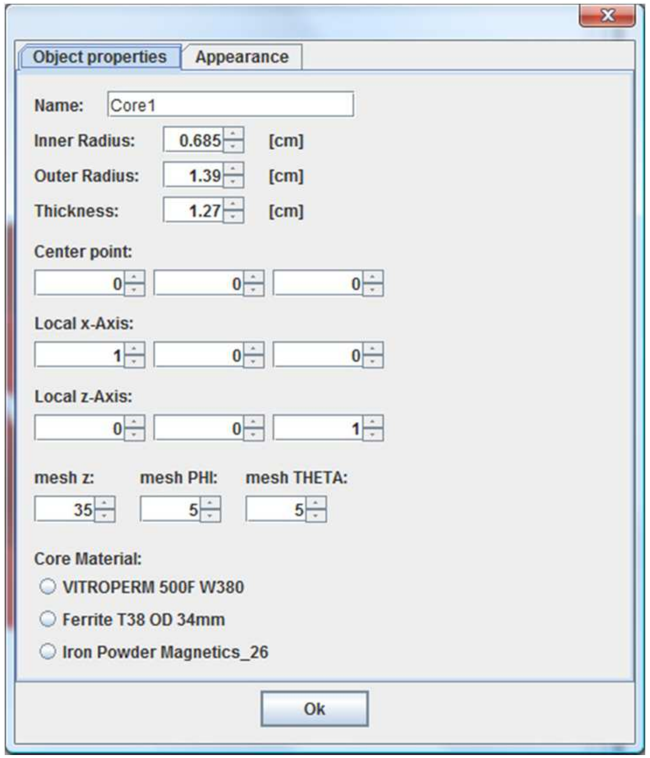
- PEEC vs. Measurements: C-L-C Filter



Virtual Prototyping – Gecko EMC Software Tool (1)

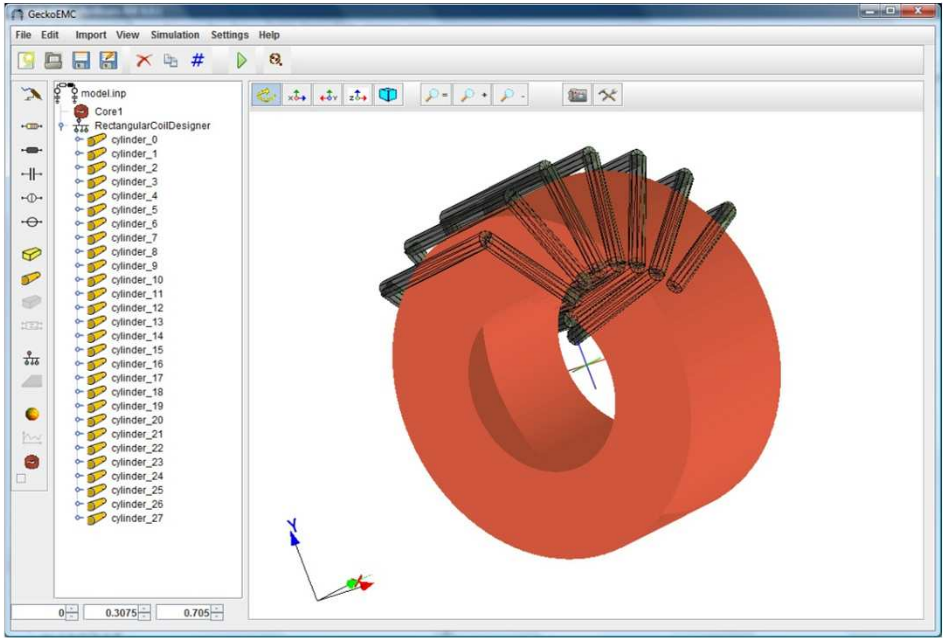
- **Inductor Model**
  - *Core properties (design parameters input)*

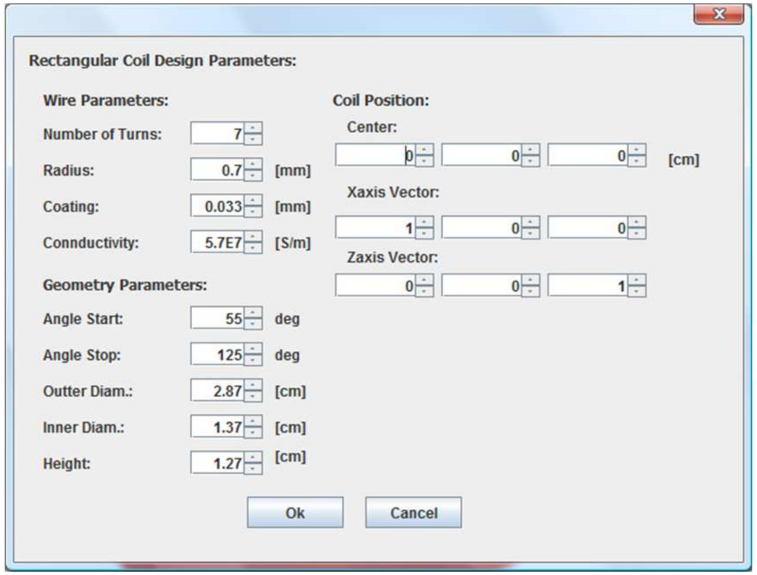




Virtual Prototyping – Gecko EMC Software Tool (2)

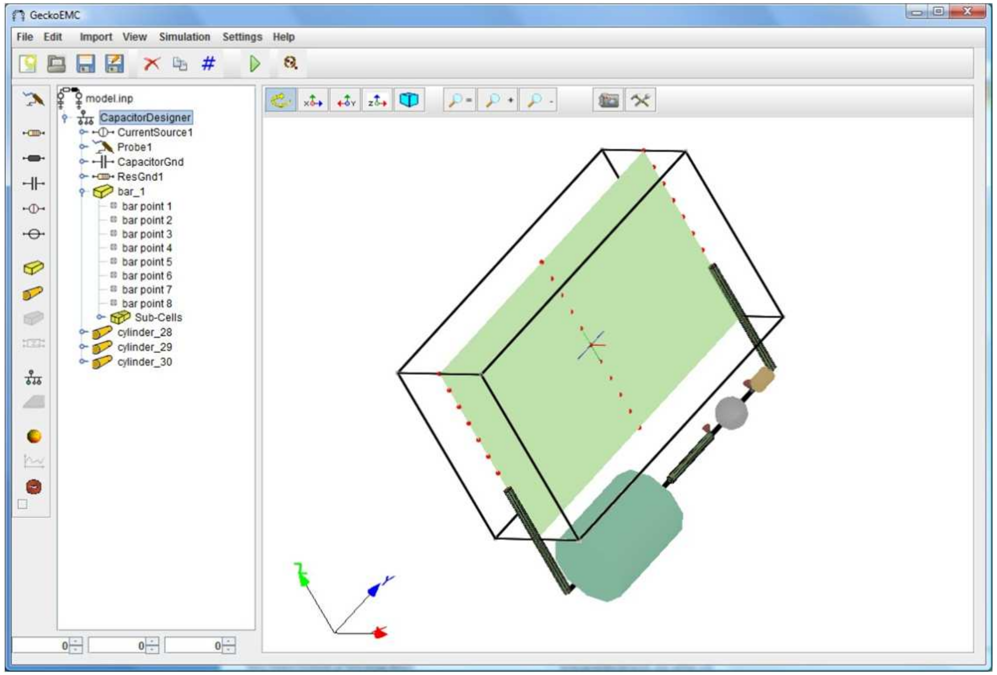
- **Inductor Model**
  - *Coil properties (Import → Rectangular Coil Design)*

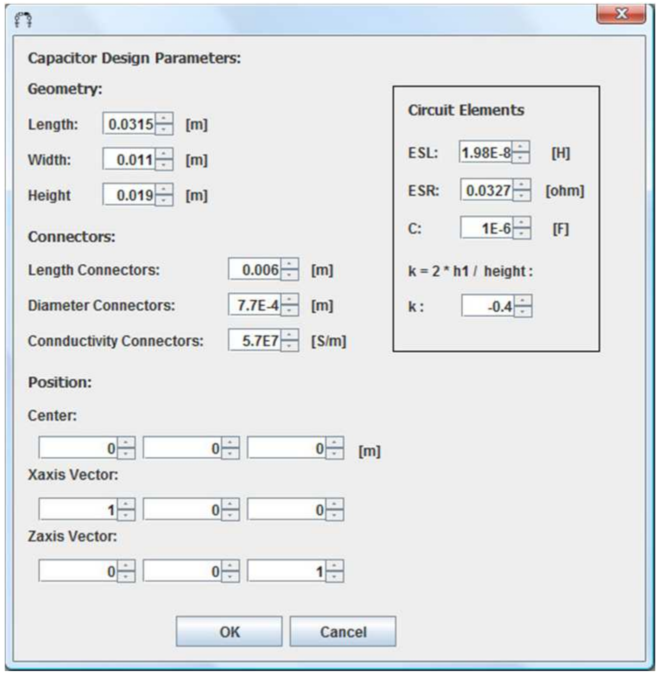




Virtual Prototyping – Gecko EMC Software Tool (3)

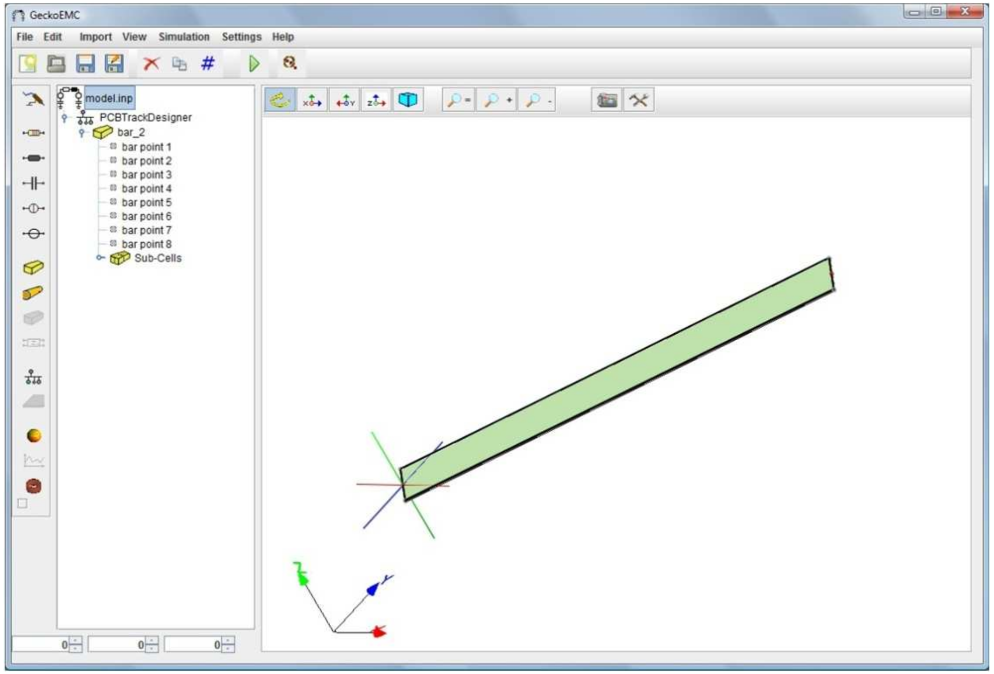
- **Capacitor Model**
  - *Capacitor properties (Import → Capacitor Design)*

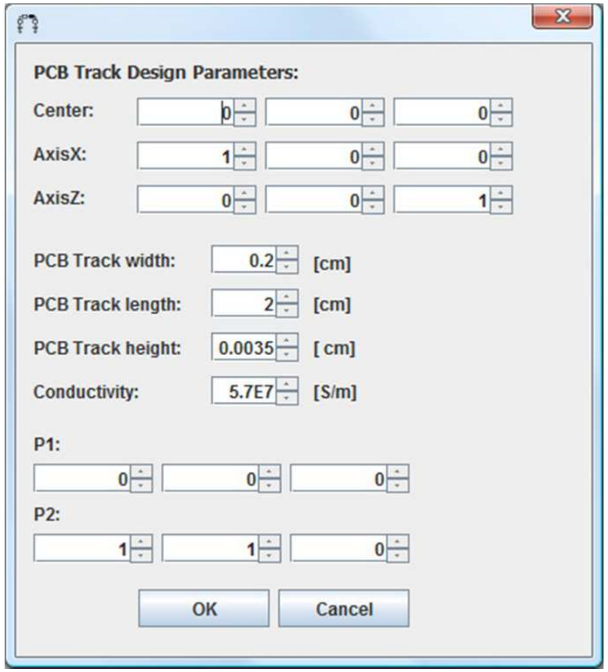




Virtual Prototyping – Gecko EMC Software Tool (4)

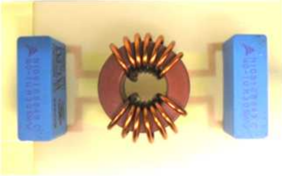
- **PCB Tracks Model**
  - *PCB Track properties (Import → PCB Track Design)*

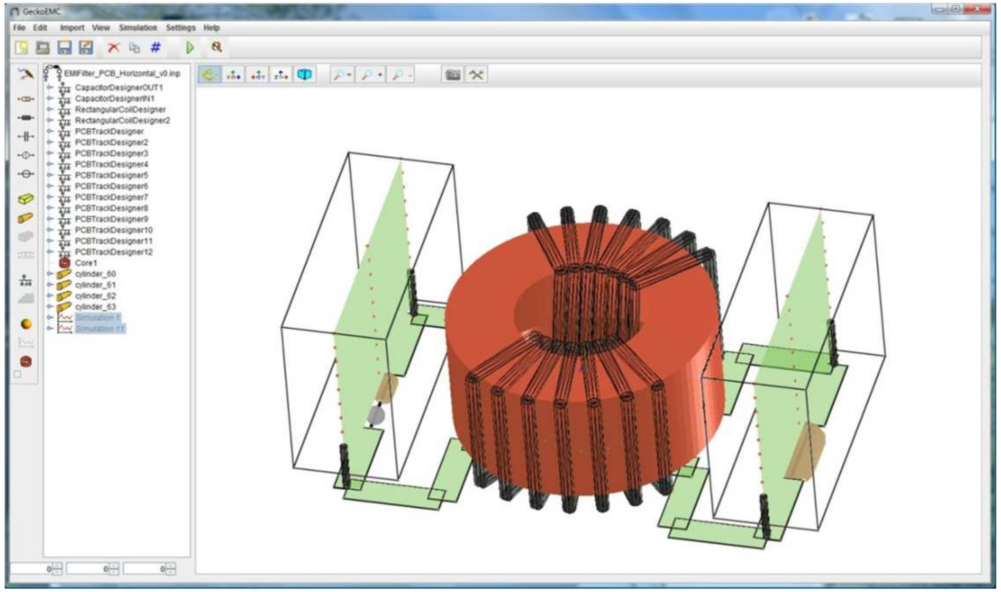


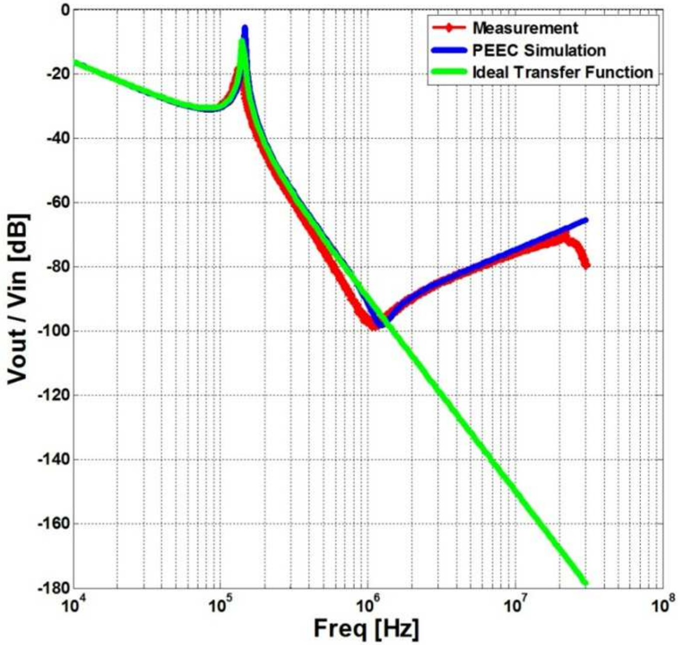


Virtual Prototyping – Gecko EMC Software Tool (5)

- **EMI Filter Model**
  - *Frequency domain: (f_{min} , f_{max}), N points*

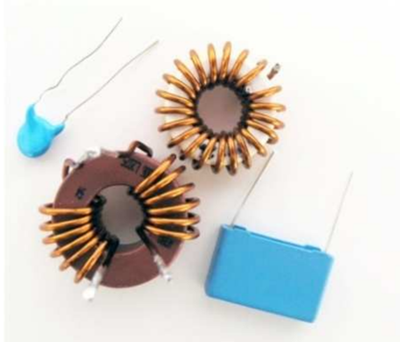






Summary

- **PEEC-Based Approach Enables Modelling of High Frequency Behaviour of EMI Filter Components**
  - *EM mutual coupling and parasitic effects, PCB placement*
  - *Magnetic core modelling via PEEC-BIM coupled method*
- **3D PEEC-Based CAD Tool (Gecko EMC)**
  - *Virtual EMI Filter Design → Finding optimal PCB arrangement of filter components and PCB layout*



- **Further Applications**
  - *Bus-bars, transformer leakage inductance etc.*
  - *Prediction of EM properties of power electronics converter systems with sufficient accuracy*

Thank You !

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