High-Fidelity, High-Performance Algorithms for Intra-System EMI Analysis of IC and Electronics

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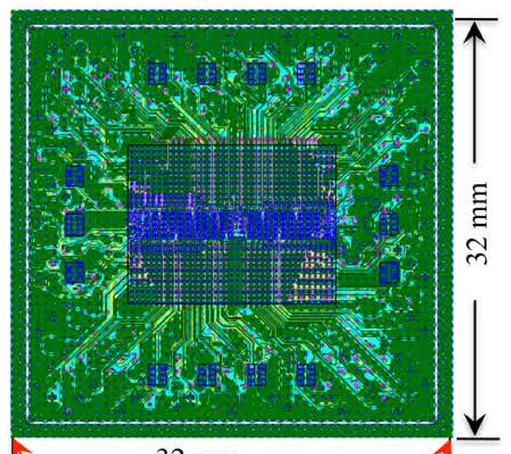
Problem Statement

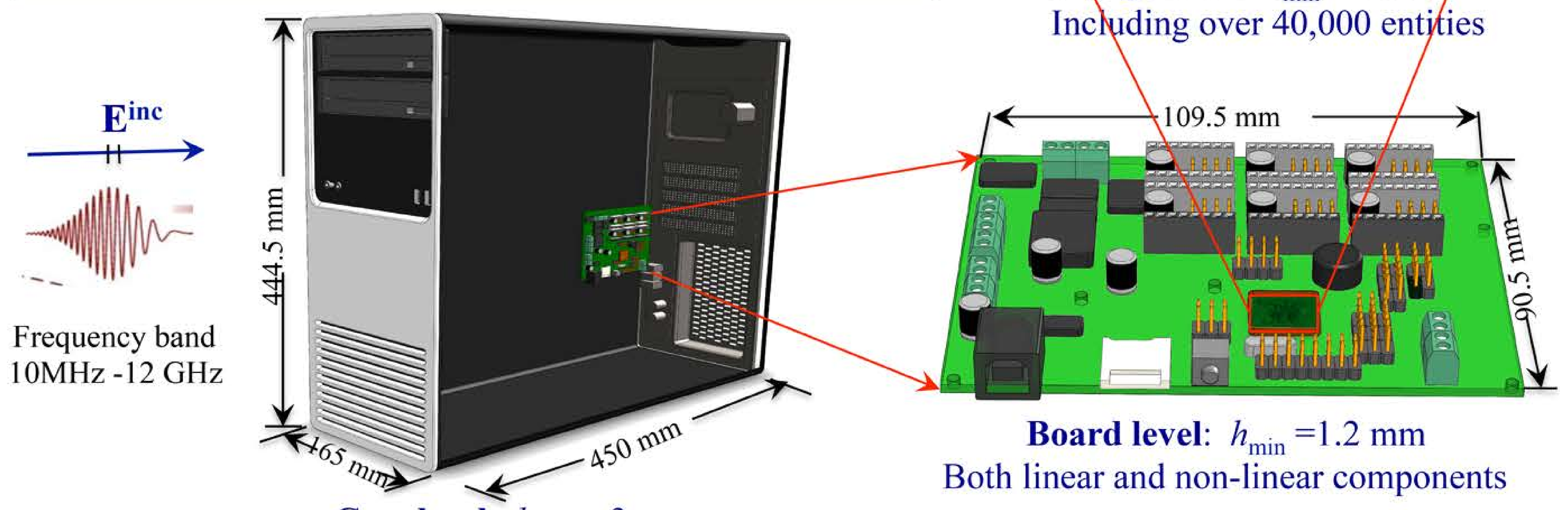
➢ Intra-System EMI/EMC of IC and Electronics

Technical Challenges

- Geometrical Characteristics
  - High-definition complex platform
  - Heterogeneous integration
  - Multi-scale modeling (structures, materials, time)
- Computational Characteristics
  - Highly resonant structures and physics
  - Non-linear component & phenomena
  - Multi-physics analysis
- Engineering Aspects
  - Reliability modeling & uncertainty qualification
  - Reconfigurable modeling and simulation



Package level: h_{min} = 0.008 mm
Including over 40,000 entities

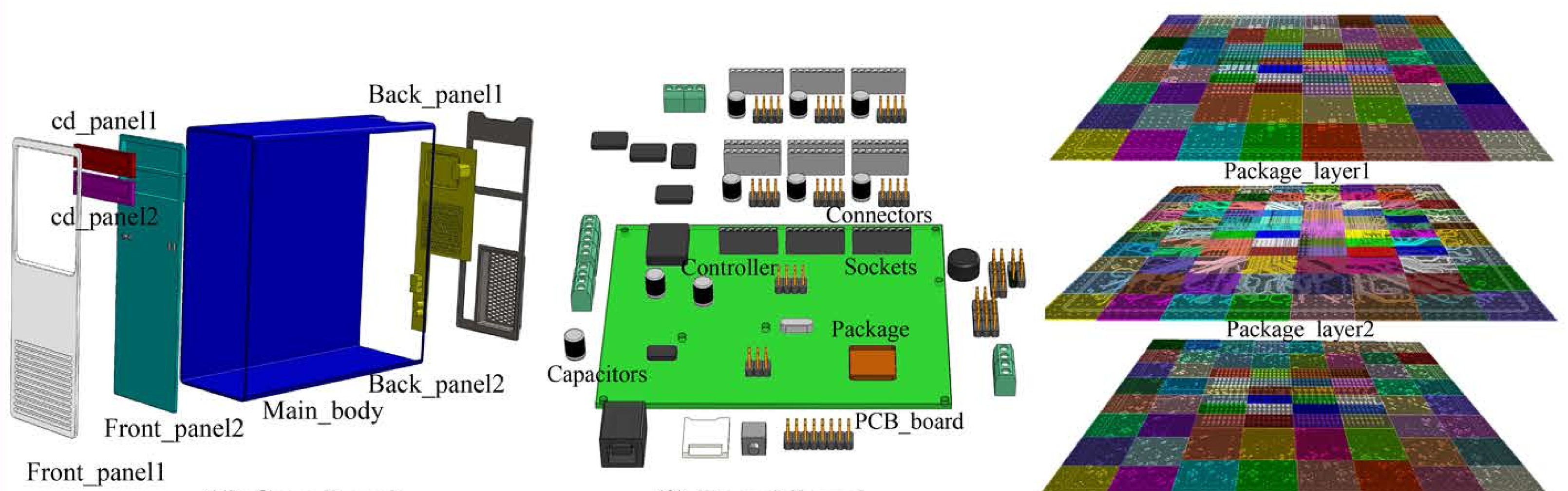


Board level: h_{min} =1.2 mm
Both linear and non-linear components

Case level: h_{min} = 3 mm

Contribution & Overview

➢ Scalable computational algorithms on concurrent triple-scale first-principles simulation for electronics ranging from IC package, board to system levels



(1) Case Level (Solver: IEDG) [Z. Peng et al, 2015,2016]

(2) Board Level (Solver: MT-CFIE) [Z. Peng et al, 2015]

(3) Package Level (DG-FEM) [Z. Peng et al, 2012, 2014]

Key mathematical ingredients:

- GA-OSM-DDM: Geometry-aware domain decomposition method with optimized Schwarz Preconditioning
- Hybrid solution strategy: Schwarz preconditioned DDM system matrix with fast direct solver for local sub-domain matrices
- Multi-scale analysis: An augmented multi-region multi-solver DD method via hierarchical skeletonization

Technical Ingredients

1) High-performance DD method for parallel computing

- Perform for $p = 1, 2, \cdots$ the following subdomain iteration

$$\mathbb{A}_m \mathbf{u}_m^p = \mathbf{y}_m^{\mathrm{inc}} \quad \text{in } \Omega_m$$

$$\mathcal{B}_{mn}\{\mathbb{T}_m \mathbf{u}_m^p\} = \mathcal{B}_{mn}\left\{\mathbb{T}_n \mathbf{u}_n^{p-1}\right\} \quad \text{on } \Gamma_{mn}, \forall \Gamma_{mn} \in \Gamma_m$$

- Γ_{mn} is for the interface between Ω_m and Ω_n
- $\mathcal{B}_{mn}$ are tangential, possibly pseudo-differential interface operator on Γ_{mn}
- Define trace operator $\mathbb{T}_m := (\gamma_D^m \quad \gamma_N^m)^T$, Dirichlet and Neumann traces
- Tangential field continuity enforced via transmission conditions

Convergence Results

Convergence analysis using the TE-TM decomposition, $\Omega_1 = (-\infty, 0) \times \mathbb{R}^2$ and $\Omega_2 = (0, \infty) \times \mathbb{R}^2$

$$\rho(k_\Gamma, k, s^{tm}, s^{te}) = \left|\frac{\lambda - \imath k}{\lambda + \imath k}\right| \max\left\{\left|\frac{\lambda - s^{te}}{\lambda + s^{te}}\right|, \left|\frac{\lambda - s^{tm}}{\lambda + s^{tm}}\right|\right\},$$

with $\lambda = \sqrt{|k_\Gamma|^2 - k^2}$ and $k = \omega\sqrt{\varepsilon\mu}$.

$$\rho \lesssim 1 - \frac{\sqrt{2}(k_+^2 - k^2)^{1/4}}{\sqrt{k^{\max}}}$$

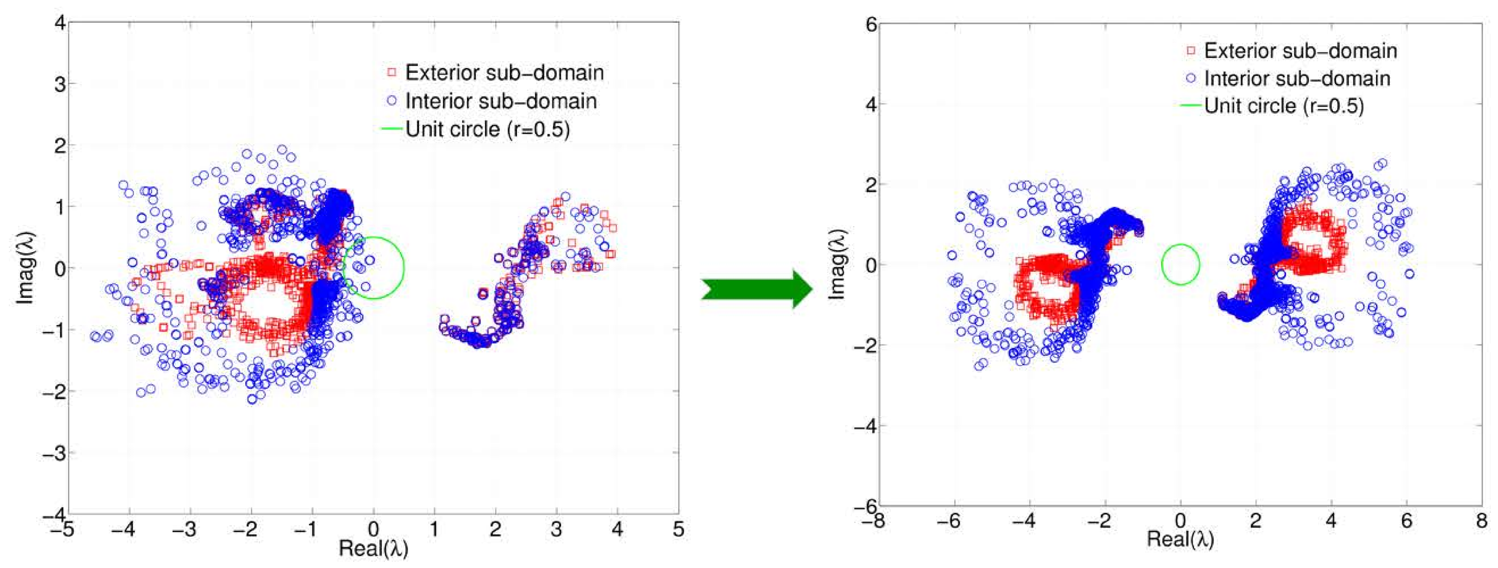
2) Coarse-grained DD system via hierarchical skeletonization

- Reduced system matrix equation with respect to skeleton surface unknowns:

$$\begin{bmatrix} \mathcal{I} & \mathcal{V}_1^T\bar{\mathcal{R}}_1\mathcal{A}_1^{-1}\bar{\mathcal{R}}_1^T\bar{\mathcal{V}}_1\mathcal{S}_{12} & \cdots & \mathcal{V}_1^T\bar{\mathcal{R}}_1\mathcal{A}_1^{-1}\bar{\mathcal{R}}_1^T\bar{\mathcal{V}}_1\mathcal{S}_{1M} \\ \mathcal{V}_2^T\bar{\mathcal{R}}_2\mathcal{A}_2^{-1}\bar{\mathcal{R}}_2^T\bar{\mathcal{V}}_2\mathcal{S}_{21} & \mathcal{I} & \cdots & \mathcal{V}_2^T\bar{\mathcal{R}}_2\mathcal{A}_2^{-1}\bar{\mathcal{R}}_2^T\bar{\mathcal{V}}_2\mathcal{S}_{2M} \\ \cdots & \cdots & \ddots & \cdots \\ \mathcal{V}_M^T\bar{\mathcal{R}}_M\mathcal{A}_M^{-1}\bar{\mathcal{R}}_M^T\bar{\mathcal{V}}_M\mathcal{S}_{M1} & \mathcal{V}_M^T\bar{\mathcal{R}}_M\mathcal{A}_M^{-1}\bar{\mathcal{R}}_M^T\bar{\mathcal{V}}_M\mathcal{S}_{M2} & \cdots & \mathcal{I} \end{bmatrix} \begin{bmatrix} \bar{\bar{\mathbf{u}}}_1 & \bar{\bar{\mathbf{u}}}_2 & \cdots & \bar{\bar{\mathbf{u}}}_M \end{bmatrix}^T = \begin{bmatrix} \bar{\bar{\mathbf{y}}}_1 & \bar{\bar{\mathbf{y}}}_2 & \cdots & \bar{\bar{\mathbf{y}}}_M \end{bmatrix}^T$$

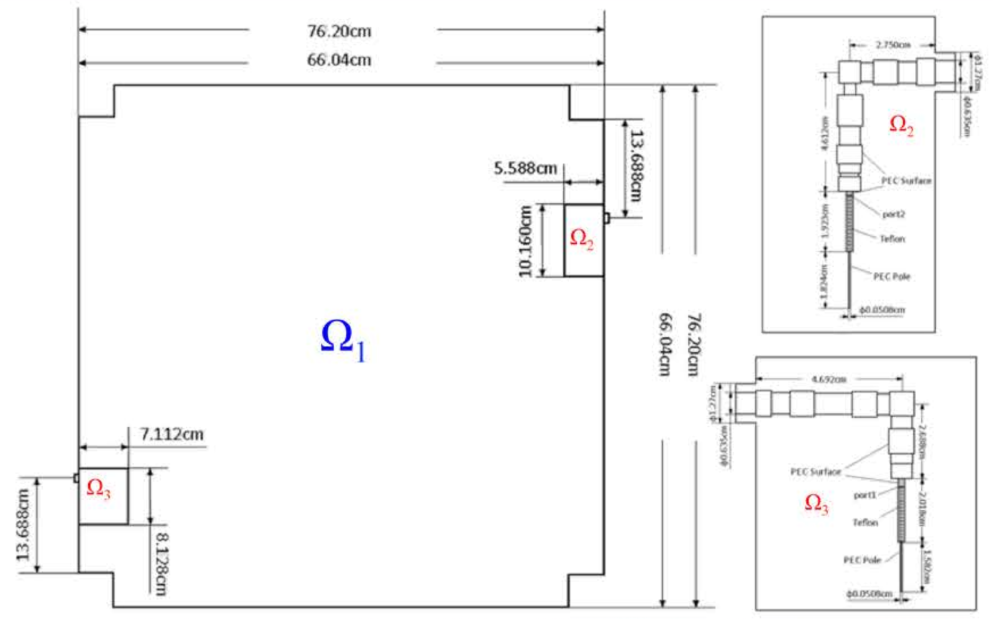
- The original unknown coefficients can be calculated by $\mathbf{u}_m = \mathcal{A}_1^{-1}\sum_{m=1}^{M} \mathcal{R}_1^T \mathcal{V}_1 \mathcal{S}_{1m} \mathcal{V}_m^T \mathcal{R}_m \bar{\bar{\mathbf{u}}}_m$.
- The computational complexity: $O(N)$ for both Memory & CPU time
- Hybrid solution strategy: Schwarz preconditioning with local direct solve

3) Novel multi-trace formulation for resonance structures

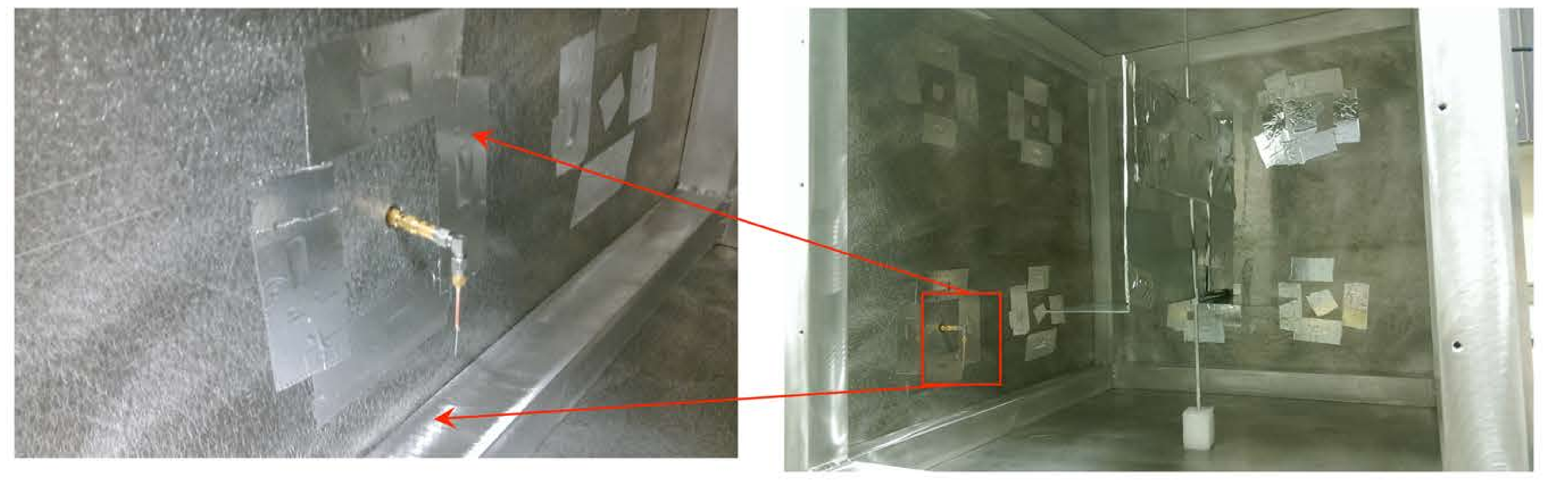


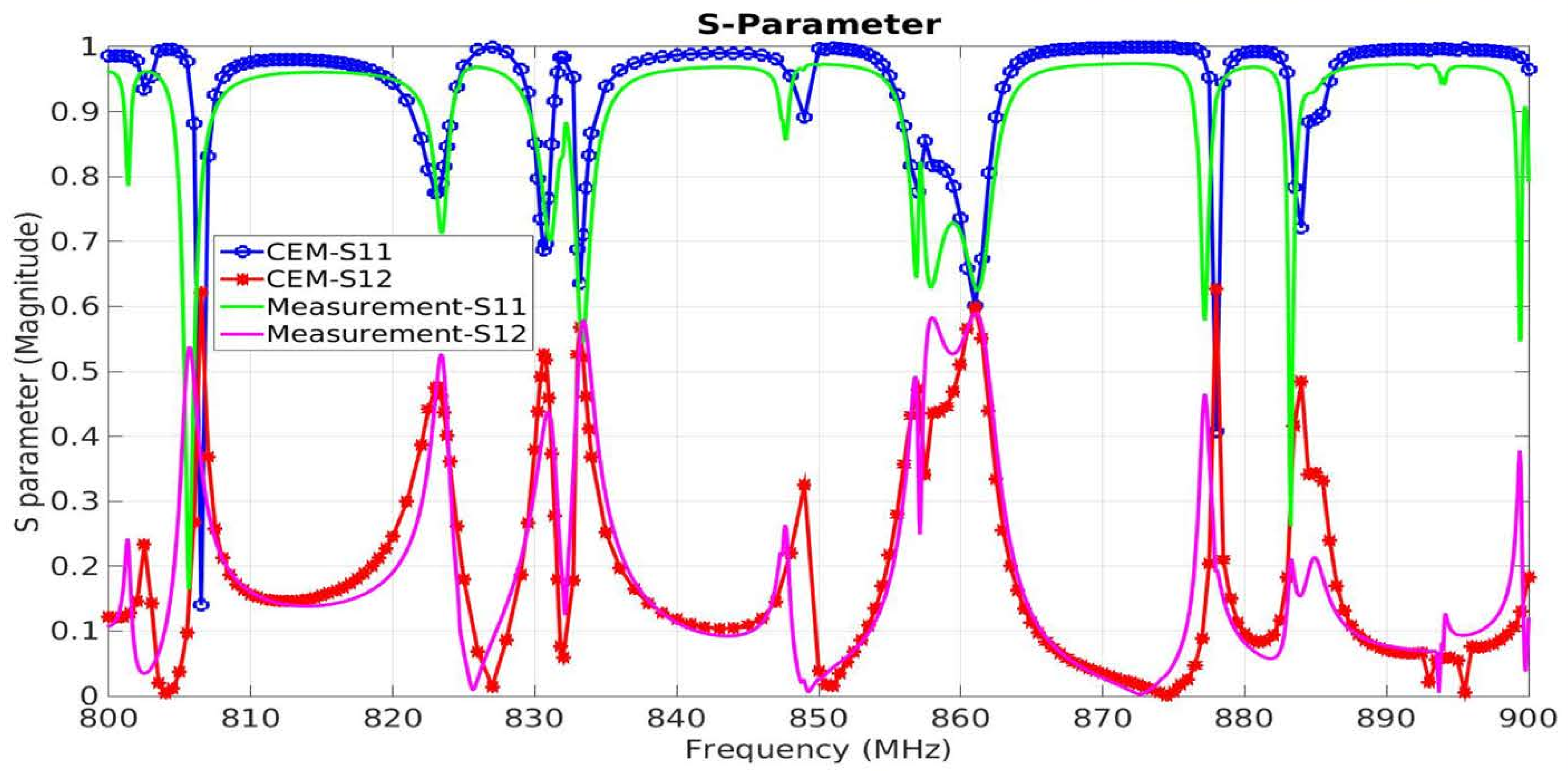
- Well-conditioned sub-domain matrices immune from the cavity resonances
- Novel transmission conditions provably convergent at sub-domain interfaces

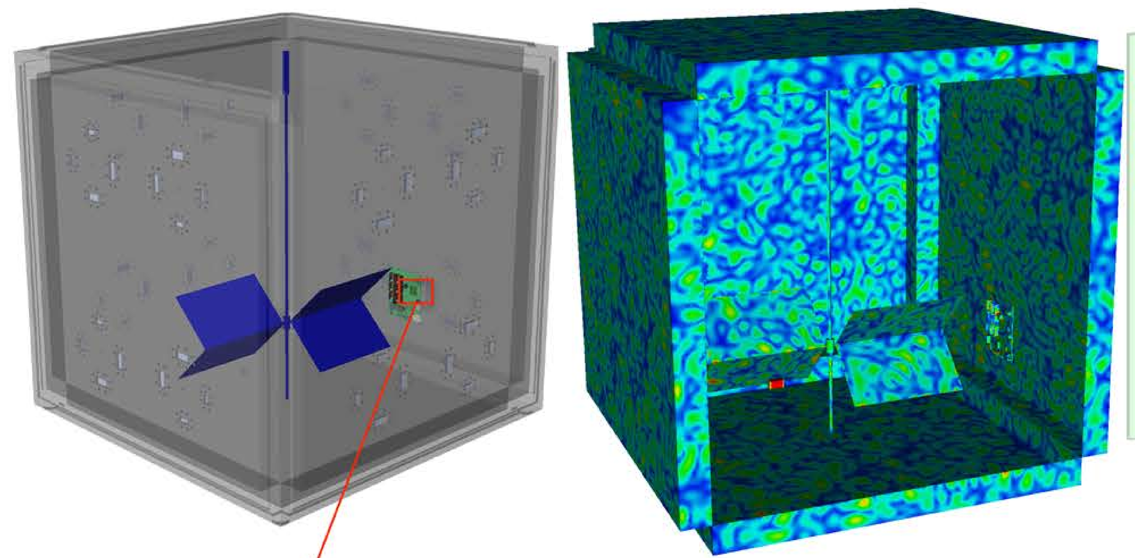
Numerical Results



Experiment conducted at Applied EM Group, UNM







- Computer Case: 7 subdomains
- PCB Board: 23 sub-domains
- IBM Package: 587 sub-domains
- Total num. of DoFs: 75 millions
- Operating Frequency: 10 GHz
- Number of Iterations: 8
- Simulation Time: 42 hours

IBM Plasma Package — Package Layer 1 — Package Layer 2