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Sandia National Laboratories

EIGER / GEMMA Electromagnetic Code Capabilities

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Overview

Problem Explained

Code Description EIGER / GEMMA

Solution Methods

Example Problem

Conclusions / Future Effort

Background

What?

- Provide high-fidelity, robust, computational tools based on Maxwell's Equations.
  - Frequency Domain → EMR/EMI Interaction with system / components

Why?

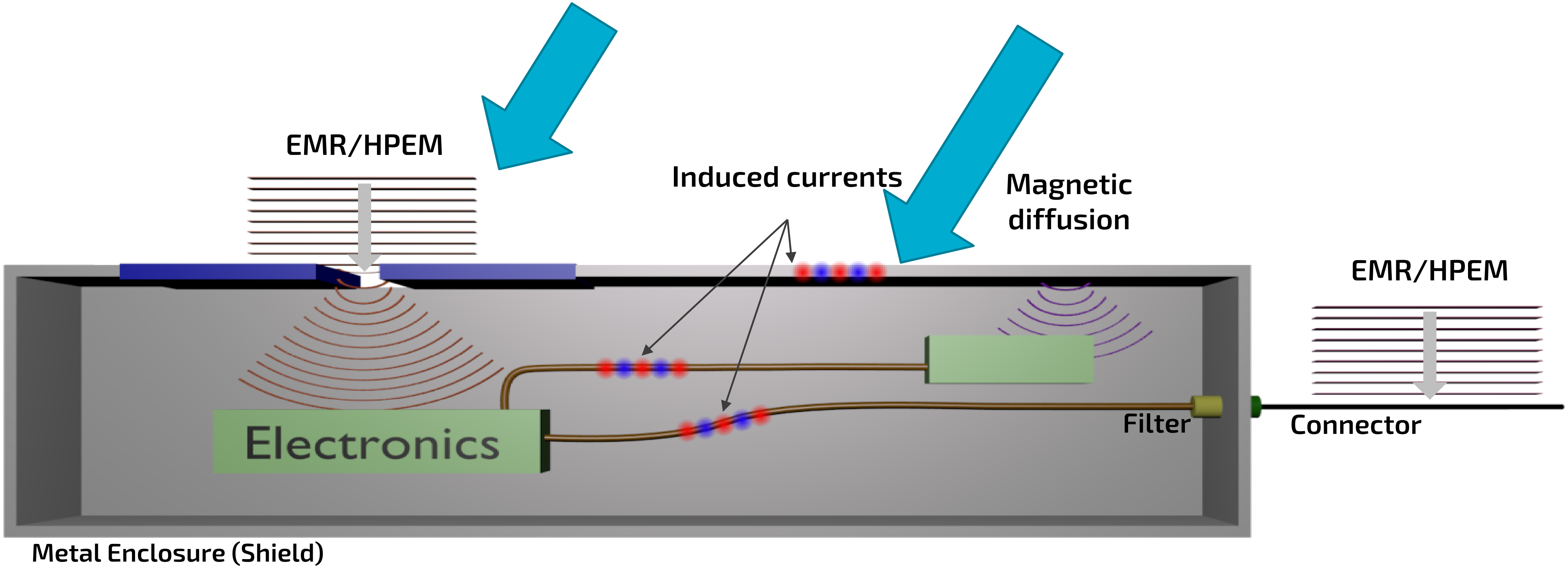
- To aid in weapons qualification in conjunction with experiments.
  - Design of experiments
- Weapon component and subsystem modeling.
  - Design guidance
- In addition, can be used to address problems for external customers.

How?

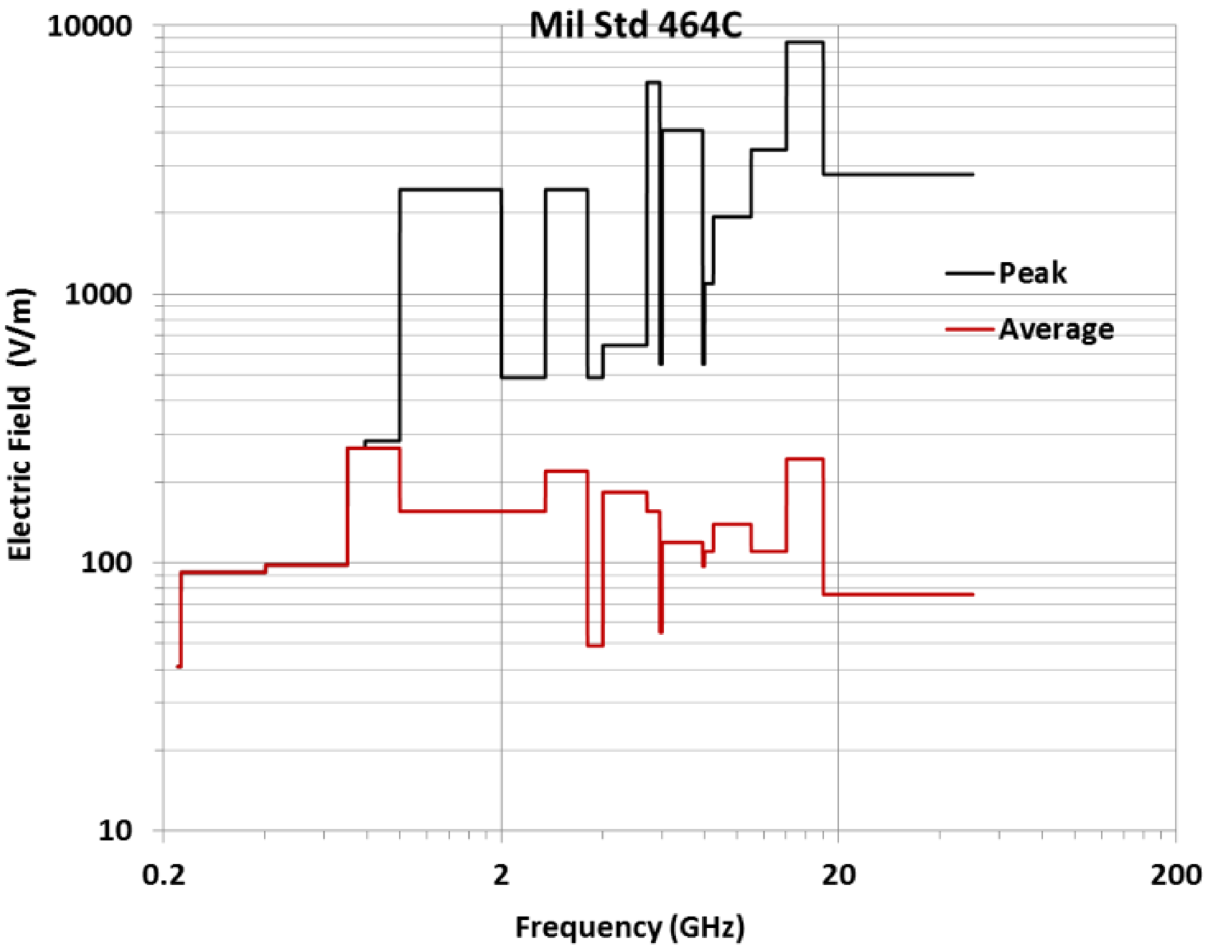
- Frequency domain boundary element formulation.
  - EIGER
  - GEMMA → Next generation EIGER

EMR Problem Overview

Focus – coupling through gaps and external currents



Electromagnetic Environment



Ground Based System **External to System**

Code Description EIGER / GEMMA

EIGER / GEMMA Basic Formulation

Frequency-domain method of moments solution

- Steady state solution
- With specialized algorithms (thin-slot, etc.)

Boundary element formulation

- Mesh surfaces of parts – interface between regions

Exact radiation boundary condition

- Due to Green's function

Formulation results in dense (fully populated) matrix

- Simulations can be limited by available memory
- Entries are double precision complex

Maxwell's Equations in the Frequency Domain

Maxwell's Equations:

$$\text{Faraday}: \quad \nabla \times \mathbf{E} = -j\omega\mathbf{B}$$
$$\text{Ampere}-\text{Maxwell}: \quad \nabla \times \mathbf{H} = \mathbf{J} + j\omega\mathbf{D}$$
$$\text{Electric Gauss}: \quad \nabla \cdot \mathbf{D} = \rho$$
$$\text{Magnetic Gauss}: \quad \nabla \cdot \mathbf{B} = 0$$

Wave Equations:

$$\nabla^2\mathbf{A} + \omega^2\mu\epsilon\mathbf{A} = -\mu\mathbf{J}$$
$$\nabla^2\Phi + \omega^2\mu\epsilon\Phi = \rho/\epsilon$$

Vector and Scalar Potentials:

$$\mathbf{E} = -j\omega\mathbf{A} - \nabla\Phi$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$

Lorenz gauge condition:

$$\nabla \cdot \mathbf{A} = -j\omega\epsilon\mu\Phi$$

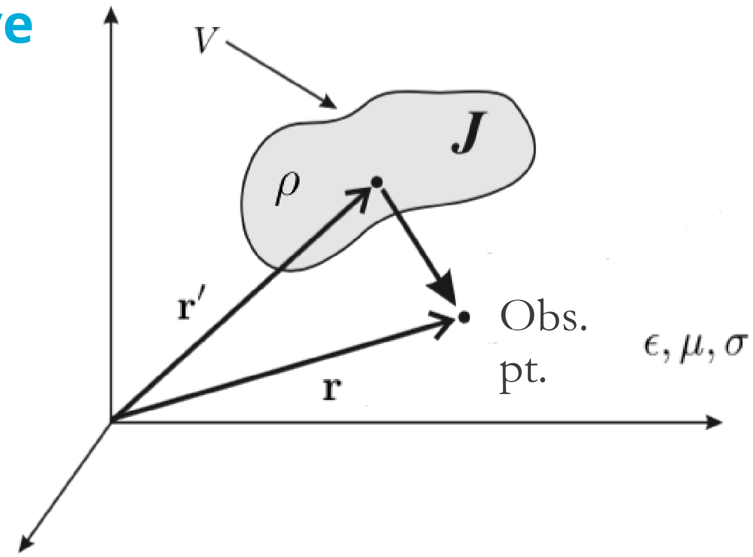
Instead of solving Maxwell's equations in 3D space via the wave equations, we solve them on the boundary between regions.

For a **linear** homogeneous, unbounded medium:

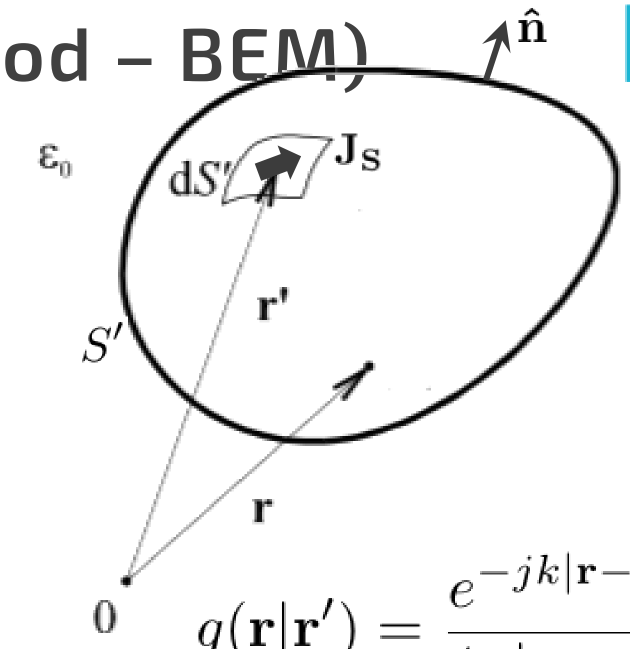
$$\mathbf{A} = \int_V \mu\mathbf{J}(\mathbf{r}')g(\mathbf{r}|\mathbf{r}')dv'$$
$$\Phi = -\int_V \frac{\rho(\mathbf{r}')}{\epsilon}g(\mathbf{r}|\mathbf{r}')dv'$$

Free-Space Green's Function:

$$g(\mathbf{r}|\mathbf{r}') = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}$$



Integral Equations (Boundary Element Method – BEM)



$$g(\mathbf{r}|\mathbf{r}') = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}$$

Example of an electric field integral equation (EFIE) for metallic scatterer:

Through the equivalence principle, we consider the current on an objects boundary instead of the field around and inside the object. Enforcing the boundary condition at the surface:

$$\hat{\mathbf{n}} \times (\mathbf{E}_{\mathbf{inc}} + \mathbf{E}_{\mathbf{scat}}) = \mathbf{0}$$

$$\mathbf{E}_{\mathbf{scat}} = -j\omega\mu \int_{S'} \left(\mathbf{J}_{\mathbf{S}}(\mathbf{r}')g(\mathbf{r}|\mathbf{r}') + \frac{1}{\omega^2\mu\epsilon}\nabla' \cdot \mathbf{J}_{\mathbf{S}}(\mathbf{r}')\nabla g(\mathbf{r}|\mathbf{r}') \right) ds'$$

results in the following integral equation:

$$\int_{S'} \hat{\mathbf{n}} \times \left(\mathbf{J}_{\mathbf{S}}(\mathbf{r}')g(\mathbf{r}|\mathbf{r}') + \frac{1}{\omega^2\mu\epsilon}\nabla' \cdot \mathbf{J}_{\mathbf{S}}(\mathbf{r}')\nabla g(\mathbf{r}|\mathbf{r}') \right) ds' = \frac{1}{j\omega\mu}\hat{\mathbf{n}} \times \mathbf{E}_{\mathbf{inc}}$$

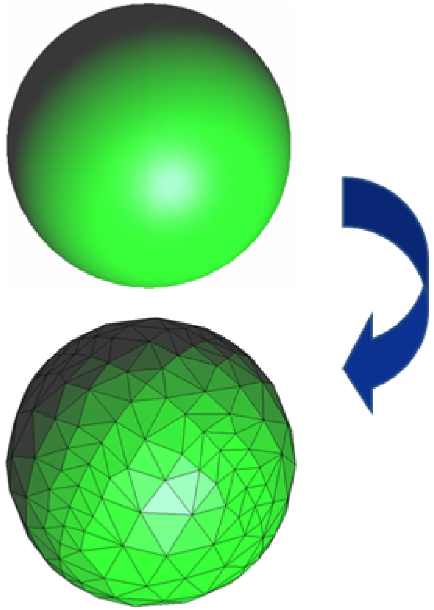
$$L\{\mathbf{J}_{\mathbf{S}}\} = \frac{1}{j\omega\mu}\hat{\mathbf{n}} \times \mathbf{E}_{\mathbf{inc}}$$

Method of Moments (MoM)

Numerical solution of integral equation:

$$L\{\mathbf{J_S}\} = \frac{1}{j\omega\mu}\hat{\mathbf{n}} \times \mathbf{E_{inc}}$$

Discretize the scatterer



Expand unknown in a set of basis functions:

$$\mathbf{J_S}(\mathbf{r}) \approx \sum_n I_n \mathbf{f_n}(\mathbf{r})$$

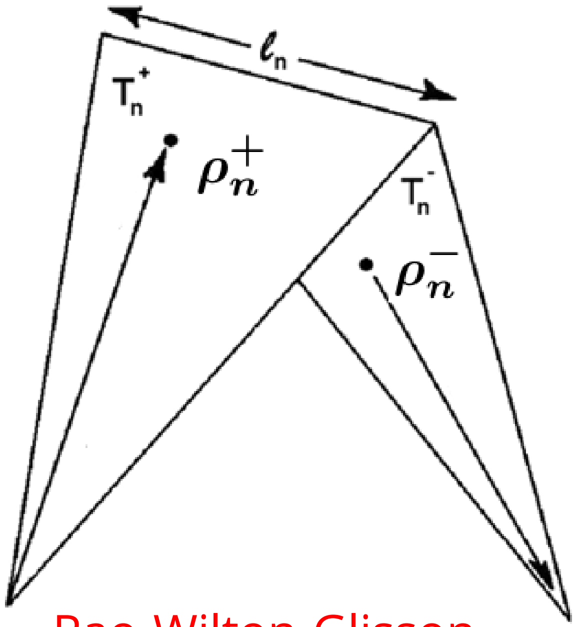
$$\mathbf{f_n}(\mathbf{r}) = \begin{cases} \frac{\ell_n}{2A_n^+}\boldsymbol{\rho}_n^+ & \mathbf{r} \in T_n^+ \\ \frac{\ell_n}{2A_n^-}\boldsymbol{\rho}_n^- & \mathbf{r} \in T_n^- \\ \mathbf{0} & \text{otherwise} \end{cases}$$

Test integral equation with basis functions.

$$\int_S \mathbf{f_m} \cdot L\{\mathbf{J_S}\}\, ds = \frac{1}{j\omega\mu}\int_S \mathbf{f_m} \cdot (\hat{\mathbf{n}} \times \mathbf{E_{inc}})\, ds$$

$$\overline{\mathbf{Z}}\mathbf{I} = \mathbf{V}$$

$$Z_{m,n} = \int_{f_m}\int_{f_n}\left[j\omega\mu \boldsymbol{f}_m \cdot \boldsymbol{f}_n - \frac{j}{\omega\epsilon}\nabla \cdot \boldsymbol{f}_m \nabla' \cdot \boldsymbol{f}_n\right]\frac{e^{-ikr}}{4\pi r}$$



Rao-Wilton-Glisson (RWG) basis functions

EIGER and GEMMA Comparison

Feature	EIGER	GEMMA
Language	Fortran 2007	C++ 11
Parallel Implementation	MPI	MPI + Threading (CPU + GPU)
Solution Options	Direct Iterative Matrix Compression	Direct, Iterative Iterative - MLFMM, Matrix Compression*
Code Implementation	Pre-processor , solver Separate Codes	Pre-processor , solver Not separate
Code Enhancements Usage Algorithms	Enhanced with SAW / IWF integration	Deep Slot Formulation Enhanced with SAW / IWF integration

*Possible Future Enhancements

Solution Methods

EIGER / GEMMA– Computational considerations

Problem Discretization Requirement

- Triangles , quadrilaterals, or bar elements (SURFACE MESH)
- Mesh requirements
  - Average Edge length should be ~ λ/10
  - (# faces x λ^2)/surface area > 250

Matrix memory requirements

- 16 * N^2 bytes (N order of the matrix)
- Example
  - W88_alt meshed and prepared for 18 GHz
    - N = 2 million
    - Memory = 64 terabytes

Matrix Solution

- Fill is $O(N^2)$
- Solve is $O(N^3)$ -- for Direct Solve
- The solution is the Current on the surfaces
  - Using the Green's function the fields can be determined.

Solution via Direct and Iterative Solve -> TRILINOS Packages

DIRECT Solve

- PLIRIS
  - C – code
    - MPI only no threading

- ADELUS
  - New packaging of PLIRIS
  - C++ code
    - MPI + Threading
    - Threading via KOKKOS
      - GPUs, CPUs

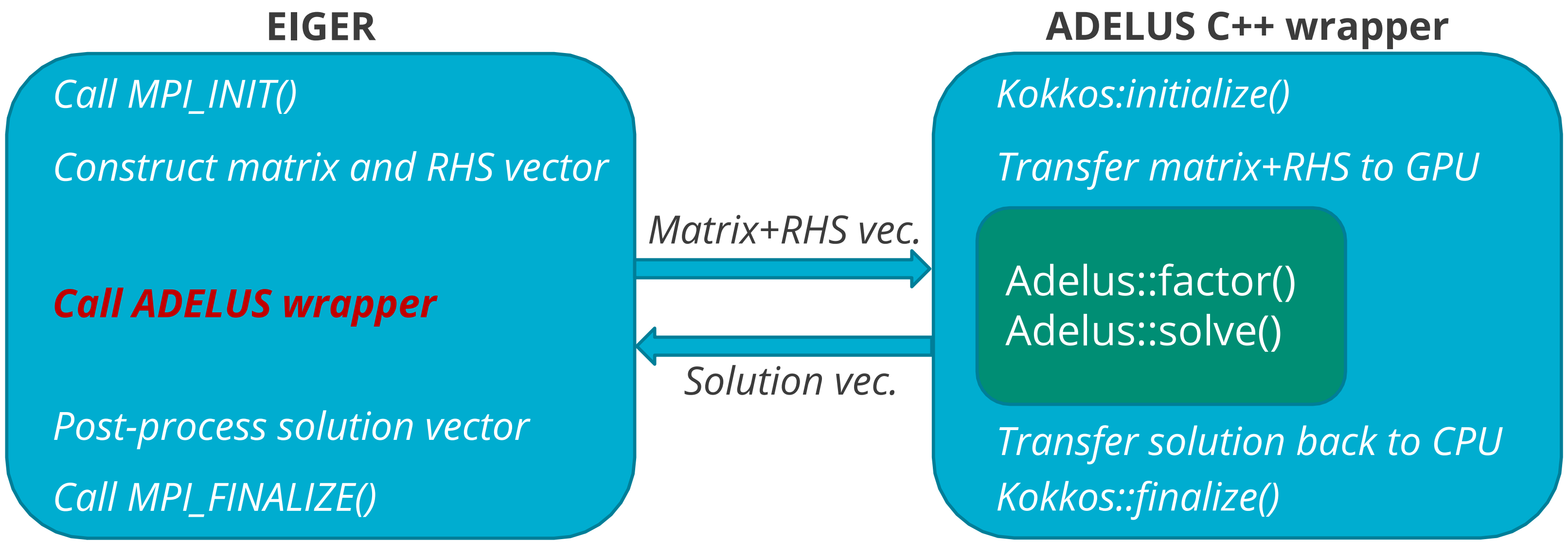
- Key Implementation Features
  - TORUS WRAP Distribution
    - Blocks supplied by user
    - No processor will have no more than 1 row or column than the other

Iterative Solve

- BELOS
  - Preconditioner usage

Large-Scale EM Simulation with EIGER with Adelus

- Couple EIGER with ADELUS to perform large-scale electromagnetic simulations on the LLNL's Sierra platform
- First time Petaflops performance with a complex, dense LU solver: 7.72 Petaflops (16.9% efficiency) when using 7,600 GPUs on 1,900 nodes on a 2,564,487-unknown problem
- ADELUS's performance is affected by the distribution of the matrix on the MPI processes
  - Assigning more processes per row yields higher performance

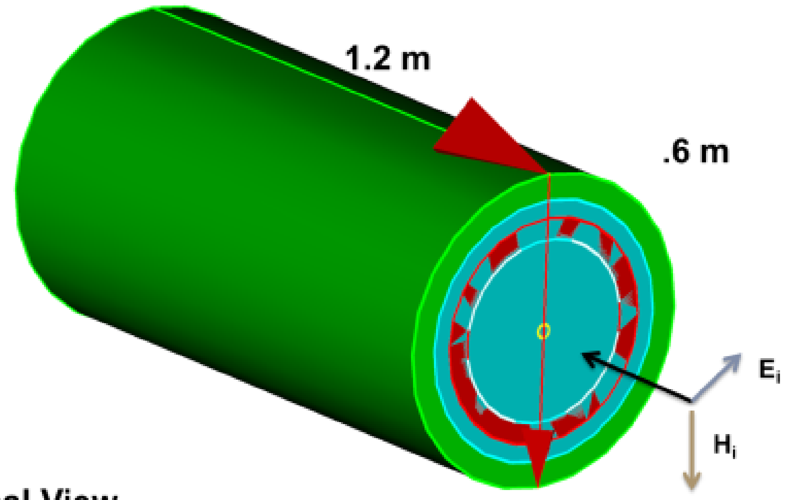


N	Nodes (GPUs)	Solve time (sec.)	TFLOPS	Procs/row
226,647	25 (100)	240.5	1291.0	10
1,065,761	310 (1240)	1905.1	1694.5	31
1,322,920	**500 (2,000)**	**6443.9**	**958.1**	**20**
1,322,920	**500 (2,000)**	**2300.2**	**2684.1**	**50**
1,322,920	**500 (2,000)**	**2063.6**	**2991.9**	**100**
2,002,566	1,200 (4,800)	3544.1	6042.6	100
2,564,487	**1,900 (7,600)**	**5825.2**	**7720.7**	**80**

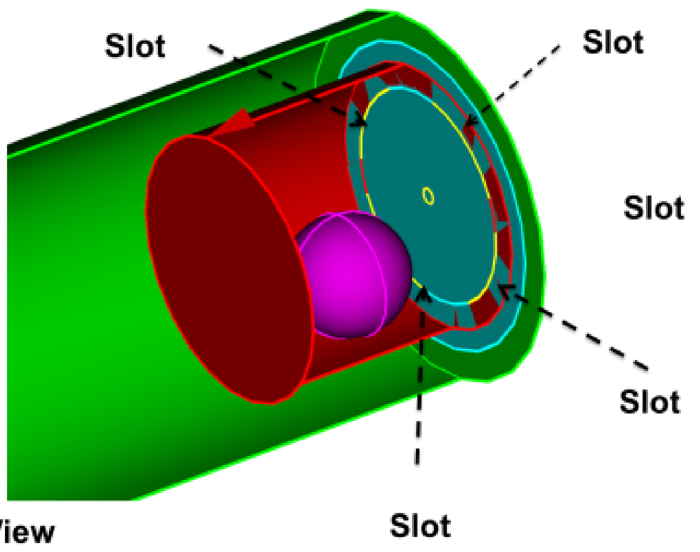
ON SIERRA

Example Problem

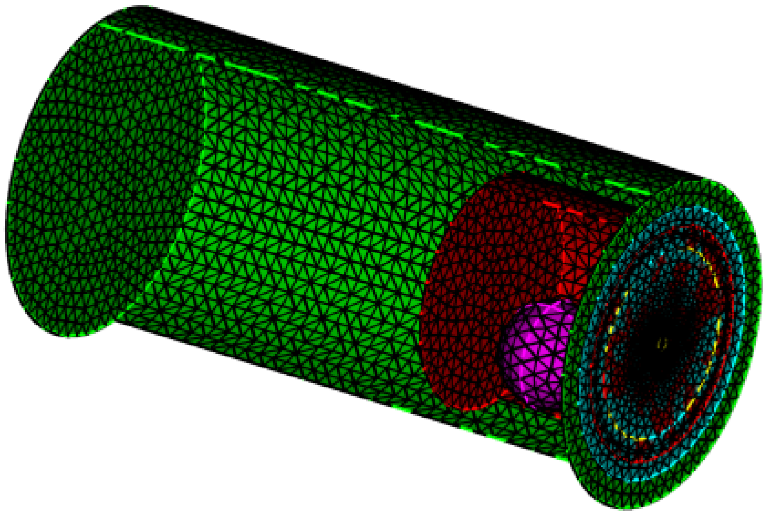
Example Problem



External View

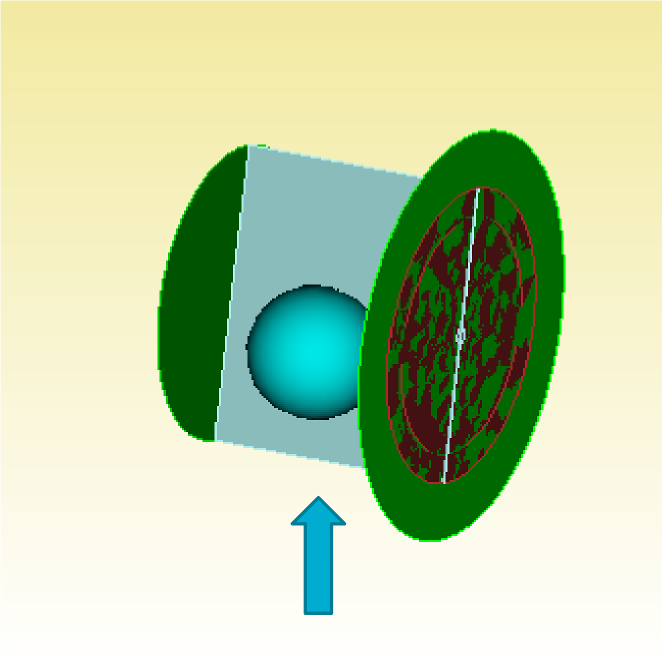


Internal View



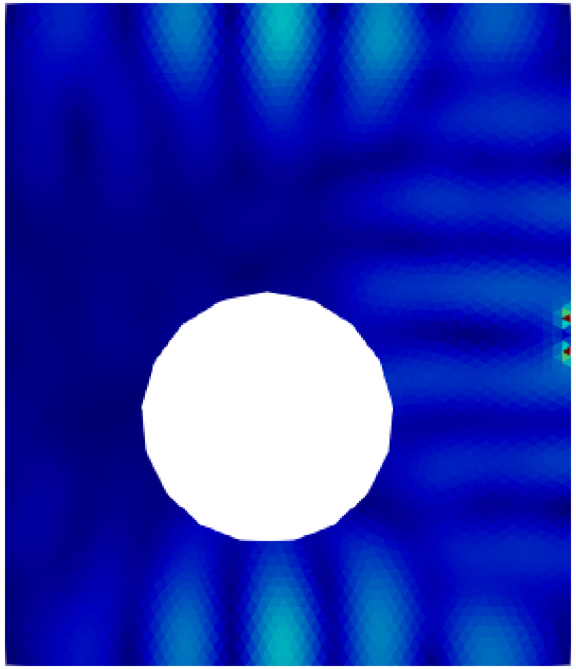
Example Mesh 10090 elements --- 15565 unknowns

Example Problem -- Results

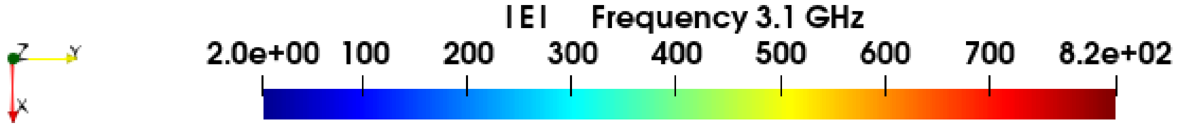


Cut Plane

494533 Unknowns



Incident Field



Magnitude of Electric Field on the Cut Plane

Conclusions

Conclusions / Future Effort

The EIGER /GEMMA codes have benefited from collaboration with the Trilinos team:

PLIRIS –> ADELUS, BELOS , KOKKOS

GEMMA

- **Additional Algorithms being pursued:**
  - **Physics models**
  - **Advanced solution methods**
    - **Preconditioner identification**

These will leverage and require continued teaming and support with the Trilinos team.