INL/CON-18-45609-Revision-0

Elk: A New MOOSE Framework Application for Radio-frequency Electromagnetics

Casey Icenhour, Alexander Lindsay, David Green, Richard Martineau, Steven Shannon

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ELK: A New MOOSE Framework Application for Radio-Frequency Electromagnetics

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71st Annual Gaseous Electronics Conference

November 6, 2018

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U.S. DEPARTMENT OF ENERGY

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Outline

- Motivation / Background
- MOOSE Framework
- **E**lectromagnetics **L**ibrary for **K**inetics and fluids (**ELK**)
- Current Progress and Issues
- Future Work

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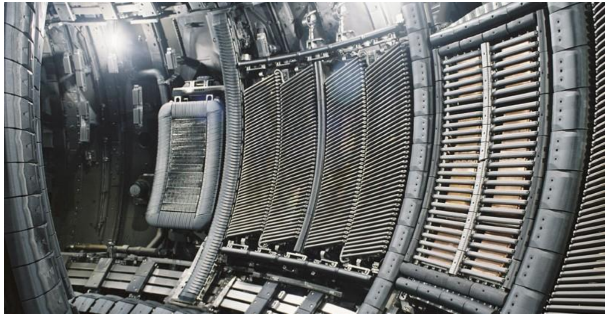
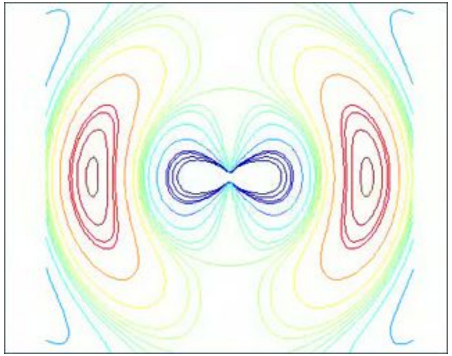
Motivation / Background

- Advanced research in science and engineering increasingly requires robust simulation tools
  - Whole device modeling - high temp. plasma physics
  - Next generation nuclear reactors - MHD flow

- However:
  - many well-used platforms are sometimes cost-prohibitive, or have a high barrier to entry.
  - some legacy applications have not been updated to modern code standards.



Credit: EUROfusion



Credit: Prof. Jin Au Kong, MIT

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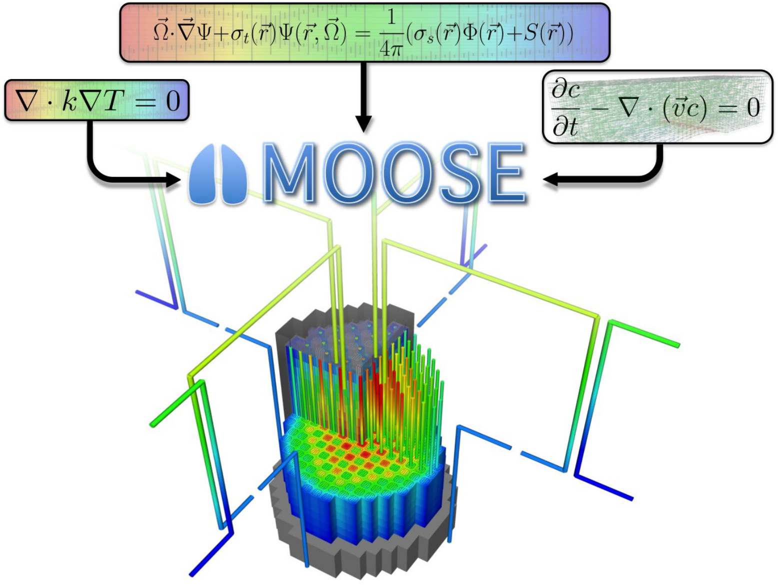
Multiphysics Object Oriented Simulation Environment (MOOSE)

- An **open source**, **highly parallel** finite element framework
- Designed for highly-coupled systems of PDEs
- Modular structure allows for **easy extensions** and maintenance of code
- NQA-1 (Nuclear Quality Assurance Level 1) development process
- http://mooseframework.org



MOOSE Code Example

Strong Form

$$\frac{\partial C}{\partial t} - D\nabla^2 C = R$$

Weak Form

$$\int_\Omega \frac{\partial C}{\partial t}\psi_i + \int_\Omega D\nabla C \cdot \nabla\psi_i - \int_{\partial\Omega} D(\nabla C \cdot \hat{n})\psi_i - \int_\Omega R\psi_i = 0$$

Kernel | Kernel | BoundaryCondition | Kernel

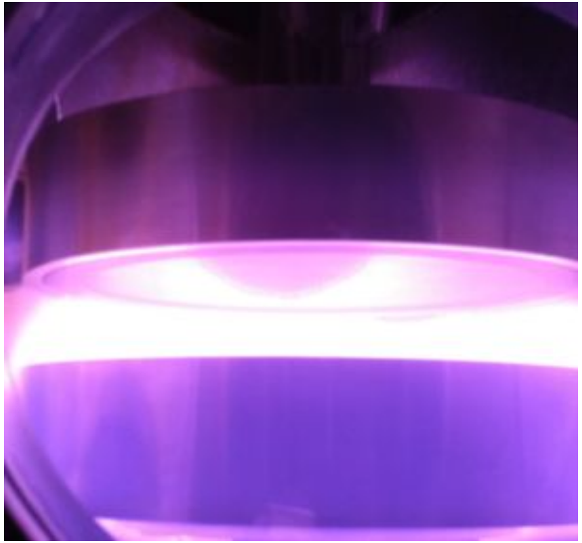
Actual Code

```
return _D[_qp]*_grad_u[_qp]*_grad_test[_i][_qp];
```

Source: MOOSE Development Team, INL

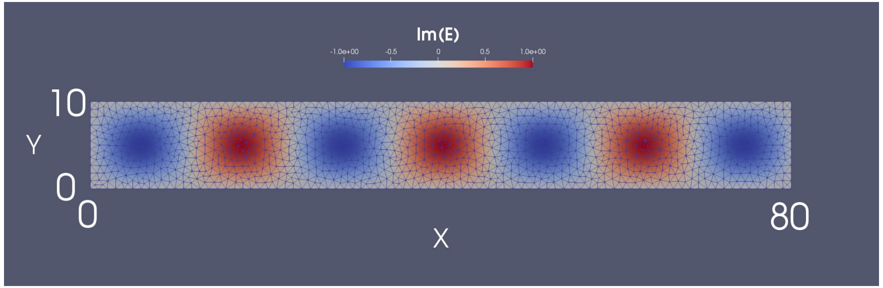
Why MOOSE for Electromagnetics / Plasma?

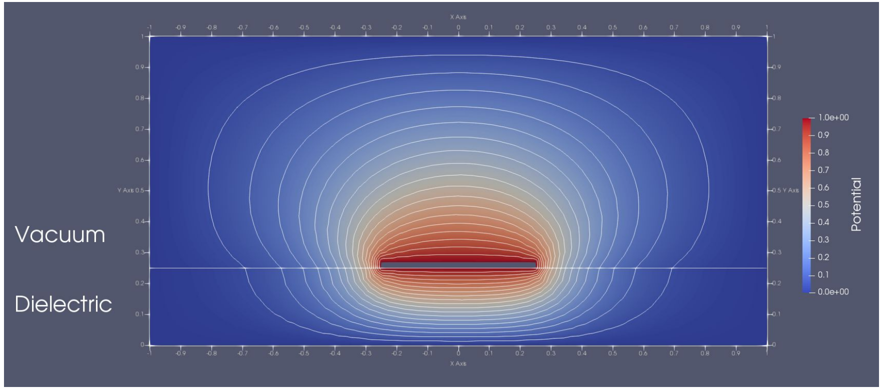
- **Open-source!**
- Responsive developer community!
- Vector Finite Elements
  - Currently: Nedelec first-order elements
- Easily mixed element types and orders
- Multiple spatial and temporal scales
- Easy mesh adaptivity
- Built-in postprocessing
- Just to name a few...



Electromagnetics Library for Kinetics and fluids (ELK)

- Originally a MATLAB teaching code begun in 2016 / 2017 and transferred to MOOSE
- Current Capabilities:
  - 1D , 2D, 3D*
  - Poisson’s Equation for scalar potential
  - Scalar (component-wise) and Vector forms of the Helmholtz Wave Equation for fields
  - Single-mode Port BCs (wave launch, absorbing, and reflection)
  - Current Sources and BCs
  - Post-processing for electrostatic field calculations, reflection coefficients



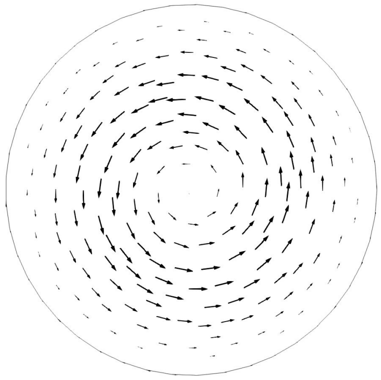


Top Right: Imaginary E-field TM11 Mode for 13.56 MHz wave launched at right

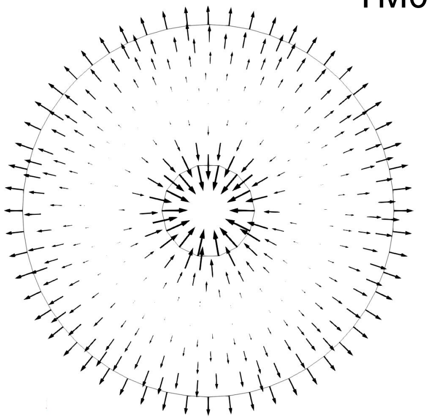
Bottom Right: calculation of potential around Teflon-backed microstrip line

MOOSE Results: Waveguide Mode Profiles (2D)

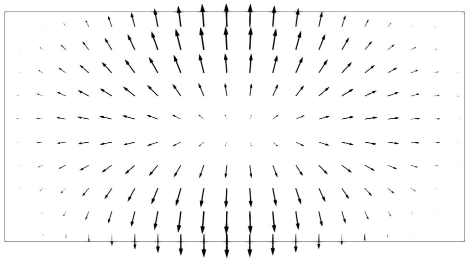
TE01

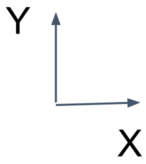


TM01



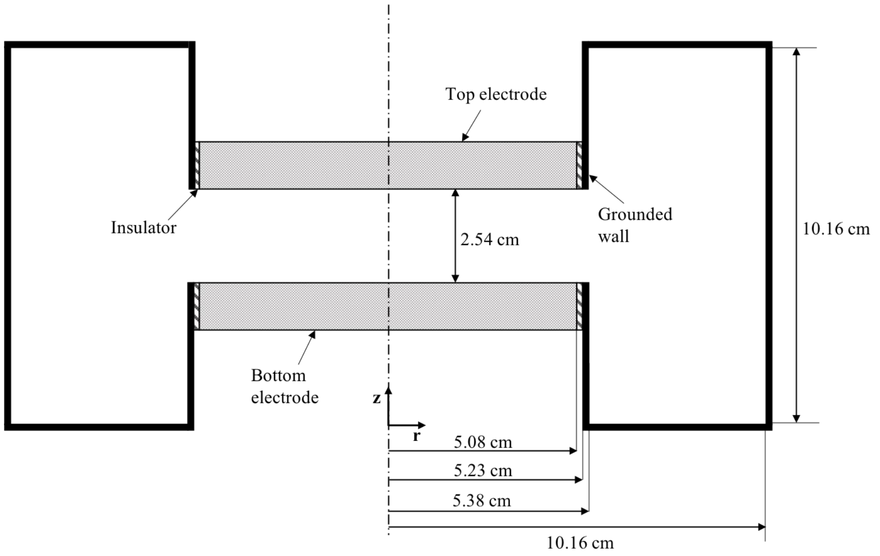
TM11

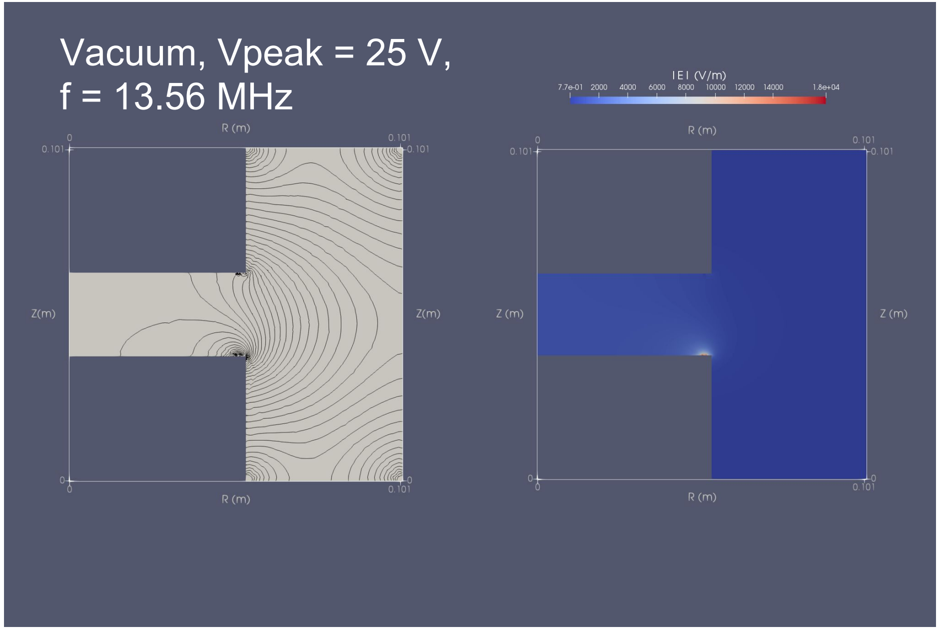




- Single Mode
- Preparing for electromagnetic eigenvalue problems for arbitrary waveguide geometries (utilizing the SLEPc package).

Target Problem - GEC CCP Reference Cell



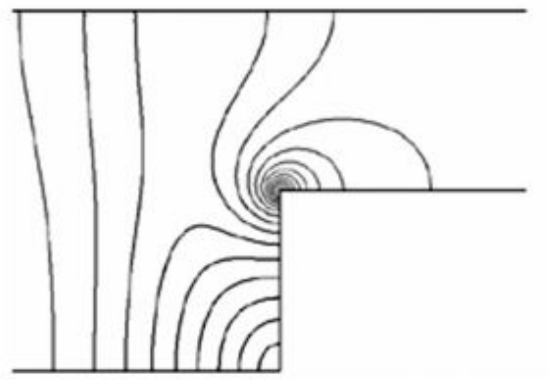


[Figure Reference]

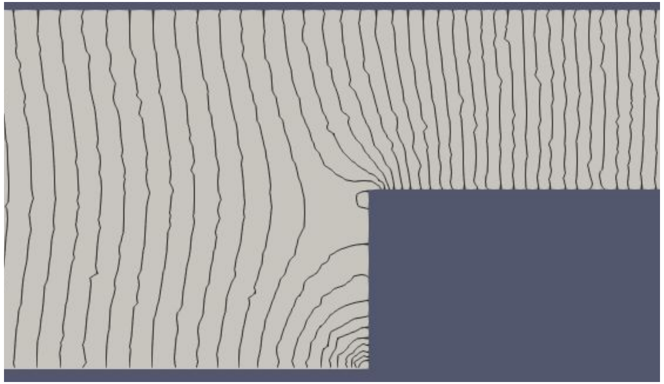
D. P. Lymberopolous and D. J. Economou, "Two-dimensional Self-Consistent Radio Frequency Plasma Simulations Relevant to the Gaseous Electronics Conference RF Reference Cell," *J. Res. Natl. Inst. Stand. Technol.*, vol. 100, p. 473, 1995.

Resolving Field Singularities at Discontinuities

Reference Solution:



MOOSE-calculated Real Electric field magnitude contour



Left: MOOSE-calculated Real E-field magnitude color plot - no wave motion?

- f = 10 GHz
- J_y = 1 A/m^2 (on left side)

Ruben Otin (2010) Regularized Maxwell Equations and Nodal Finite Elements for Electromagnetic Field Computations, Electromagnetics, 30:1-2, 190-204, DOI: [10.1080/02726340903485489](10.1080/02726340903485489)

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Future Work

- Expansion of available boundary conditions
  - Multi-mode wave launching, absorption, etc.
- Electromagnetic Eigenvalue calculations
- Coupling to Zapdos (a MOOSE-based low temperature plasma fluid code) for simulation of RF plasma sources
  - For more on Zapdos for simulating the COST APPJ source: Session GT1, Poster 074
- Open-source licensing
- ELK $\rightarrow$ MOOSE Electromagnetics Module?

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Thank You!

Questions??