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Verification and validation for computational electromagnetics in the ALEGRA code

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Physics Department Colloquium

Howard University

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Sandia National Laboratories: mission and expertise

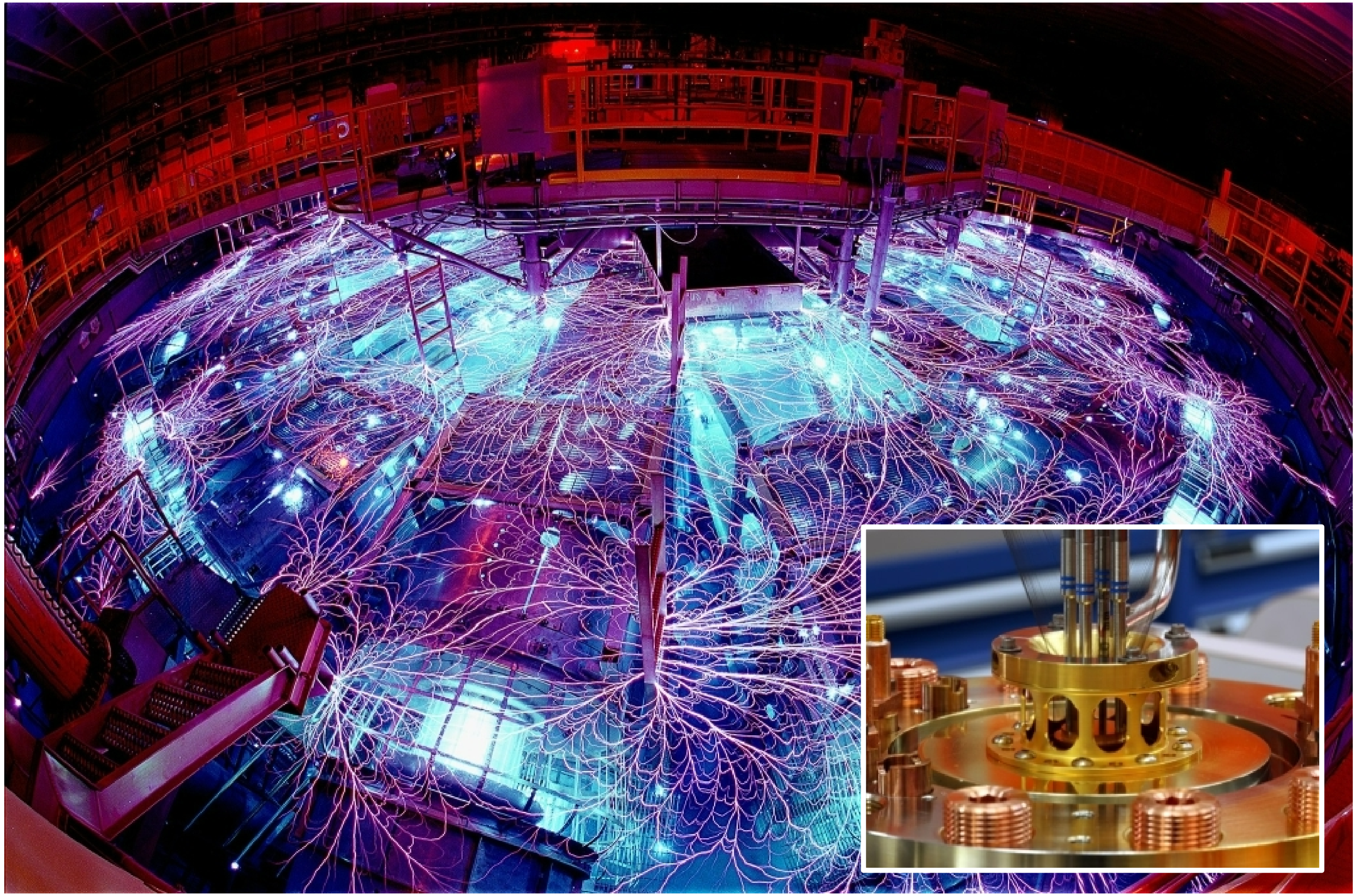
Mission areas

- Nuclear deterrence
- National security
- Nonproliferation
- Energy infrastructure

Physics and engineering research focus areas:

- Pulsed power
- Radiation effects
- Robotics
- Sensors
- Ballistics
- Renewable energy

See https://www.sandia.gov/about/



Sandia's Z Accelerator concentrates electric currents on the order of 10^7 Amperes in a tiny load (inset) to produce enormous pressures and/or radiation fluxes.
(Photo by Randy Montoya)

Sandia National Laboratories: who we are

- Federally-funded research and development center under DOE/NNSA.
- Established in 1949
- 14,500 employees in 2020

Locations:

- Albuquerque, NM (KAFB)
- Livermore, CA
- Sites in NV and HI
- Virtual workers across U.S.

Technical staff discipline

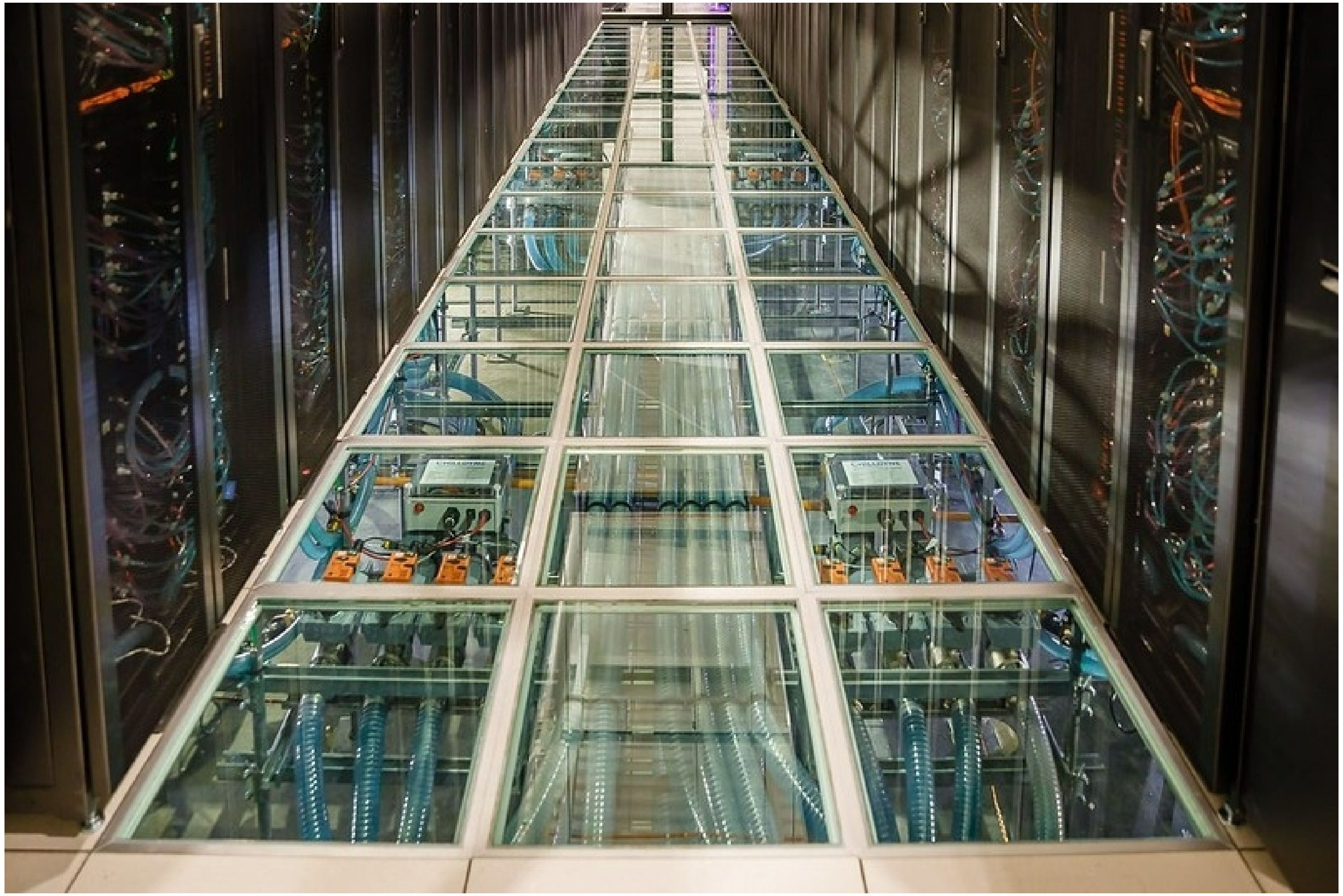
- Engineering, 59%
- Computer science, 25%
- Physics, 3%
- Other science, 13%

Sandia's Technology Park (left) and Tech Area I (right), in Albuquerque, NM within Kirtland AFB. (Photos courtesy of Sandia)

Sandia's Center for Computing Research

Research focus areas:

- Computational physical simulation
  - Electromagnetics — Focus of this talk
  - Shock hydrodynamics
  - Molecular dynamics
  - Climate modeling
- Scalable computing
  - Architecture
  - System software
  - Algorithms
- Optimization and UQ
- Quantum computing
- Machine learning and artificial intelligence



Water-cooled server racks in Sandia's High Performance Computing data center. (Photo by Bret Latter)

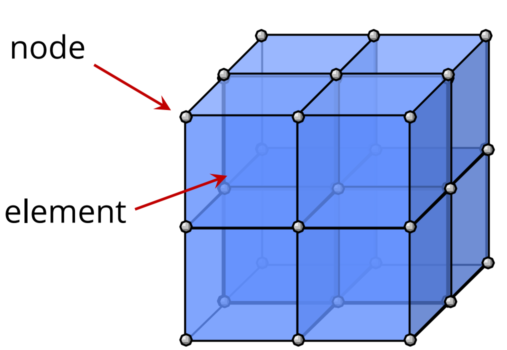
ALEGRA: Sandia's finite-element multiphysics software

ALEGRA solves the transient equations of Lagrangian solid dynamics (balance laws)…

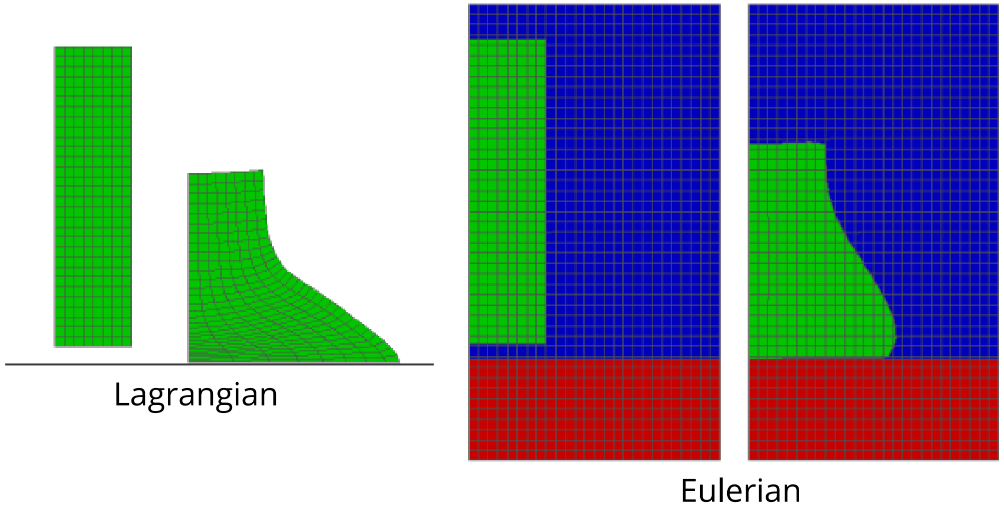
Conservation of momentum
Units: momentum/volume/time

Conservation of energy
Units: energy/volume/time

…using a finite-element discretization…



…with Eulerian and arbitrary Lagrangian-Eulerian (ALE) capability.



$\mathbf{v}$ = velocity
$\mathbf{T}$ = stress tensor
$\mathbf{f}$ = body force
e = specific internal energy

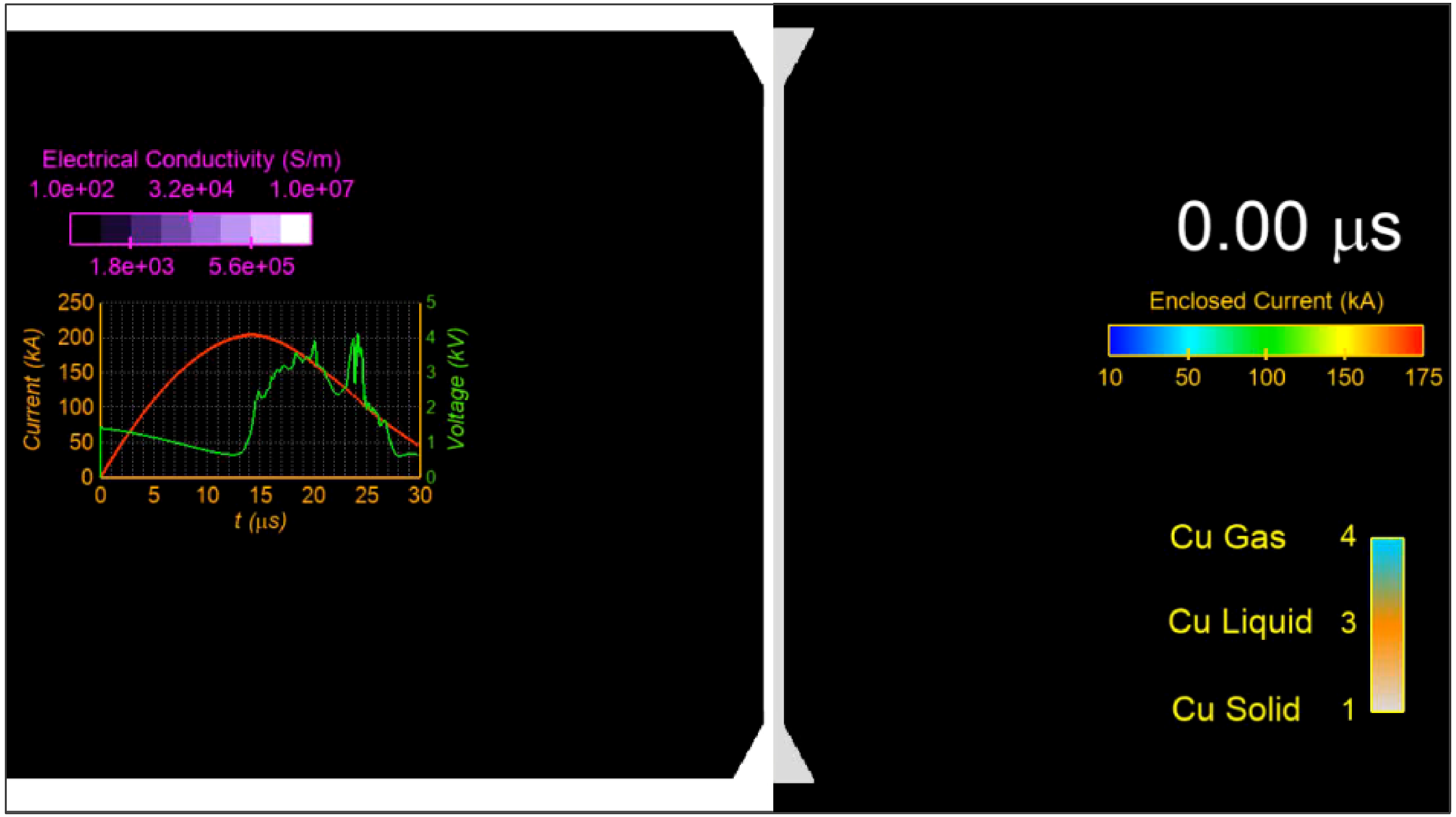
ρ = mass density
s = heat source
$\nabla\mathbf{v}$ = velocity gradient
$\mathbf{q}$ = heat flux

ALEGRA = ALE General Research Application

Multiphysics in ALEGRA

ALEGRA's defining capability is to allow users in US-government-funded research institutions to couple high-deformation solid dynamics to other physical processes:

- Electric circuits
- Electromagnetic induction
- Resistive heating
- Permanent magnets
- Electrostatic effects
- Chemical reactions
- Thermal conduction
- Radiative heat transport



For details see A. C. Robinson et al, 2008 https://www.doi.org/10.2514/6.2008-1235

ALEGRA simulation for burst of metallic wire by rapid pulse of electric current (Courtesy R. Doney, US Army Research Laboratory)

Computational electromagnetics in ALEGRA

1. Governing equations: Maxwell's equations with Ohm's law as closure

Ampére	$\nabla \times \mathbf{H} - \frac{\partial \mathbf{D}}{\partial t} = \mathbf{J}$	$\square = \frac{\square}{\square} - \square$
Gauss	$\nabla \cdot \square = \square$	$\square = \square\square + \square$
Faraday	$\nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0$	$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + q\mathbf{v}$
	$\nabla \cdot \square = 0$	$\square_{\mathrm{em}} = \square\square + \square \times \square$

Magnetohydrodynamics (MHD) approximation: neglect charge q and displacement current $\partial \mathbf{D}/\partial t$.

$$\mathbf{E} = \frac{1}{\mu\sigma}\nabla \times \mathbf{B} \longrightarrow \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} = -\nabla \times \frac{1}{\mu\sigma}\nabla \times \mathbf{B}$$

$\mathbf{H}$ = magnetic field

$\mathbf{D}$ = electric displacement

$\mathbf{J}$ = free current density

q = free charge density

$\mathbf{E}$ = electric field

$\mathbf{B}$ = magnetic induction

μ = magnetic permeability

ϵ = electrical permittivity

$\mathbf{M}$ = material magnetization

$\mathbf{P}$ = material electric polarization

$\mathbf{f}_{\mathrm{em}}$ = electromagnetic force density

$\mathbf{v}$ = charge velocity

Computational electromagnetics in ALEGRA

2. Balance-law formulation for magnetic flux in moving, conducting material:

$$\frac{d}{dt}\int_{S(t)} \mathbf{B}\cdot d\mathbf{a} = \int_{S(t)} \left[\frac{\partial \mathbf{B}}{\partial t} + \nabla\times(\mathbf{B}\times\mathbf{v}) + \mathbf{v}(\nabla\cdot\mathbf{B})\right]\cdot d\mathbf{a}$$

See Reference [1]

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\times(\mathbf{B}\times\mathbf{v}) = -\nabla\times\frac{1}{\mu\sigma}(\nabla\times\mathbf{B})$$

Magnetic induction **Magnetic diffusion** (electromagnetism only)

This balance law for the magnetic flux is used along with those for the mass and momentum in the core of the finite element formulation of ALEGRA.

[1] A. C. Eringen and G. A. Maugin, *Electrodynamics of Continua I, Foundations and Solid Media,* Springer-Verlag, New York, 1990.

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Computational electromagnetics in ALEGRA

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See Reference [1]

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\times(\mathbf{B}\times\mathbf{v}) = -\nabla\times\frac{1}{\sigma}\left(\nabla\times\frac{1}{\mu}\mathbf{B} - \nabla\times\mathbf{M}\right)$$

Magnetic induction | **Magnetic diffusion** | (with material magnetization)

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Computational electromagnetics in ALEGRA

3. Operator splitting approach

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{B} \times \mathbf{v}) = -\nabla \times \frac{1}{\sigma}\left(\nabla \times \frac{1}{\mu}\mathbf{B} - \nabla \times \mathbf{M}\right)$$

Magnetic induction → **1** Advance finite-element solution assuming material is perfectly conducting ($\mathbf{B}$ is an advected quantity)

Explicit time integration

Magnetic diffusion → **2** Advance transient magnetic ("eddy current") diffusion solution using real finite conductivity σ.

Implicit time integration, iterative solver

Focus of this talk

$\mathbf{H}$ = magnetic field

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$\mathbf{f}_{\mathrm{em}}$ = electromagnetic force density

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Iterative solvers in ALEGRA are provided by Trilinos

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \frac{1}{\sigma}\left(\nabla \times \frac{1}{\mu}\mathbf{B} - \nabla \times \mathbf{M}\right) \longrightarrow A\mathbf{x}^* = \mathbf{b}$$

Magnetic diffusion

When discretized for finite elements, this is a linear system assembled from the finite-element degrees of freedom and the discrete differential operators.

https://trilinos.github.io/

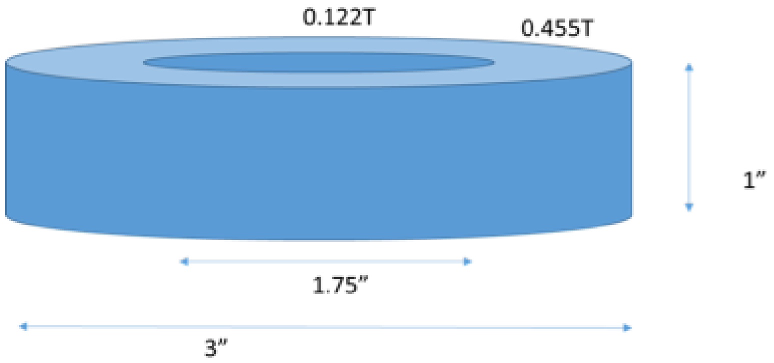
The solver iterates until the "convergence" criterion is reached: $A\mathbf{x}^* - \mathbf{b} < \varepsilon$

The system is solved in ALEGRA using various methods provided by Trilinos packages:

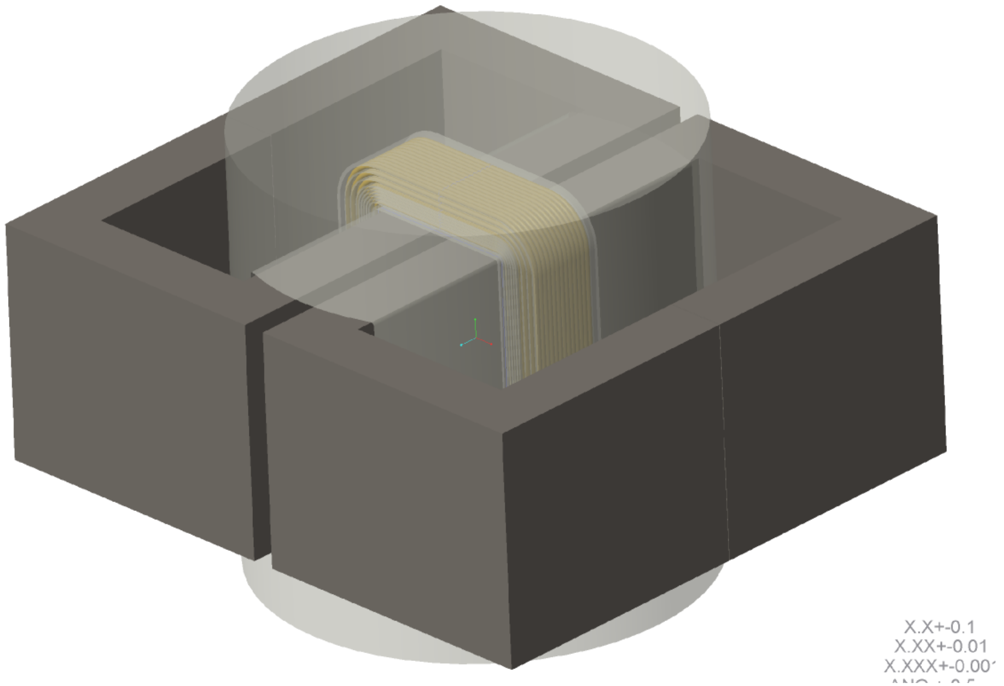
- Direct solve (LU decomposition)
- Multilevel solver (`aztecoo`) – parallelized for traditional multicore (CPU)
- Multilevel solver (`muelu`) – parallelized for modern architectures (GPU)

Choose your adventure: 3 verification/validation problems

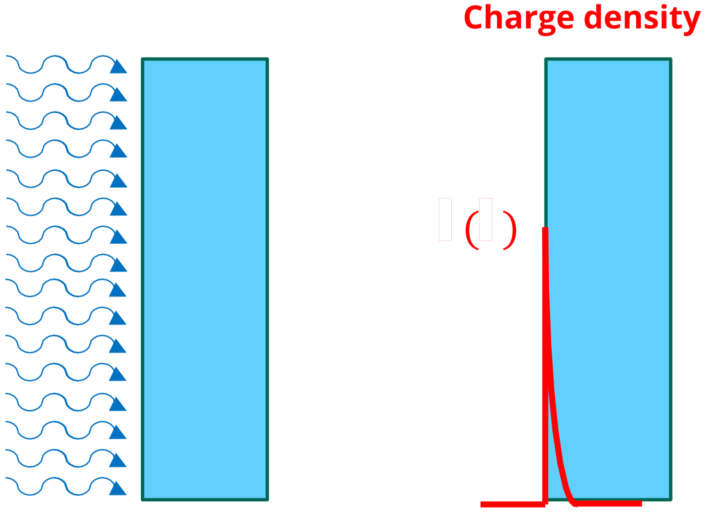
1 Ring magnet



2 Transformer coil



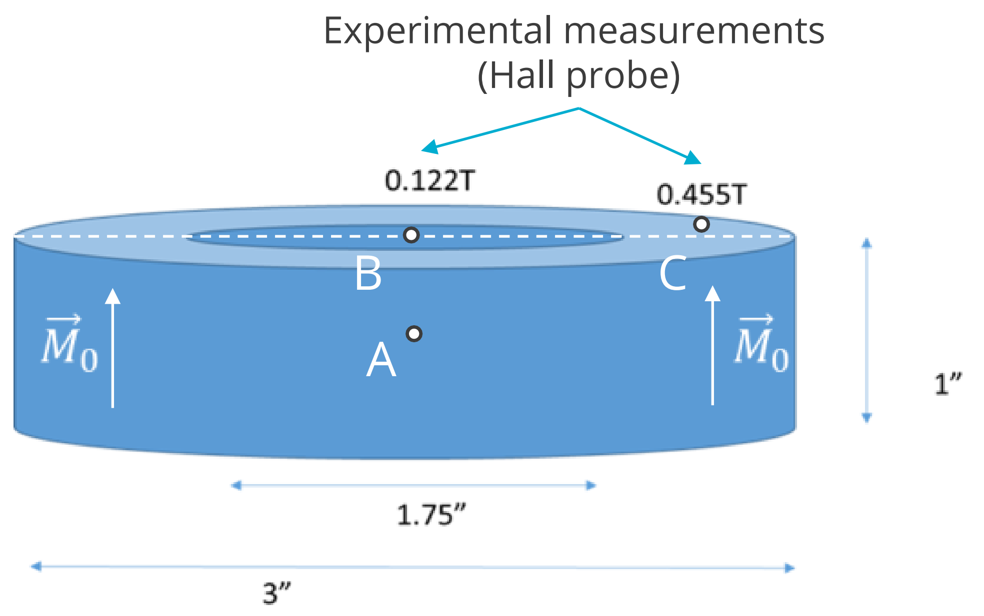
3 Charged slab



Problem 1: magnetic field due to a ring magnet

Sandia engineers wished to optimize the $\vec{B}$ field for a diagnostic sensor involving a magnet with 3D geometry. A simplified axisymmetric ring magnet was used for testing:

- Neodymium alloy
- N42 grade
- Manufactured by K&J Magnetics (https://www.kjmagnetics.com)
- Known magnetization $M_0 = 1.007$ A/μm
- Known dimensions
- Known relative permeability $\mu_r = 1.05$



Was ALEGRA going to be reliable to model this "simple" system?

Details: https://cfwebprod.sandia.gov/cfdocs/CompResearch/docs/SAND2020-9623-RingMagnet.pdf

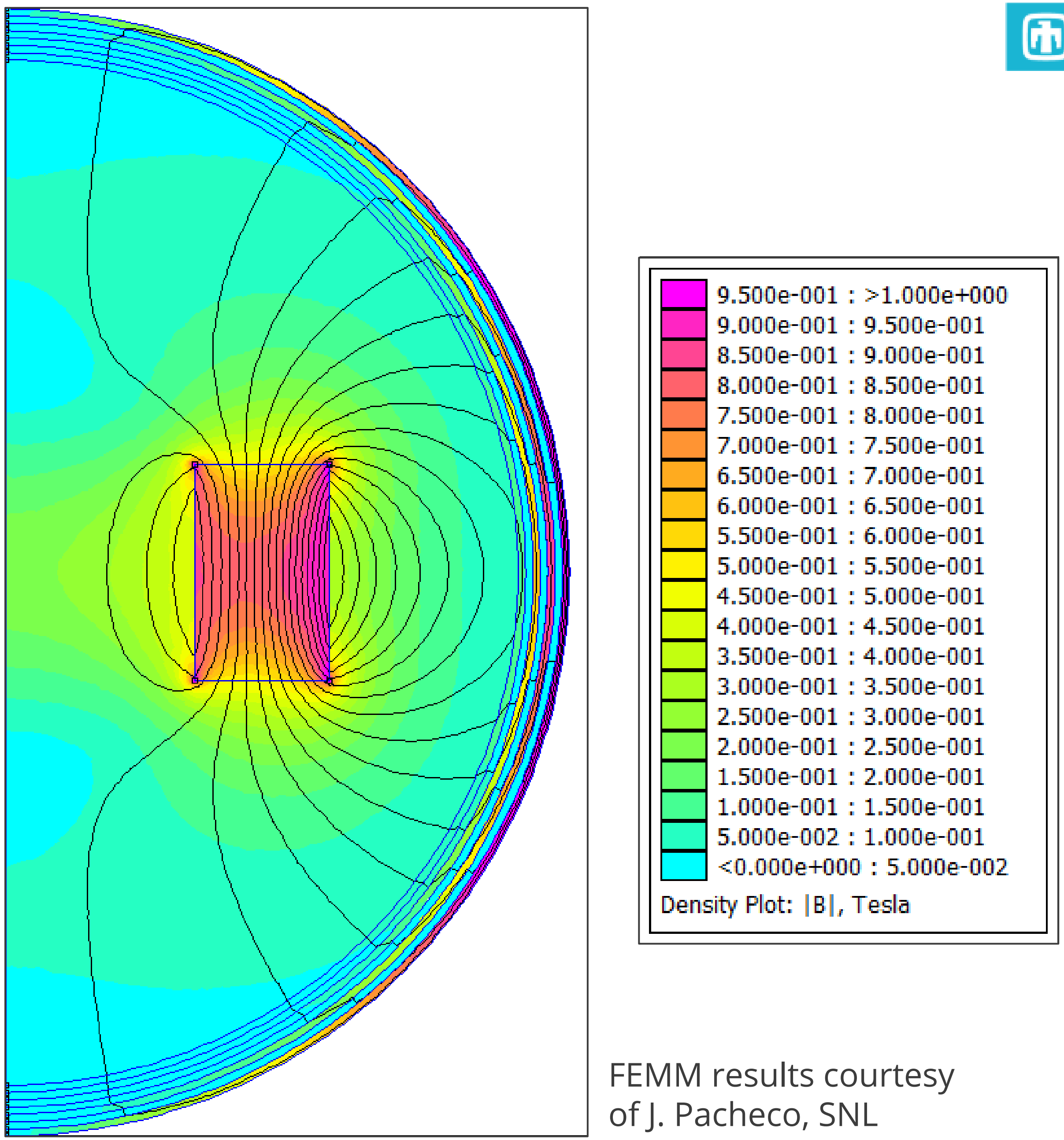
The FEMM code

The industry-standard modeling software for permanent magnets: Finite Element Method Magnetics (FEMM)

- Open source, available at https://www.femm.info/wiki/Download
- Well documented – see Refs [2] and [3]
- Triangular elements for ease of meshing
- Useful boundary conditions
- **2D only (Cartesian and cylindrical)**

[2] D. Meeker, FEMM user manual, October 2015. http://www.femm.info/wiki/Documentation/

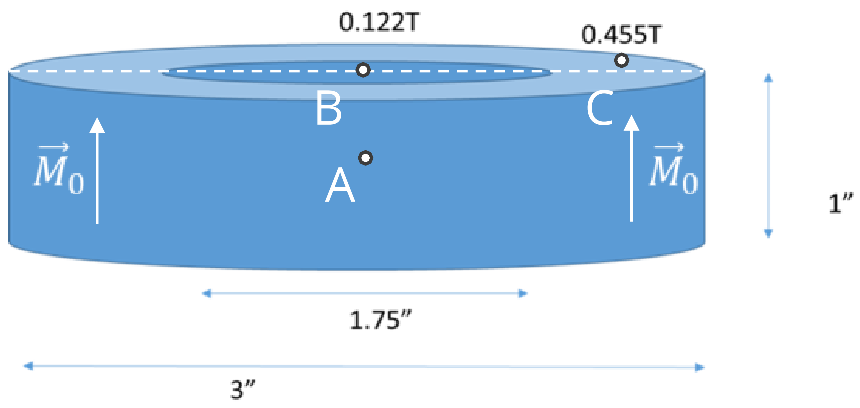
[3] D. Meeker, *IEEE Transactions on Magnetics* **49**(10), 5243 -5247, 2013. https://www.doi.org/10.1109/TMAG.2013.2260348



FEMM results courtesy of J. Pacheco, SNL

Analytic prediction

Camacho and Sosa [4] show how to write a closed-form expression for the z-component of the field on the axis of symmetry of a ring magnet with inner radius R_i, outer radius R_o, and axial length L:

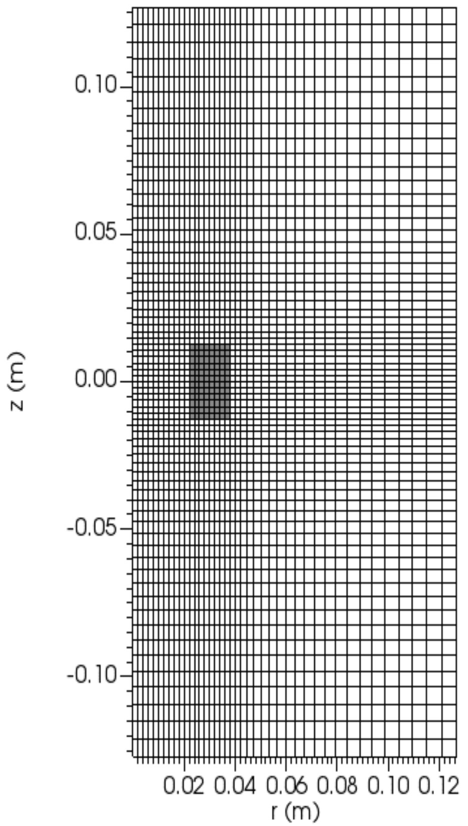


$$B_z(z) = \frac{\mu_r \mu_0 M_{0,z}}{2}\left[\left(\frac{z}{\sqrt{z^2+R_i^2}} - \frac{z-L}{\sqrt{(z-L)^2+R_i^2}}\right) - \left(\frac{z}{\sqrt{z^2+R_o^2}} - \frac{z-L}{\sqrt{(z-L)^2+R_o^2}}\right)\right]$$

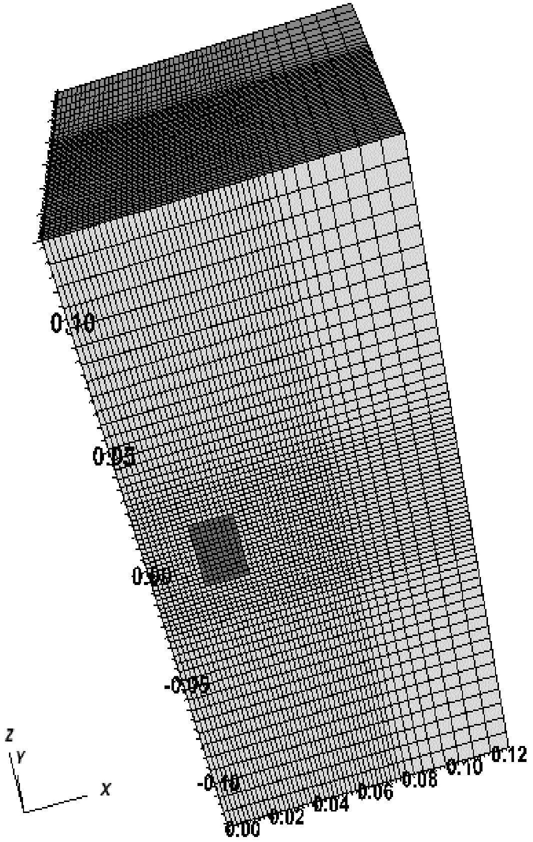
[4] J. M. Camacho and V. Sosa, "Alternative method to calculate the magnetic field of permanent magnets with azimuthal symmetry," *Revista Mexicana de F´ısica E* **59**, 8–17, 2013 http://www.scielo.org.mx/pdf/rmfe/v59n1/v59n1a2.pdf

Values in Tesla	**Analytic (Camacho & Sosa)**	**Manufacturer specification**	**Measured**
Point A	0.239	0.238	-
Point B	0.131	0.131	0.122
Point C	-	-	0.455

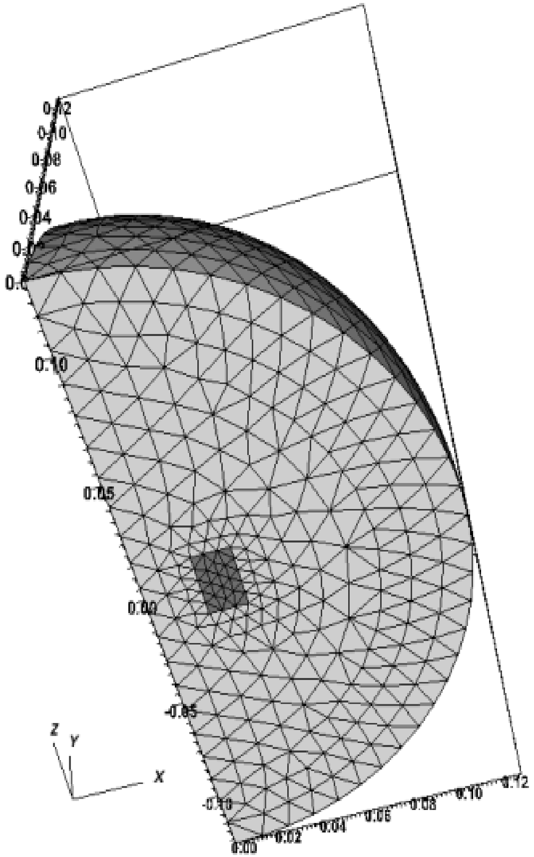
Configuration of ALEGRA simulations



2D axisymmetric Quad elements



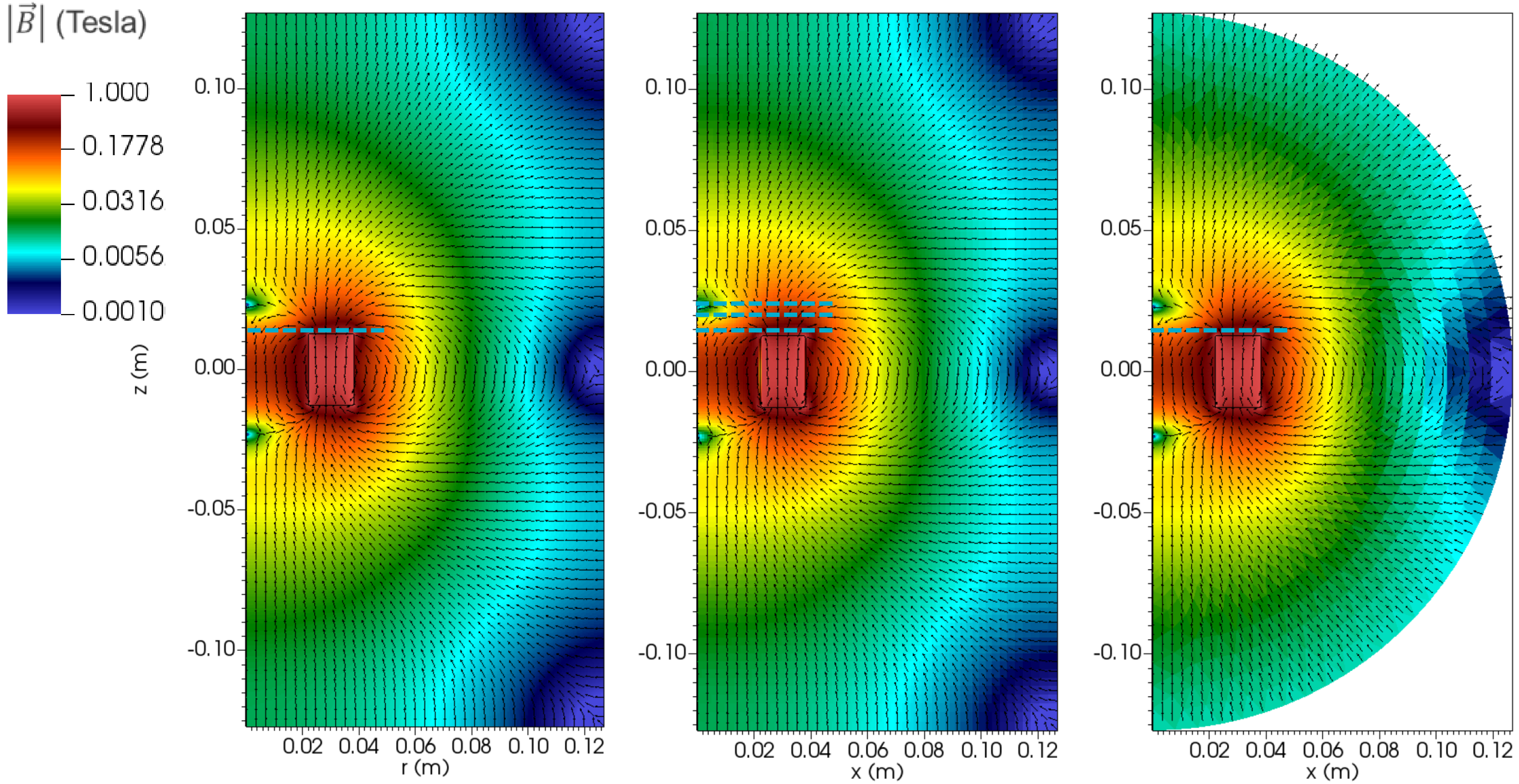
3D Cartesian Hex elements



3D conformal Tet elements

- Exterior boundary condition: $\mathbf{H} \times \hat{n} = 0$.
- Initial condition:
  - Neodymium ring with $M_{0,z} = 1.007$ A/m and $\mu_r = 1.05$.
  - Exterior with $\mathbf{H} = 0$ and $\mu = \mu_0$.
- No internal BC at interface.
- No static capability, so this is a transient simulation to reach steady state.
- Trick: assume electrical conductivity $\sigma = 10^{-6}$ S/m

ALEGRA simulation results

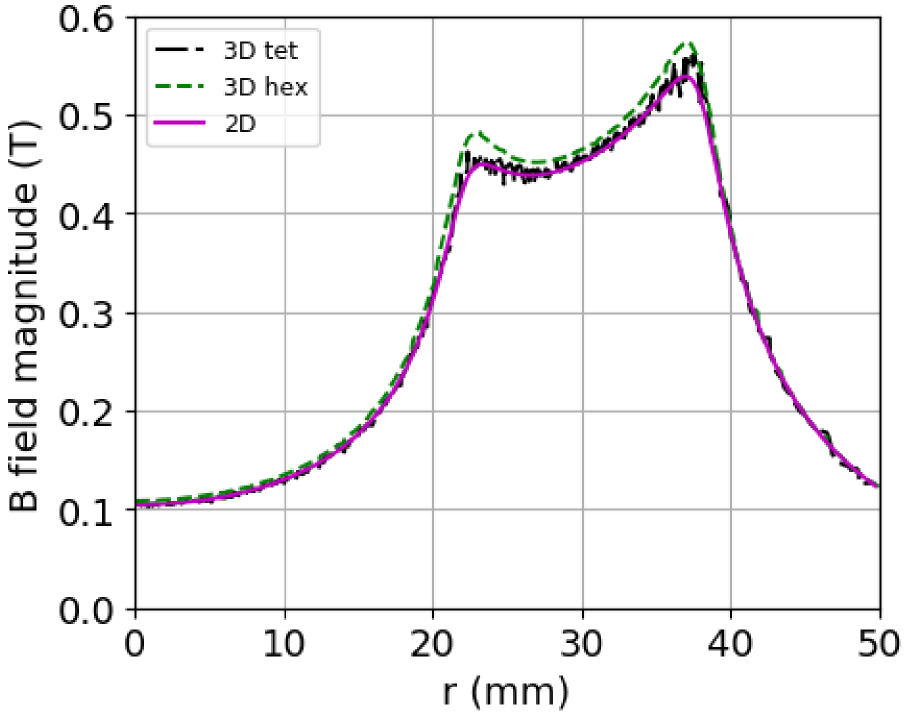


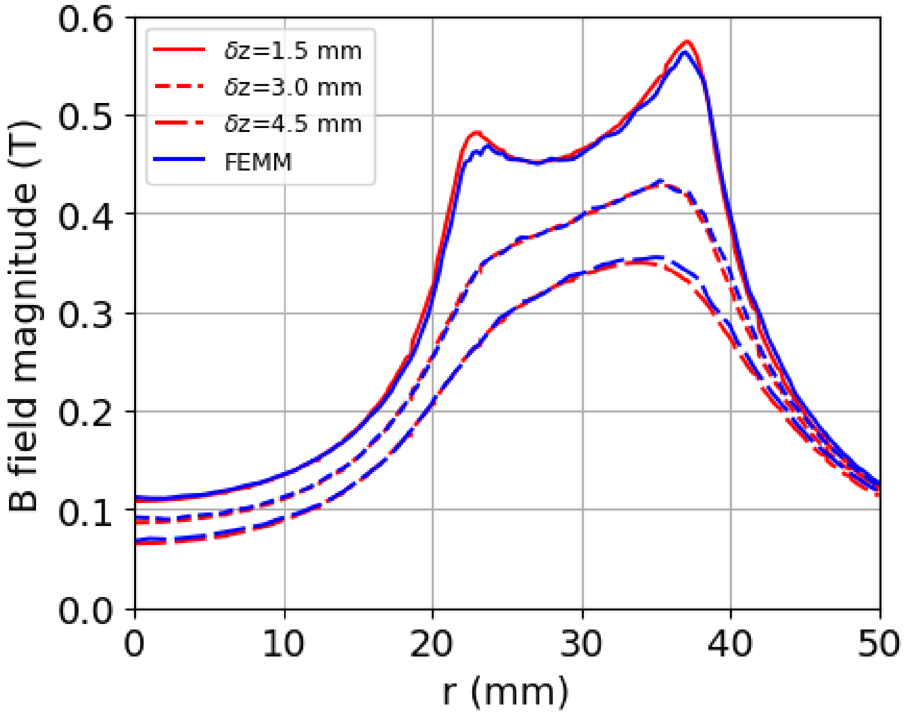
2D axisymmetric Quad elements

3D Cartesian Hex elements

3D conformal Tet elements

ALEGRA simulation results: line samples



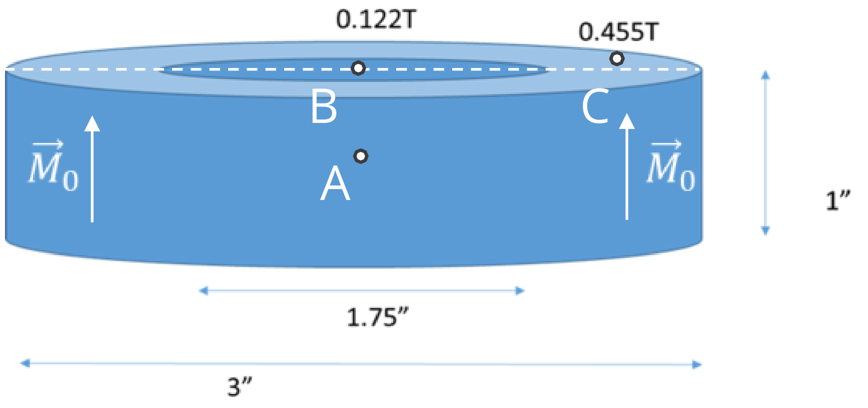


Sample profiles show:
(1) Tet mesh solution has unexplained high-frequency noise.
(2) Hex mesh solution matches FEMM results to within and RMS deviation of 8 mT (~1%)

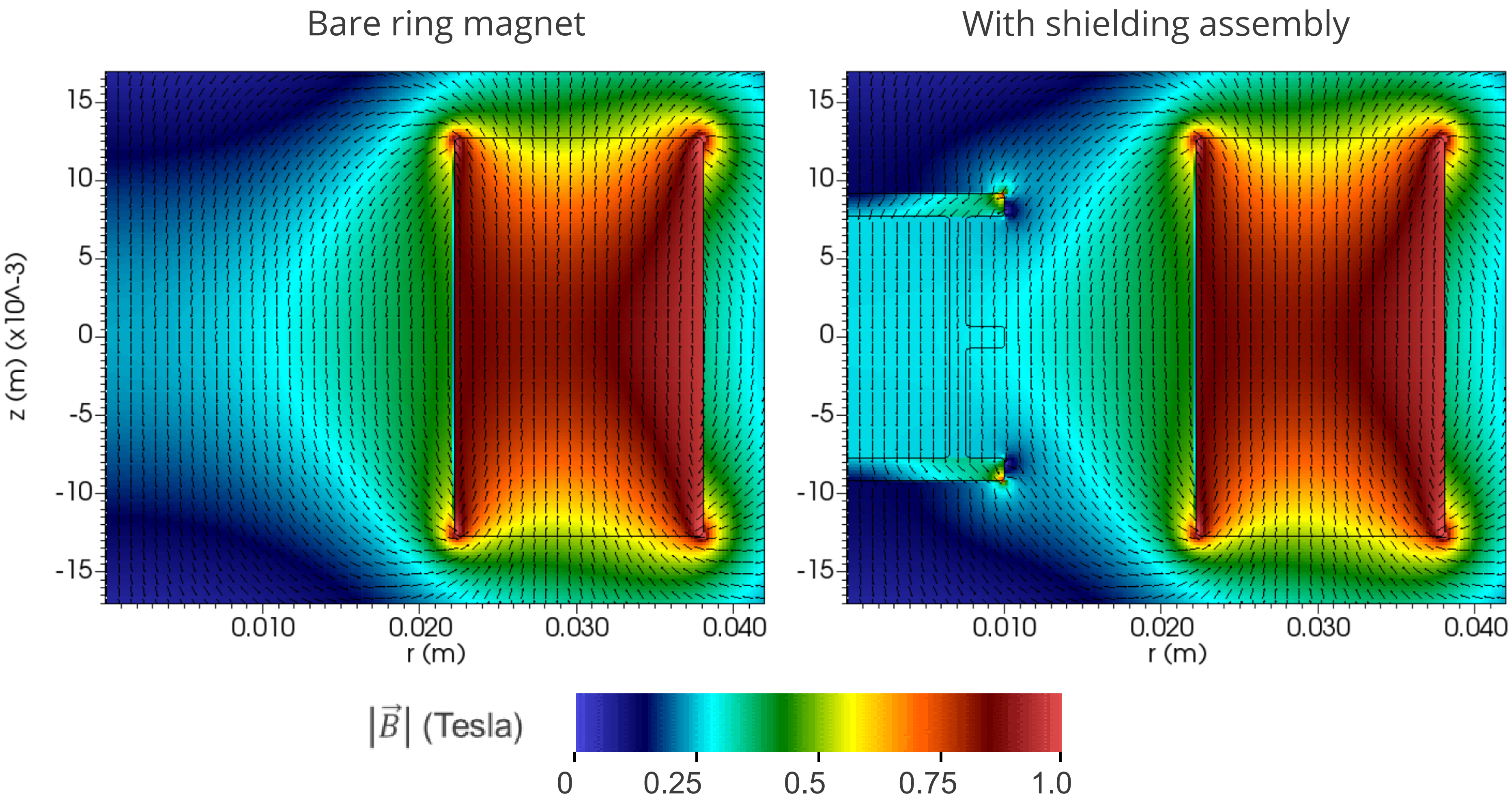
ALEGRA simulation results: point samples

Magnetic induction magnitude in Tesla	**Analytic (Camacho & Sosa)**	**Manufacturer specification**	**Measured**	**FEMM**	**ALEGRA 2D**	**ALEGRA 3D hex**	**ALEGRA 3D tet**
Point A	0.239	0.238	-	0.234	0.232	0.232	0.231
Point B	0.131	0.131	0.122	0.131	0.135	0.125	0.124
Point C	-	-	0.455	0.472	0.480	0.494	0.499

- FEMM and ALEGRA results agree to within 1.5% or less.
- FEMM and ALEGRA both produce smaller values than the analytic expression. (-2-5%)
- FEMM and ALEGRA both produce larger values than the Hall probe measurement. (+5-7%)



ALEGRA simulation results with shielding



- Iron disks (top and bottom)
  - $\mu_r = 1.5 \times 10^4$.
  - $\sigma = 10^7$ S/m.
- Copper ring (middle)
  - $\sigma = 5.9 \times 10^7$ S/m.
- ALEGRA shows uniform interior field.
- But much longer time is required to reach steady state, due to eddy currents in disks.

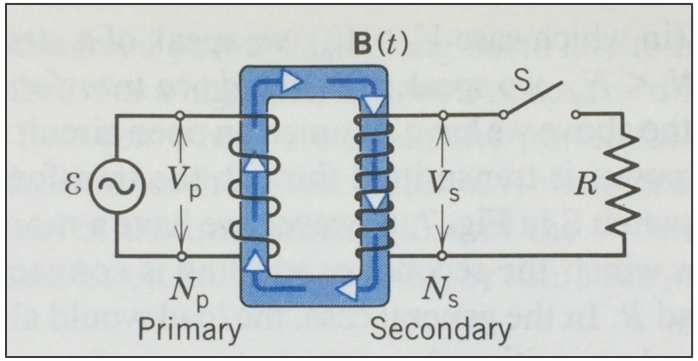
Go to final comments

Problem 2: magnetic field due to a transformer coil

Sandia engineers need a computational model for design of transformer systems.

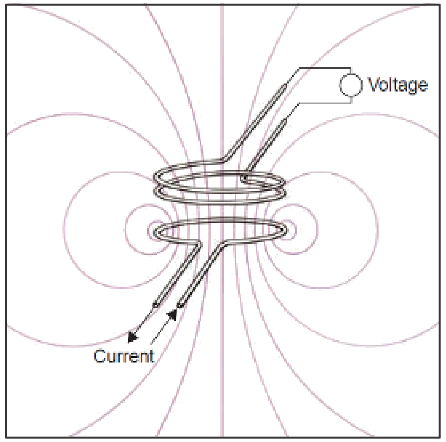
Model needs to capture these properties of transformers:

- A time-varying applied voltage on a primary coil
  induces
  a time-varying voltage response on a secondary coil
- Voltage step-up is based on magnetic flux, characterized by the **inductance**.

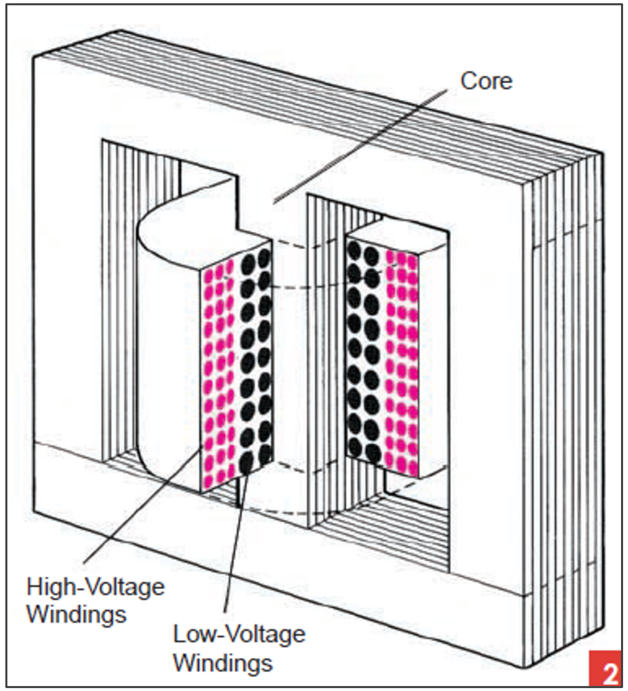


D. Halliday, R. Resnick, and K. S. Krane, *Physics*, 4th edition, 1991.

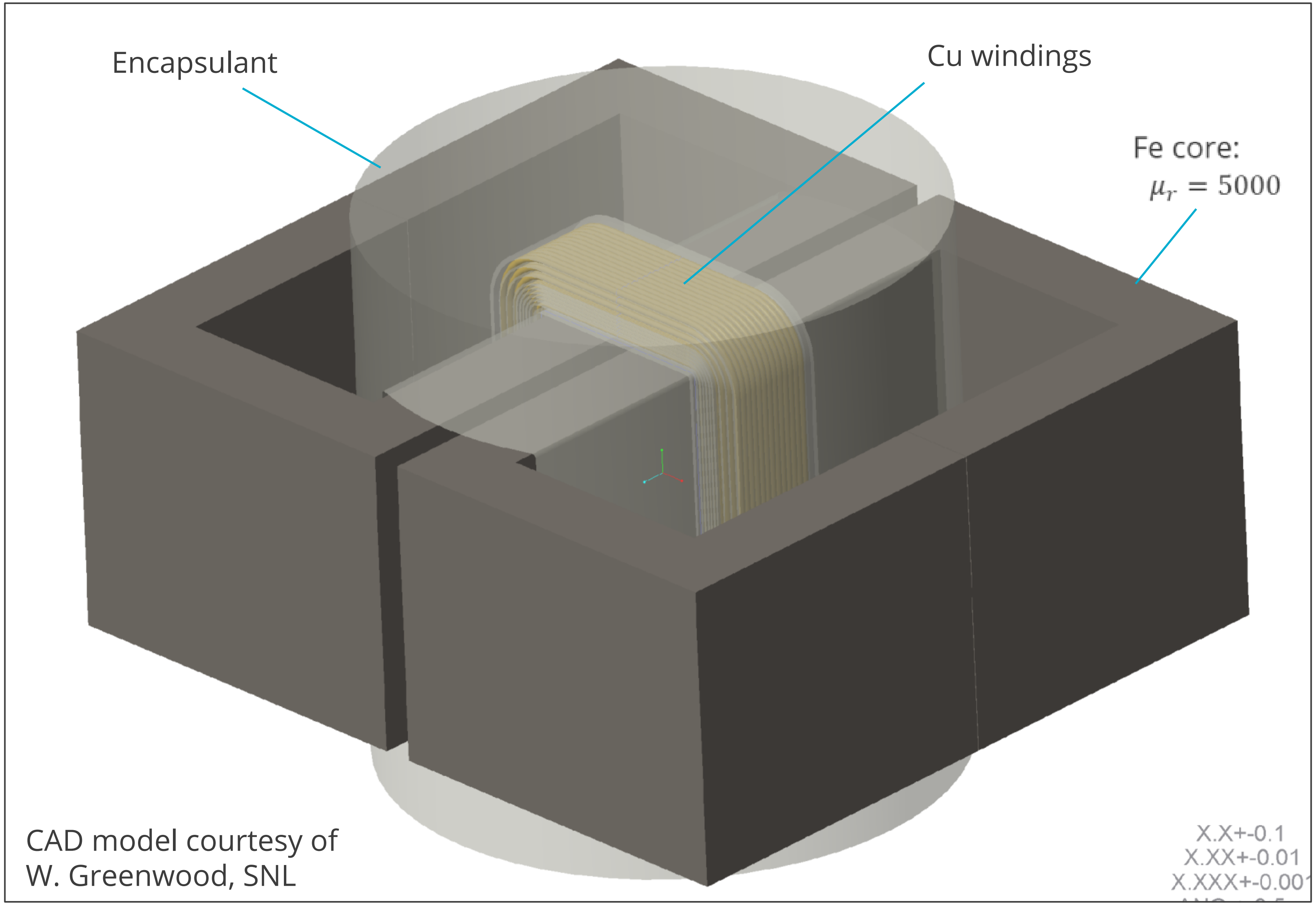
$$\frac{V_p}{N_p} = \frac{V_s}{N_s}$$



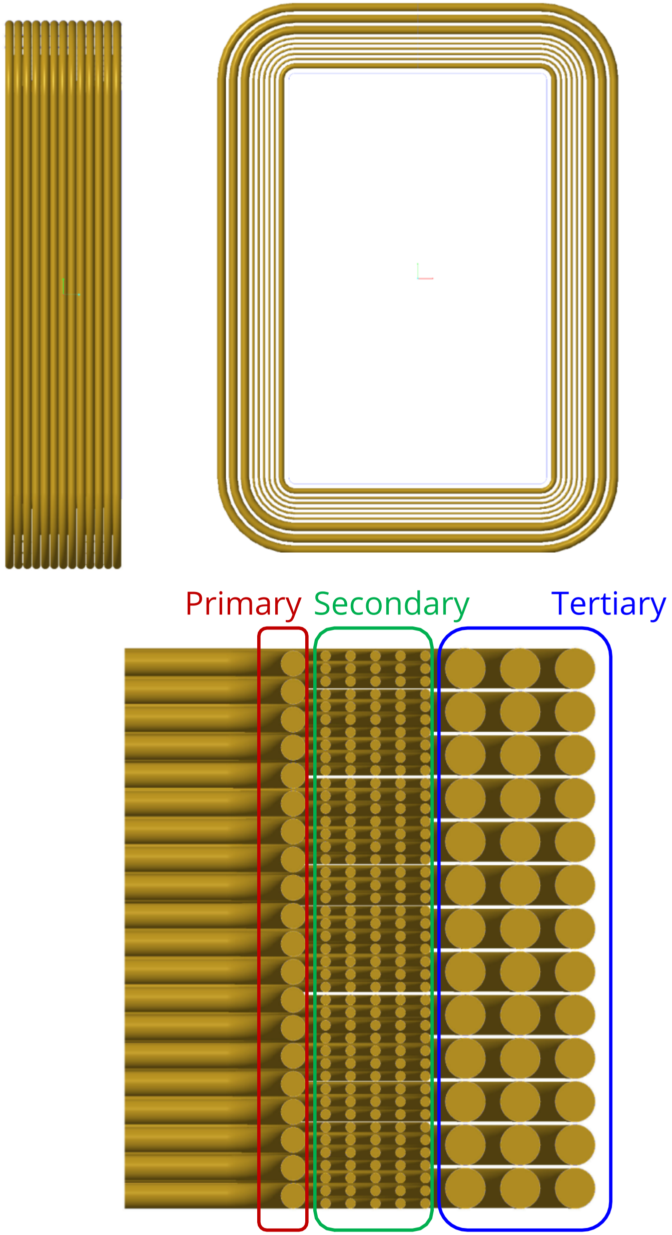
J. W. Coltman, "The Transformer," *IEEE Industry Applications Magazine*, January 2002.



Notional transformer geometry



CAD model courtesy of
W. Greenwood, SNL



Inductance of a rectangular coil: analytic estimates

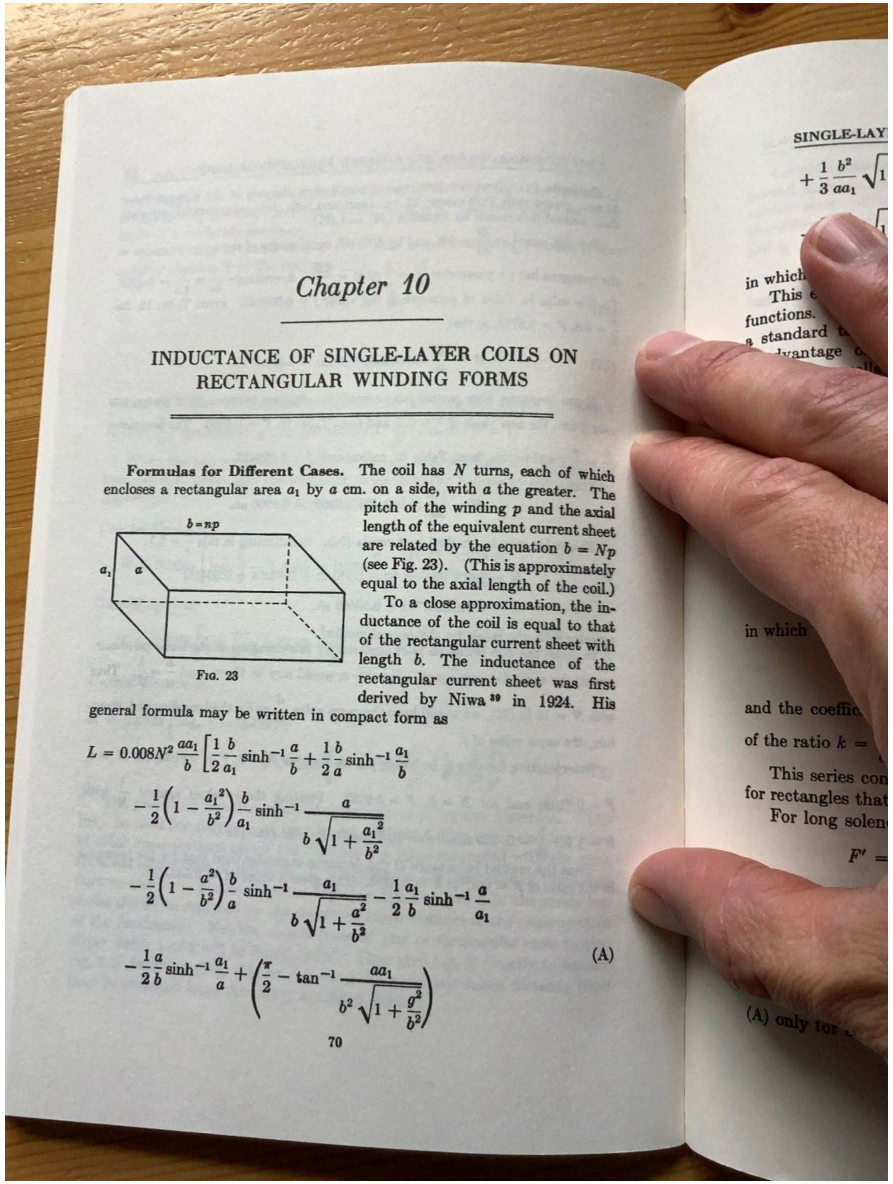
Grover (1946) [5] is a widely accepted resource for inductance calculations. Chapter 10 has a formula credited to Y. Niwa (1918) for rectangular coils, treating each leg as a current sheet. See [6] for details.

Several online calculators are available:

- http://www.moshier.net (astronomer)
- http://structbio.biochem.dal.ca/jrainey/downloads.html (molecular biologist)
- http://electronbunker.ca/eb/InductanceCalcRc.html (radio electronics developer) – R . Weaver

[5] F. W. Grover, *Inductance Calculations*, D. Van Nostrand Company, 1946. Reprint, Dover, 2009.

[6] R. K. Rainey et al., *Journal of Magnetic Resonance* **187**(1), 27-27, 2007. https://doi.org/10.1016/j.jmr.2007.03.016



Chapter 10

INDUCTANCE OF SINGLE-LAYER COILS ON RECTANGULAR WINDING FORMS

Formulas for Different Cases. The coil has N turns, each of which encloses a rectangular area a_1 by a cm. on a side, with a the greater. The pitch of the winding p and the axial length of the equivalent current sheet are related by the equation $b = Np$ (see Fig. 23). (This is approximately equal to the axial length of the coil.)

To a close approximation, the inductance of the coil is equal to that of the rectangular current sheet with length b. The inductance of the rectangular current sheet was first derived by Niwa [39] in 1924. His general formula may be written in compact form as

FIG. 23

$$L = 0.008N^2\frac{aa_1}{b}\left[\frac{1}{2}\frac{b}{a_1}\sinh^{-1}\frac{a}{b} + \frac{1}{2}\frac{b}{a}\sinh^{-1}\frac{a_1}{b} - \frac{1}{2}\left(1-\frac{a_1^2}{b^2}\right)\frac{b}{a_1}\sinh^{-1}\frac{a}{b\sqrt{1+\frac{a_1^2}{b^2}}} - \frac{1}{2}\left(1-\frac{a^2}{b^2}\right)\frac{b}{a}\sinh^{-1}\frac{a_1}{b\sqrt{1+\frac{a^2}{b^2}}} - \frac{1}{2}\frac{a_1}{b}\sinh^{-1}\frac{a}{a_1} - \frac{1}{2}\frac{a}{b}\sinh^{-1}\frac{a_1}{a} + \left(\frac{\pi}{2} - \tan^{-1}\frac{aa_1}{b^2\sqrt{1+\frac{g^2}{b^2}}}\right) \right. \quad \text{(A)}$$

70

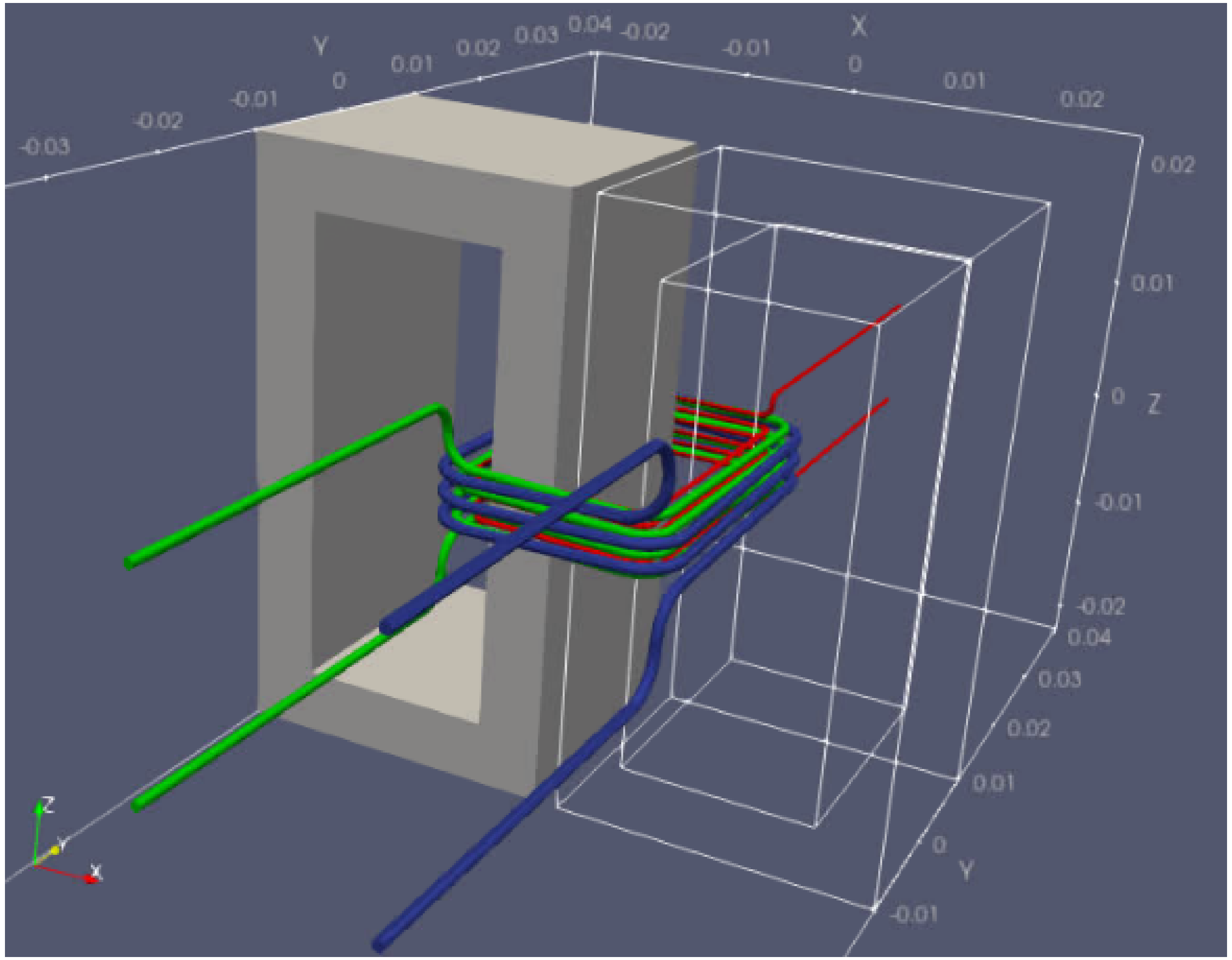
Modeling difficulties

Capturing the electromagnetic field of a coil is very tricky in ALEGRA:

- Windings and gaps must be resolved.
- Entire magnetic core must be included.
- All magnetized space including an exterior buffer must be included.
- Leads must extend to the boundary.
- Tet meshes are not reliable – hex meshing is required.
- Solver struggles to converge.

Our practical approach:

- Reduce the winding count by n/N.
- Adjust the simulated inductance by $(N/n)^2$.
- Use highly biased hex meshes.



ALEGRA simulation geometry. (Courtesy of A. Rodriguez, SNL)

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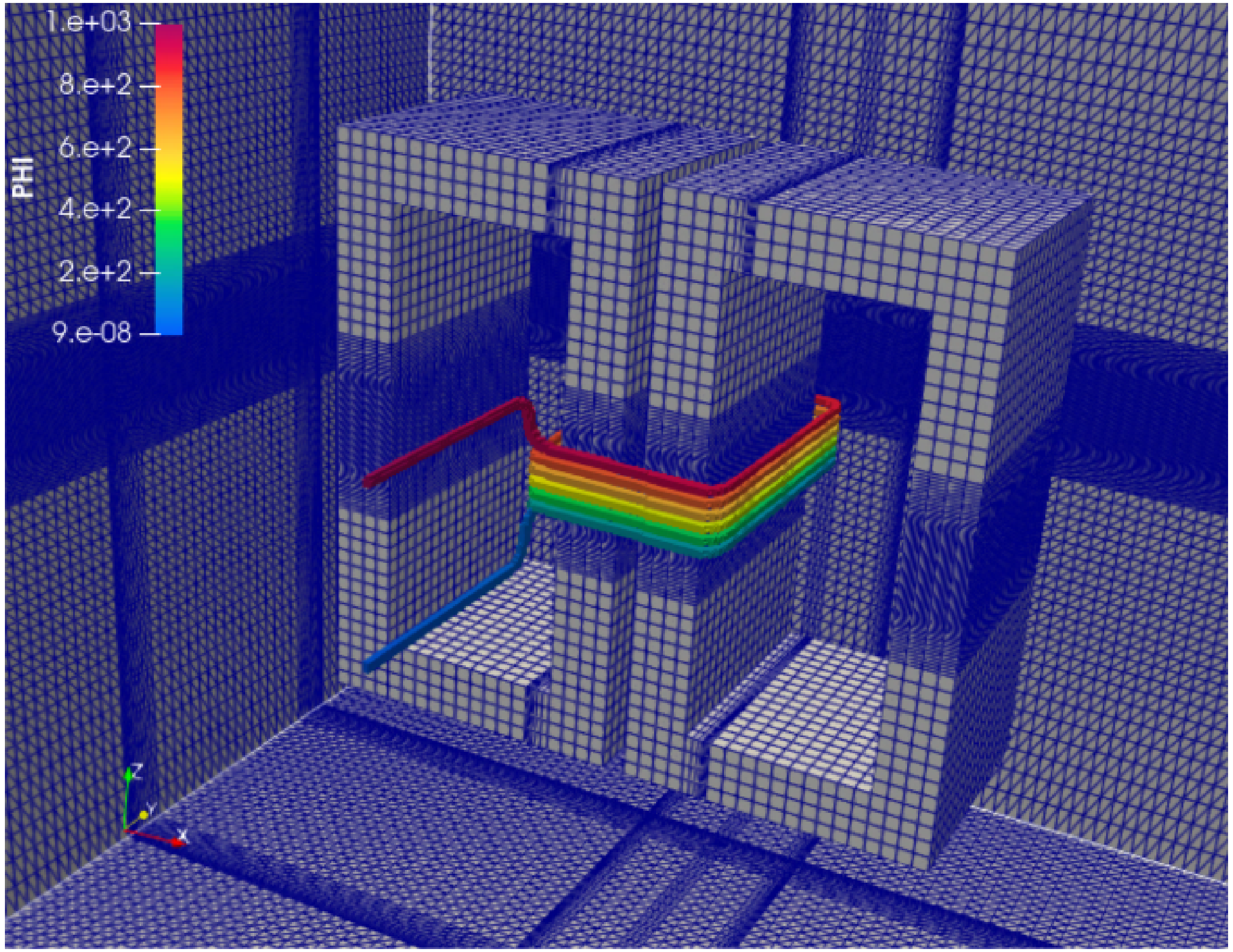
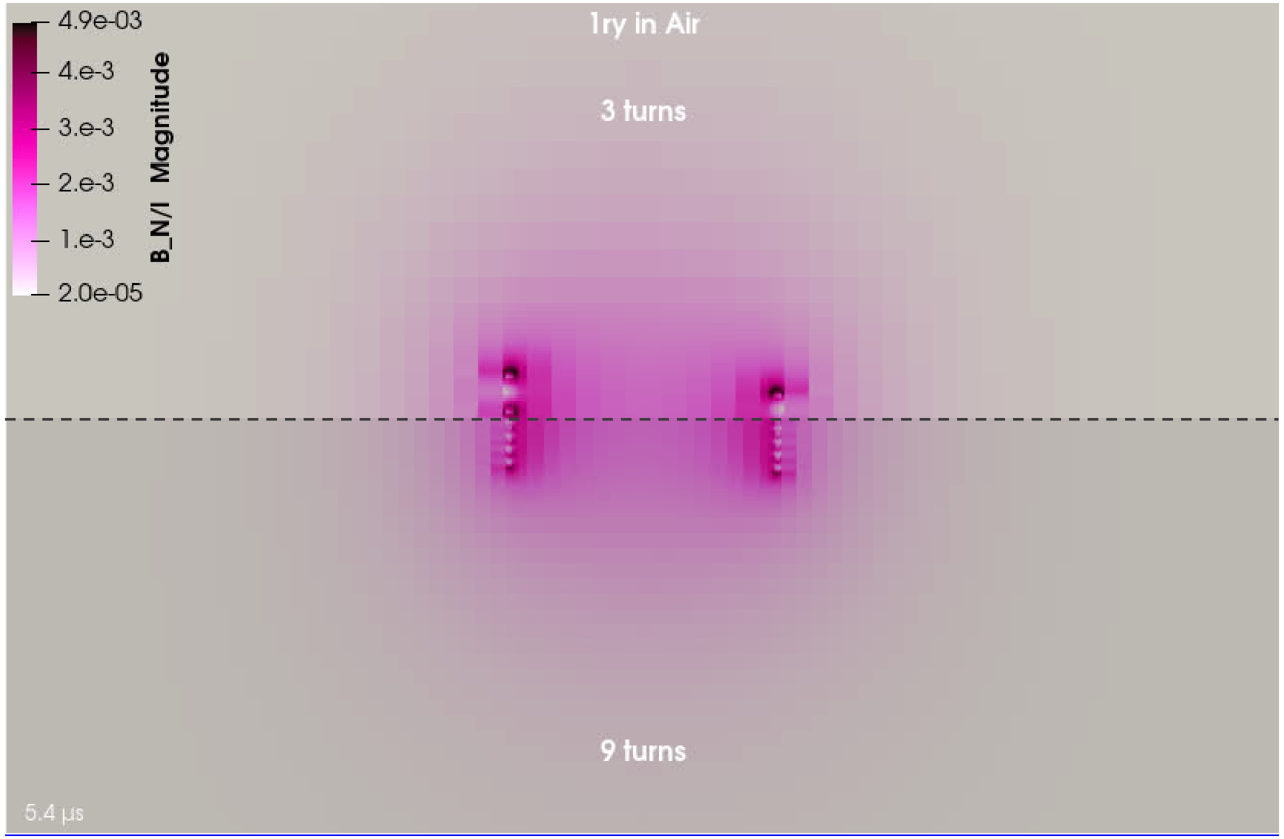


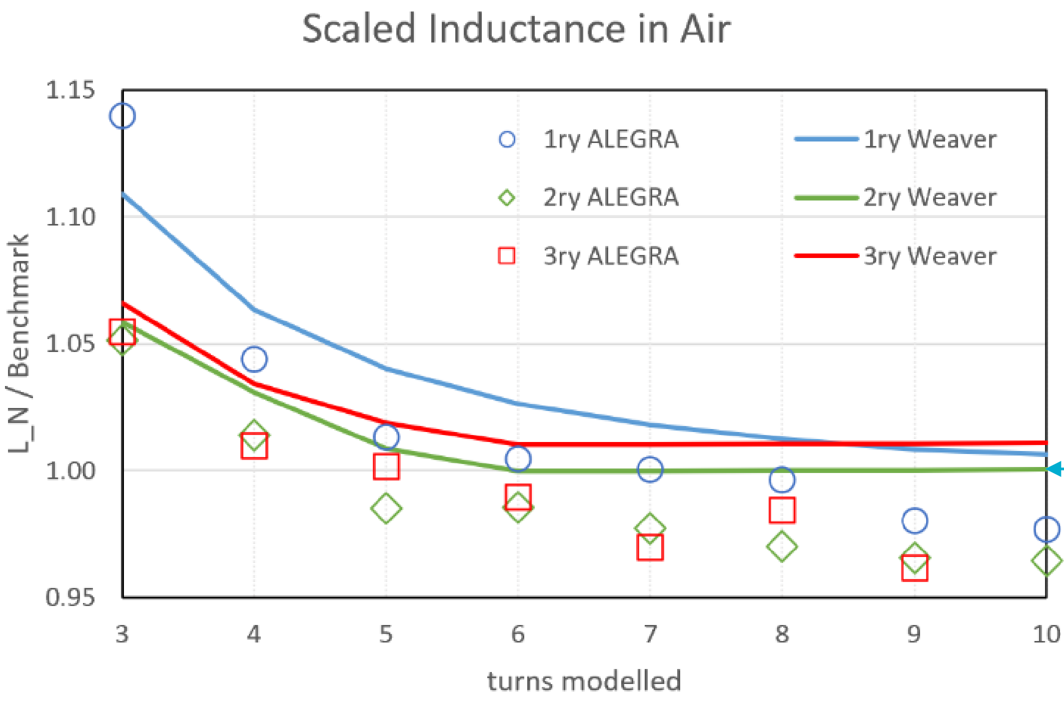
ALEGRA simulation initial condition for a single reduced coil, showing the electric potential (PHI) and mesh lines, with void space removed. (Courtesy of A. Rodriguez, SNL)

ALEGRA results: single coil in air

Analytic formulae and calculators do not include any magnetic core. Best verification test case for us: air background.



ALEGRA simulation snapshot showing scaled magnetic induction magnitude, comparing different winding counts for air background. (Courtesy of A. Rodriguez, SNL)

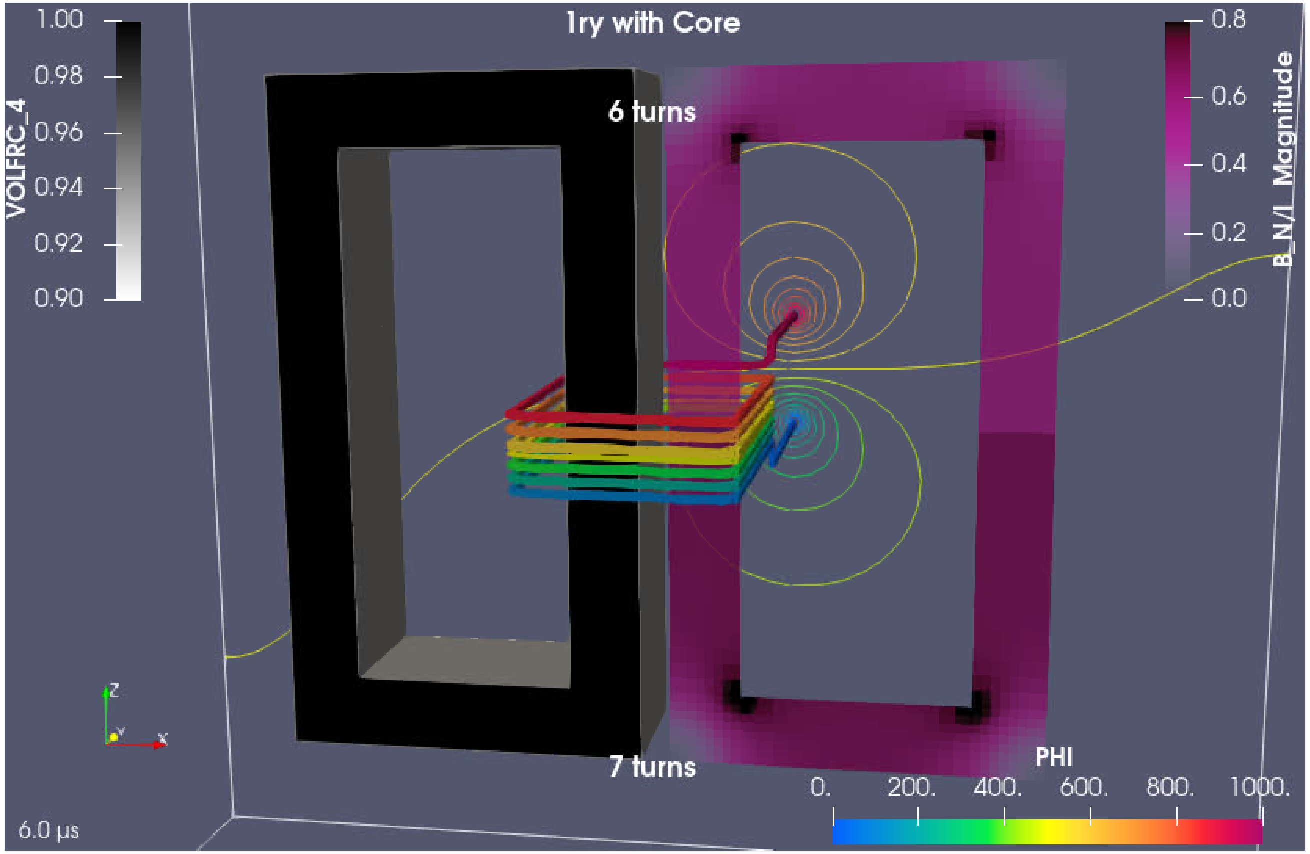


Benchmark: Weaver calculator, full coil winding count.

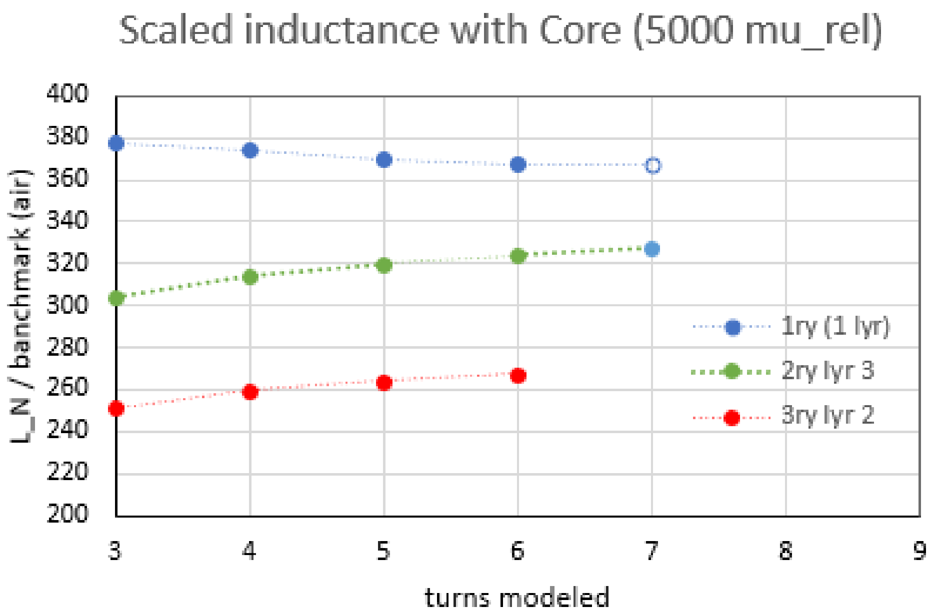
- **Solution is accurate to within 5%.**
- **Solver fails to converge for $n > 10$.**

Effect of the core

ALEGRA can provide an estimate of the inductance when a magnetic core is present, but it is not verifiable without direct measurement or another electromagnetics model.



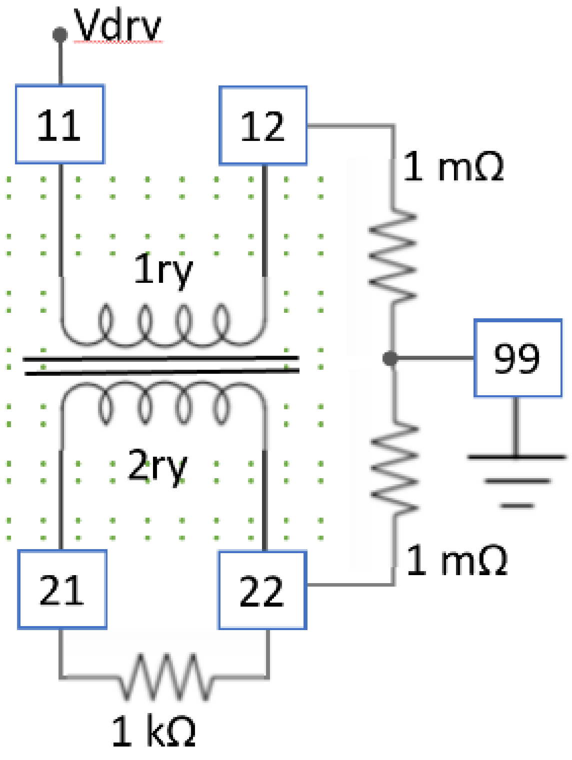
ALEGRA simulation snapshot showing scaled magnetic induction magnitude, comparing different winding counts with iron core. (Courtesy of A. Rodriguez, SNL)



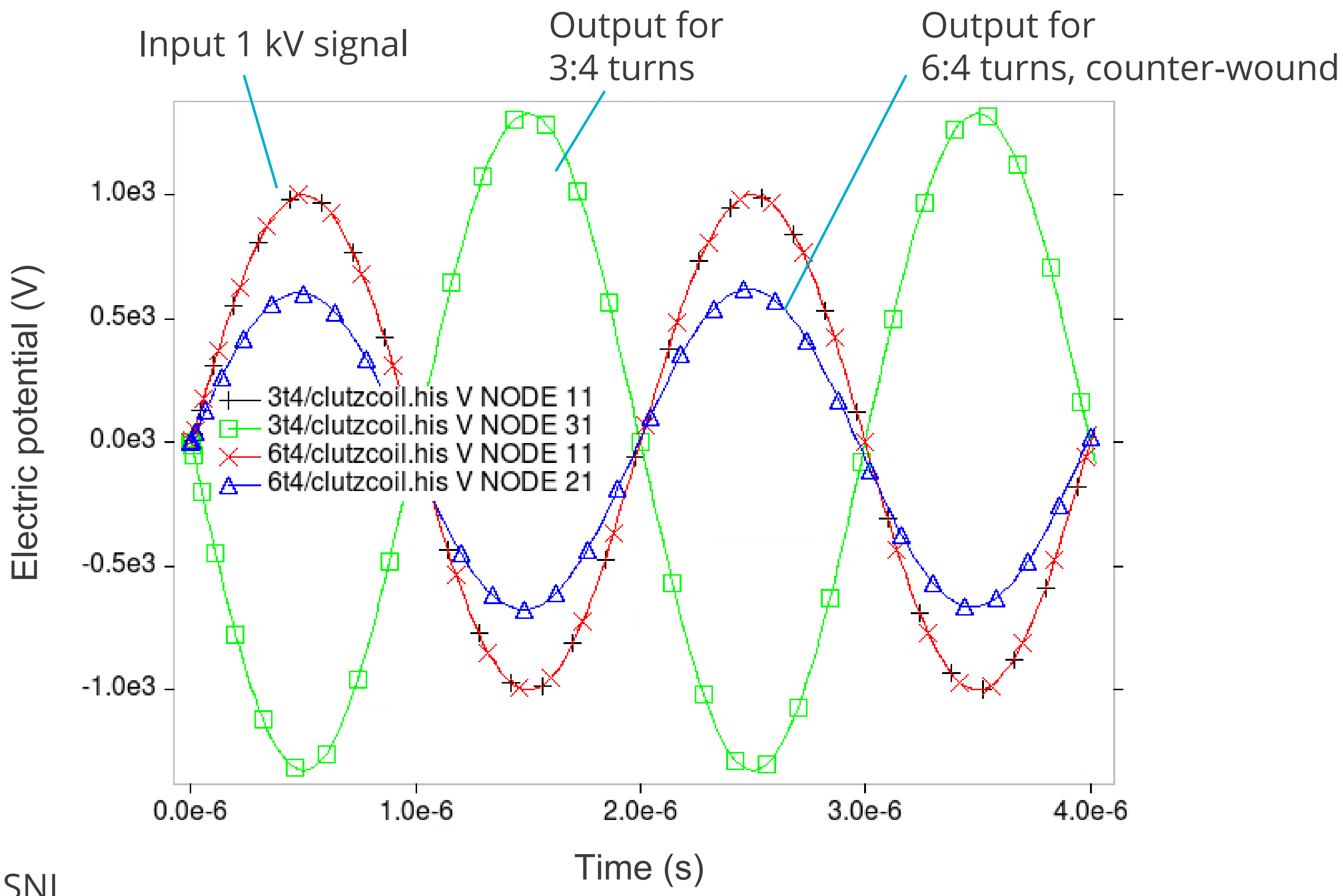
- **Inductance is within the expected range.**
- **Solver fails to converge for $n > 7$.**

Modeling transformer function

ALEGRA models with multiple coils do capture the expected voltage step-up or step-down.



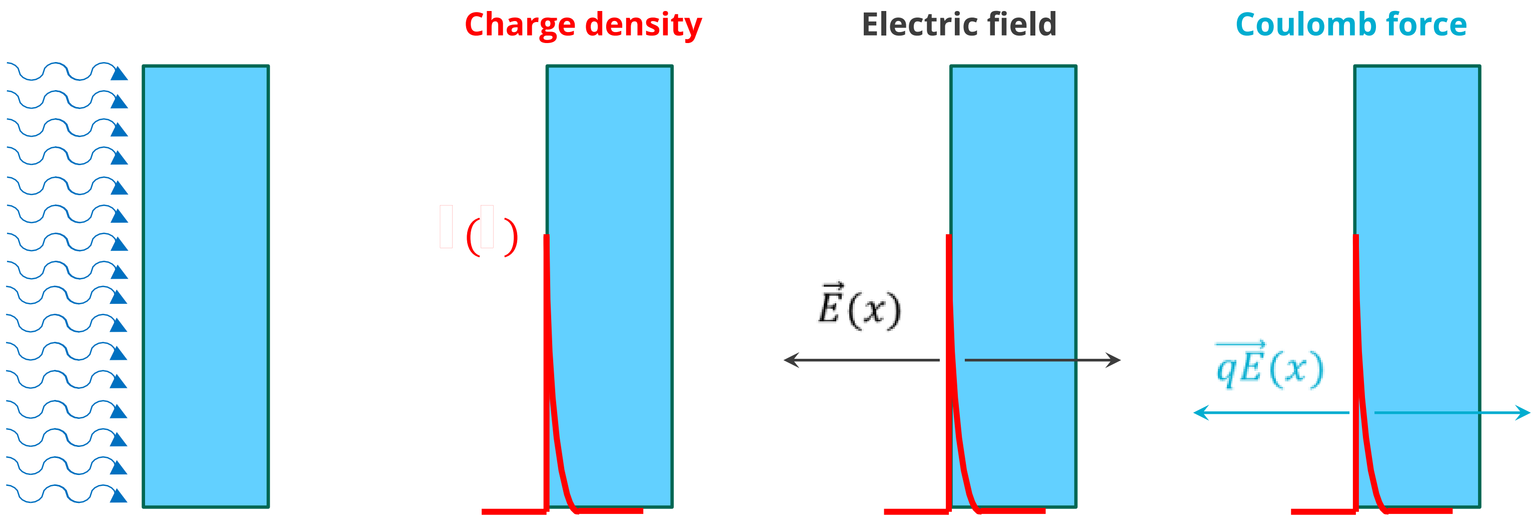
Courtesy of A. Rodriguez, SNL



Go to final comments

Problem 3: electric field due to radiation-deposited charge

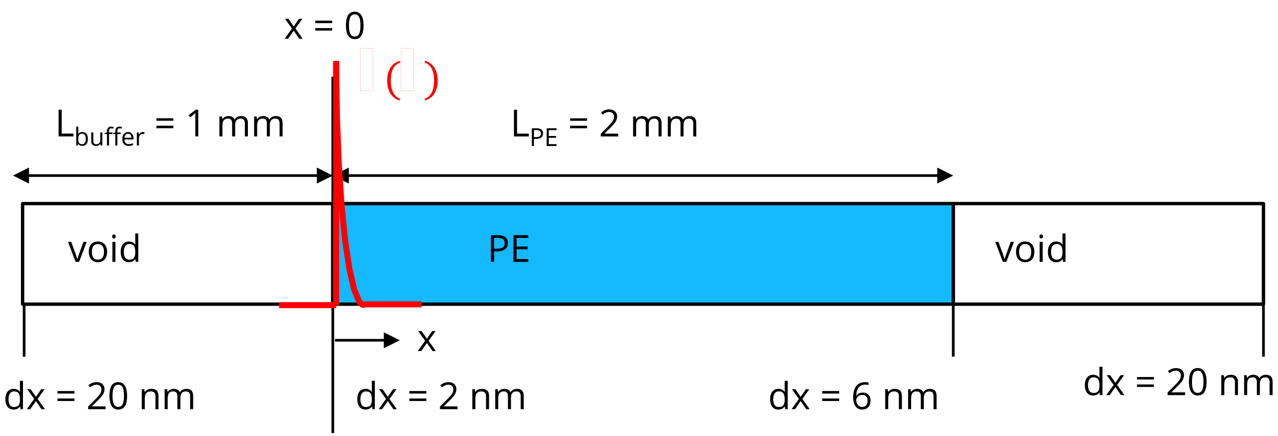
- Sandia engineers want to study effects of electrostatics on degradation of irradiated material surfaces.
  - Details: N. W. Moore et al., *Journal of Applied Physics*, 2020. https://aip.scitation.org/doi/abs/10.1063/5.0017566
- Consider this environment: a slab of polyethylene irradiated by a ns burst of 3-keV x rays.



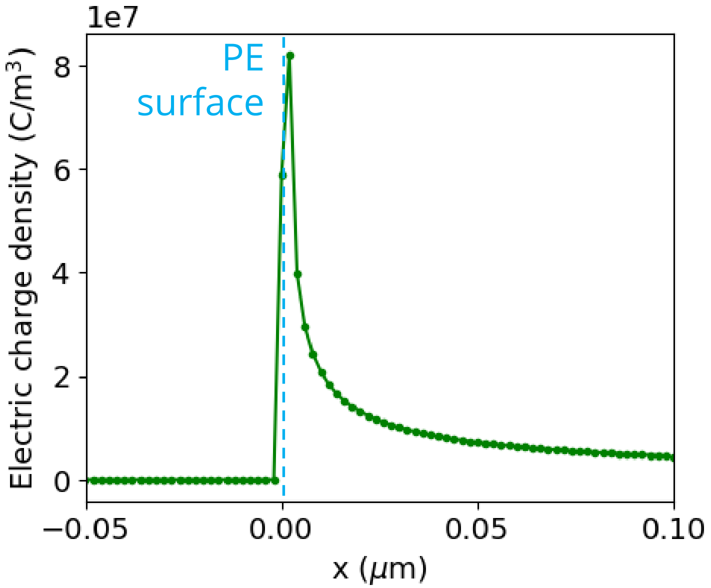
- Electron backscattering results in a predominantly positive charge profile: maximum of 10^7 C/m^3 at nm – μm depths for laboratory fluences from Sandia's Z accelerator.
- Can ALEGRA's "full-Maxwell" module compute the electric field for a 1D charge density profile?

Initial ALEGRA results were surprising

Geometry:



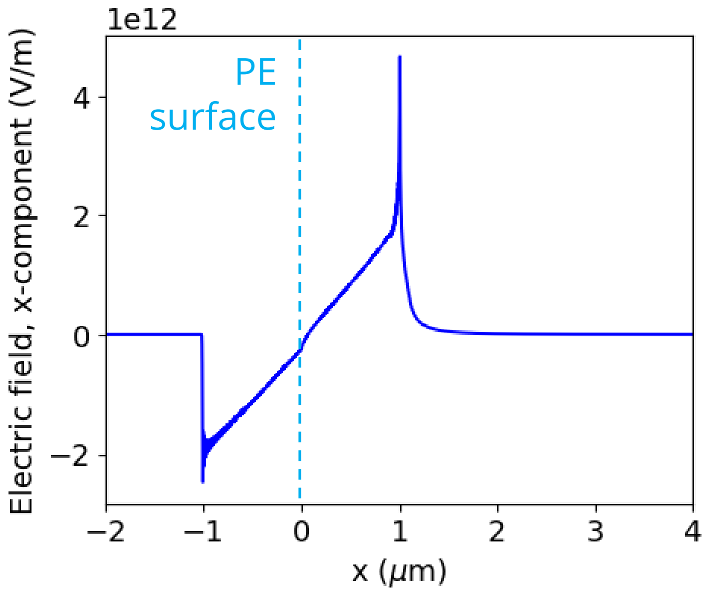
Linear mesh biasing, 700K elements total



Boundary conditions:

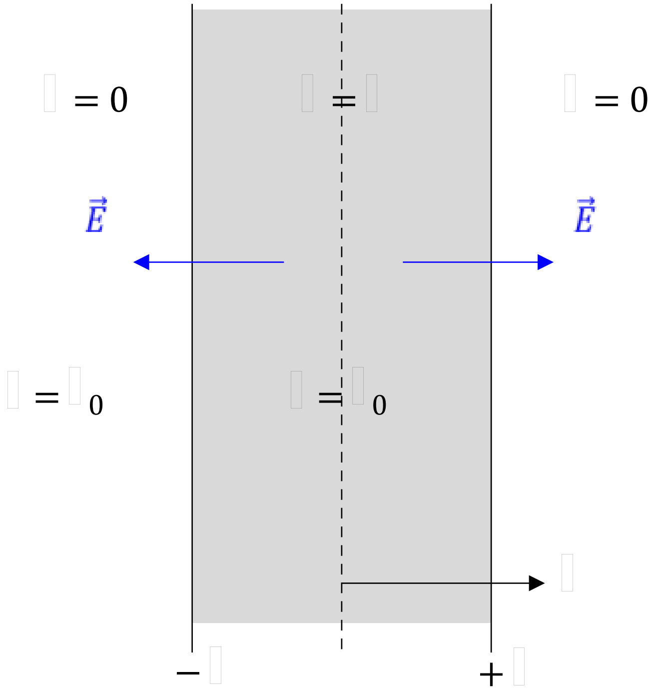
$\vec{E} \times \hat{n} = 0$ at left and right

$\vec{H} \times \hat{n} = 0$ at top and bottom



Produces Coulomb pressure on the order of 100 GPa!

Back to basics: consider a uniform charge density profile

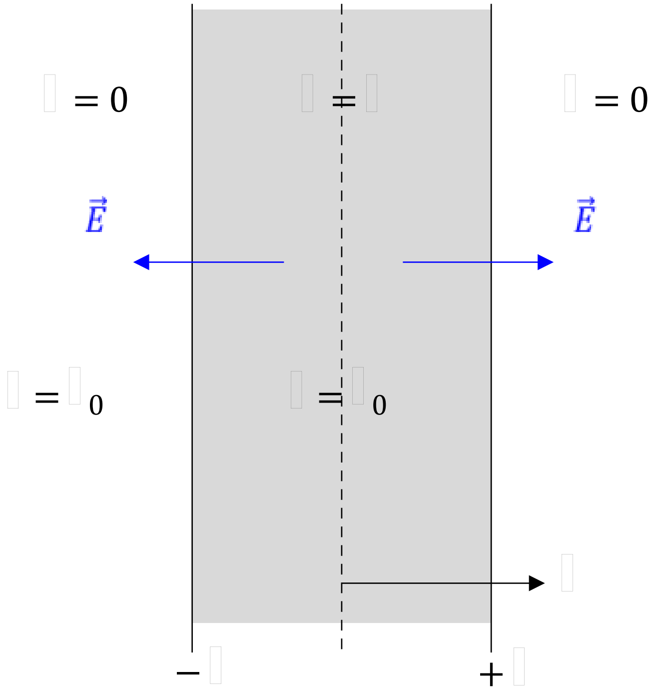


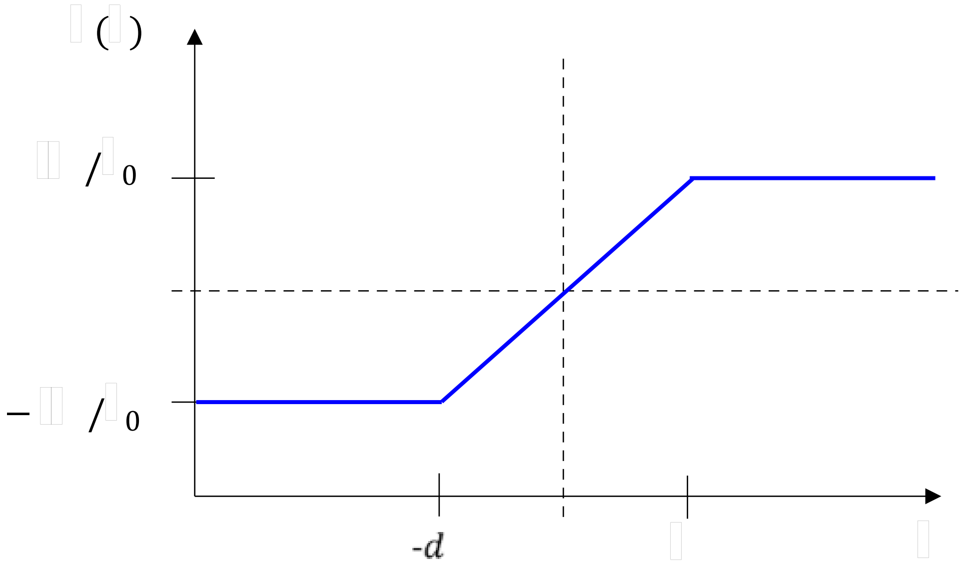
Permittivity of free space:
$\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{C^2/Nm^2}$

- Infinite plane slab with uniform volume charge density Q.
- The "pillbox" method of integrating Gauss's Law can easily be applied here to find $\vec{E}(x)$.
  - See Griffiths, *Introduction to Electrodynamcs* (3rd ed.), Problem 2.17
- Results in a symmetric linear electric field profile, diverging from the midplane:

$$E(x) = \begin{cases} -Qd/\epsilon_0, & x < -d \\ Qx/\epsilon_r\epsilon_0, & -d \le x \le d \\ Qd/\epsilon_0, & x > d \end{cases}$$

Back to basics: consider a uniform charge density profile

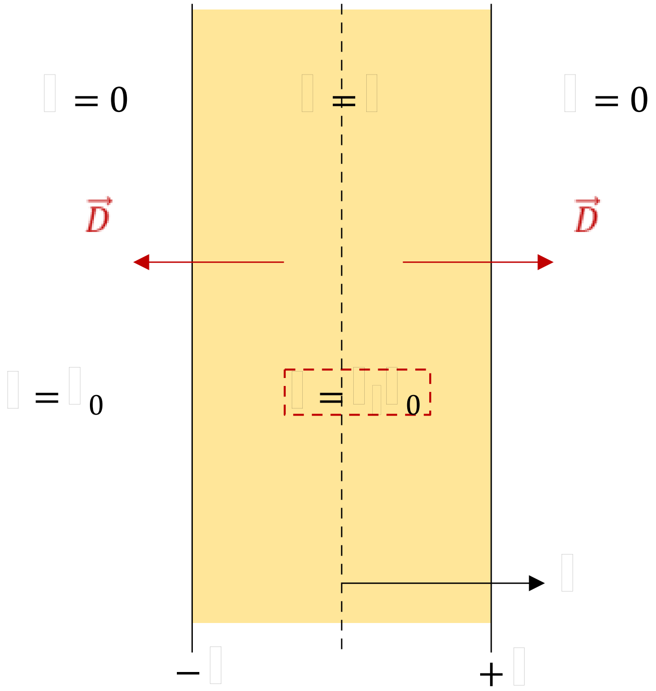




$E(x)$

$$E(x) = \begin{cases} -Qd/\epsilon_0, & x < -d \\ Qx/\epsilon_r\epsilon_0, & -d \le x \le d \\ Qd/\epsilon_0, & x > d \end{cases}$$

But wait, polyethylene is a dielectric material!



PE relative permittivity:
$\epsilon_r \approx 2.3$

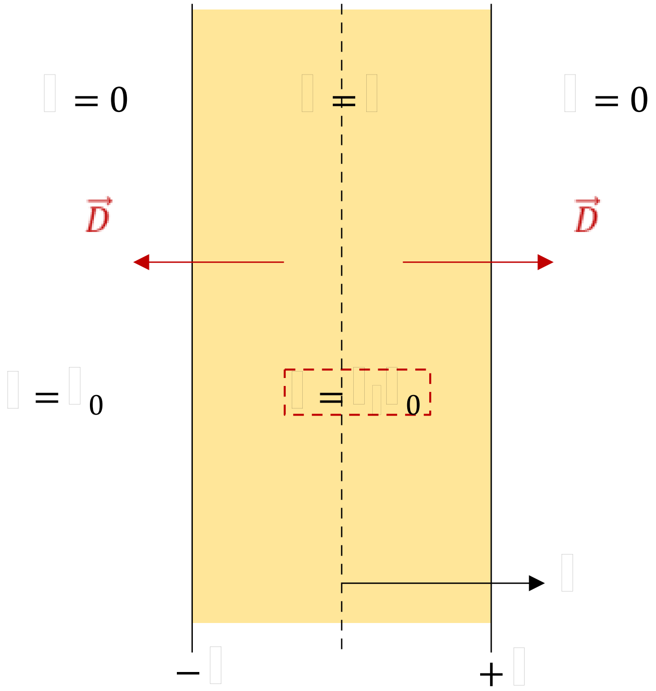
- Use the electric displacement $\vec{D} = \epsilon\vec{E}$ in Gauss's law, where $\epsilon = \epsilon_r\epsilon_0$:

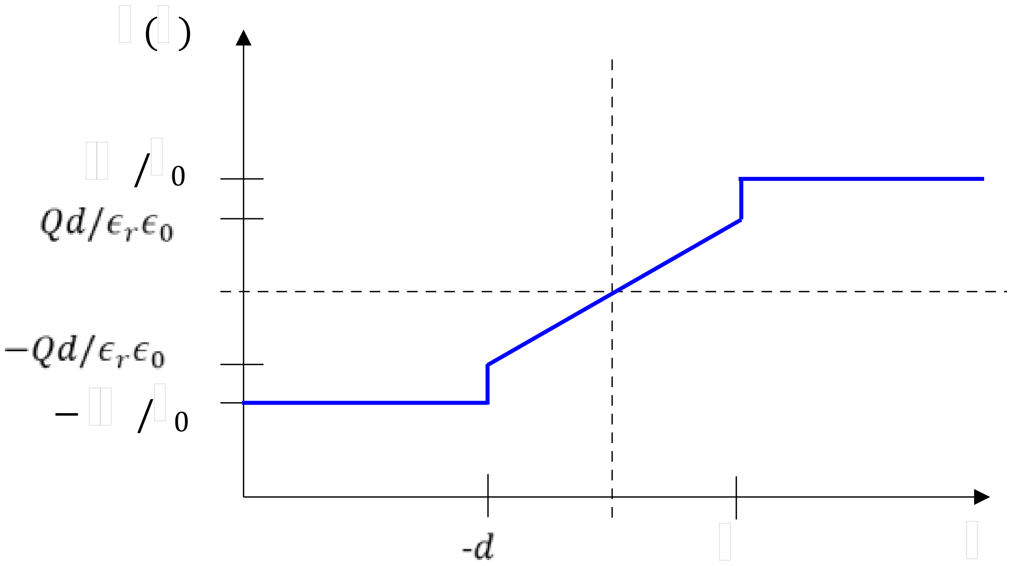
$$\oint \vec{D} \cdot d\hat{a} = \int_V q dV$$

$$D(x) = \begin{cases} -Qd, & x < -d \\ Qx, & -d \le x \le d \\ Qd, & x > d \end{cases}$$

$$E(x) = \begin{cases} -Qd/\epsilon_0, & x < -d \\ Qx/\epsilon_r\epsilon_0, & -d \le x \le d \\ Qd/\epsilon_0, & x > d \end{cases}$$

But wait, polyethylene is a dielectric





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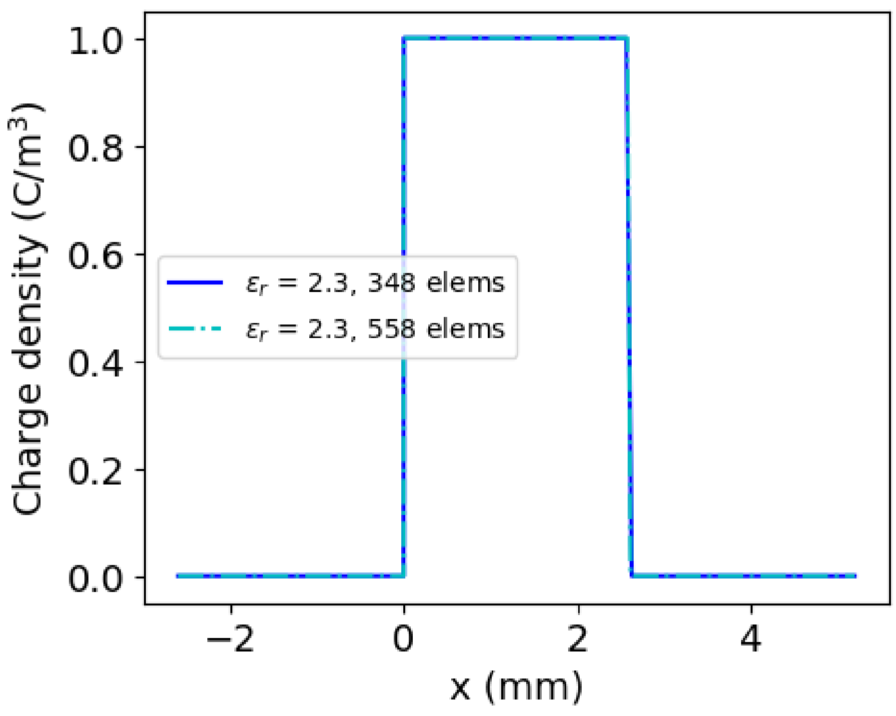
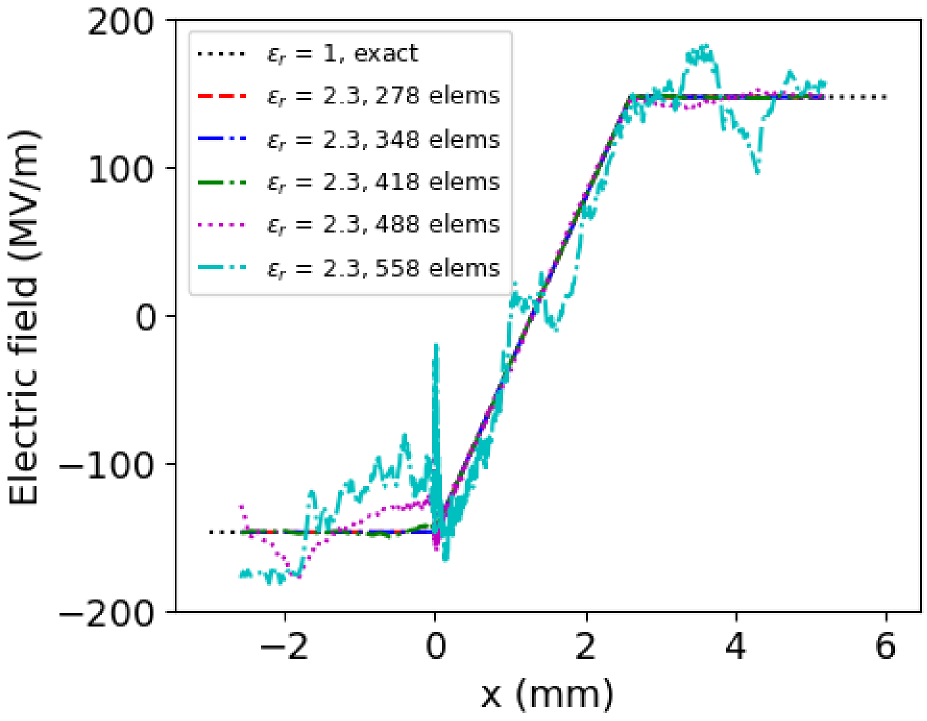
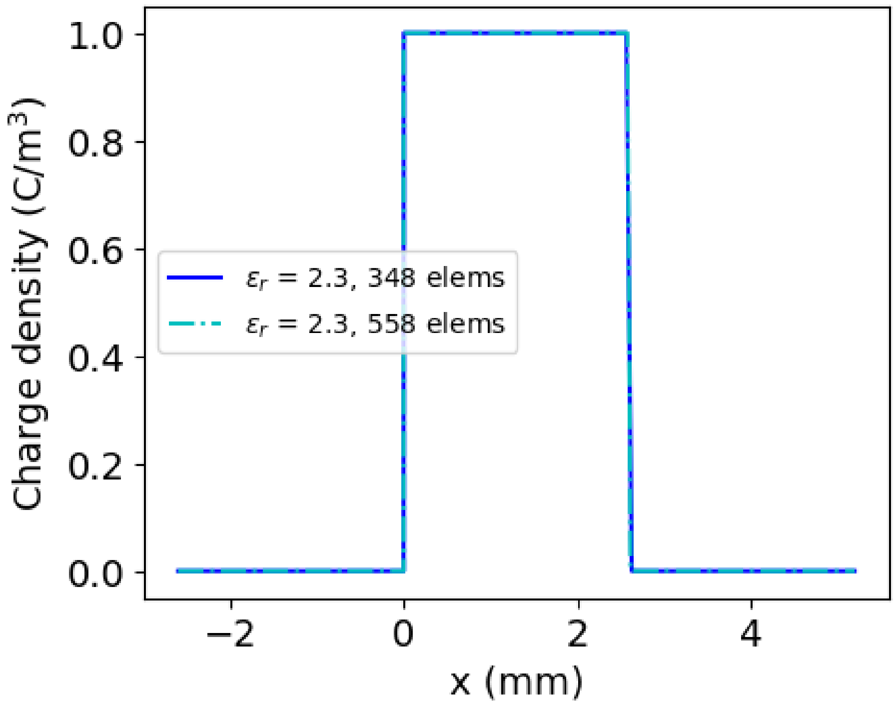
ALEGRA simulations for charged infinite slab

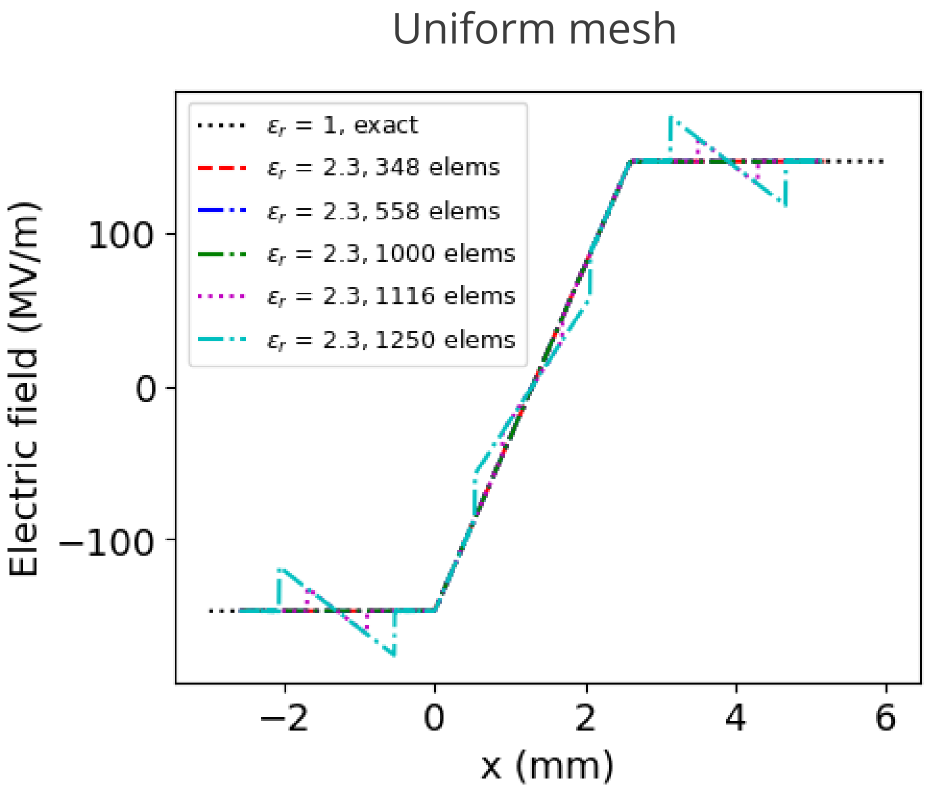


Biased mesh



ALEGRA simulations for charged infinite slab

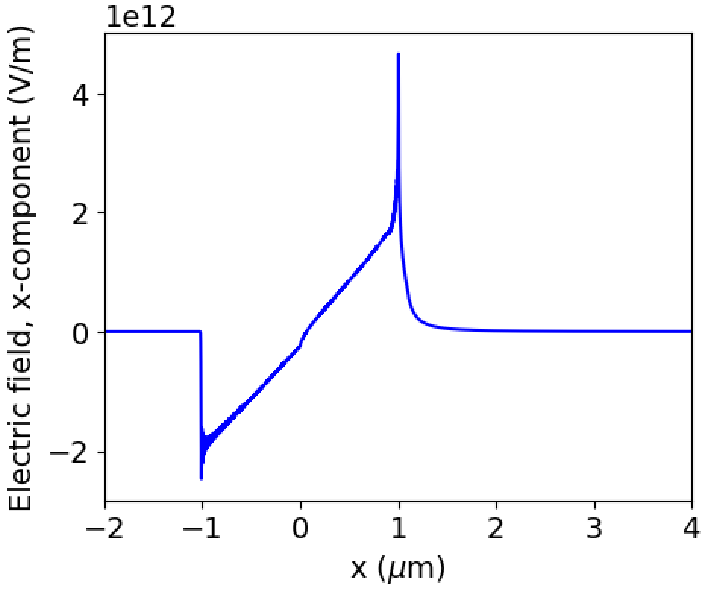




ALEGRA simulations for charged infinite slab

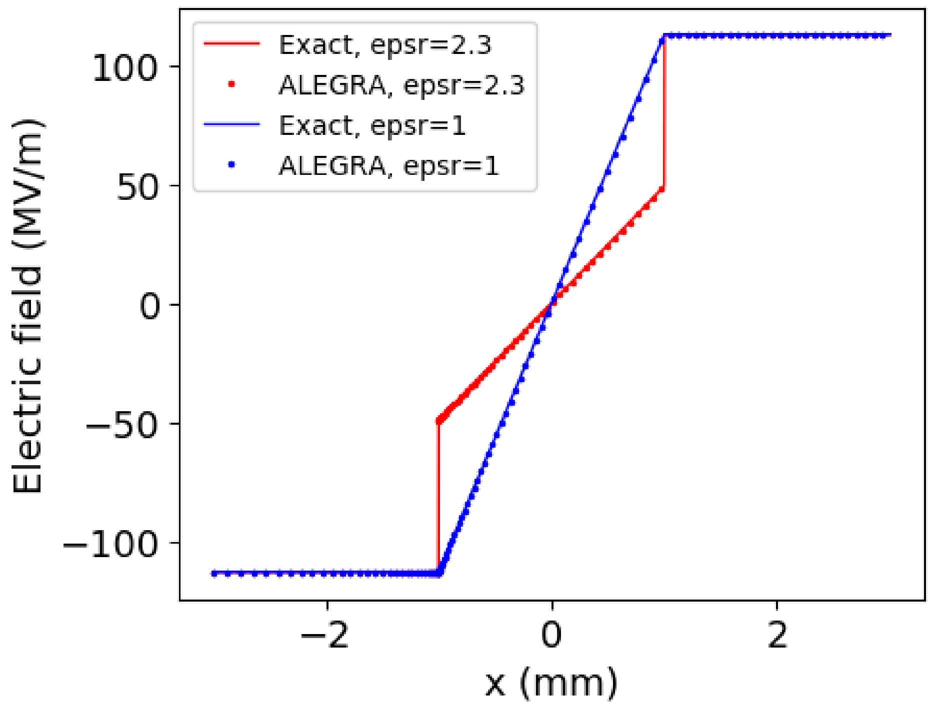
Investigation into these results found multiple issues with the integration of Gauss's law in ALEGRA version 7.7:

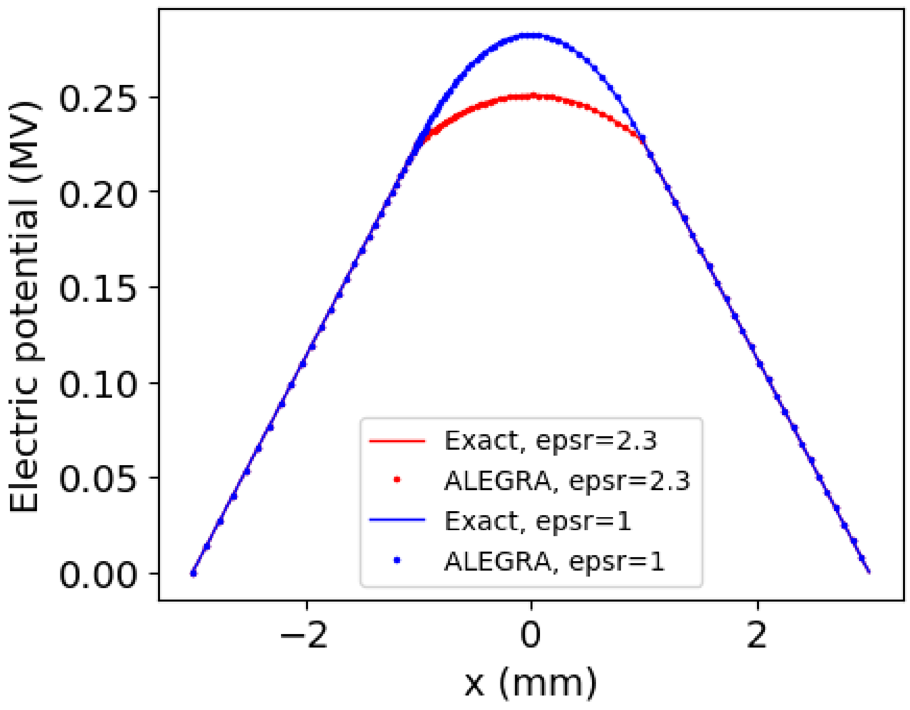
- The iterative solver was failing to converge and did not notify the user.
  - Improved preconditioning was needed.
  - Solver could not handle very fine or highly biased meshes.
- The solver did not account for electrical permittivity.



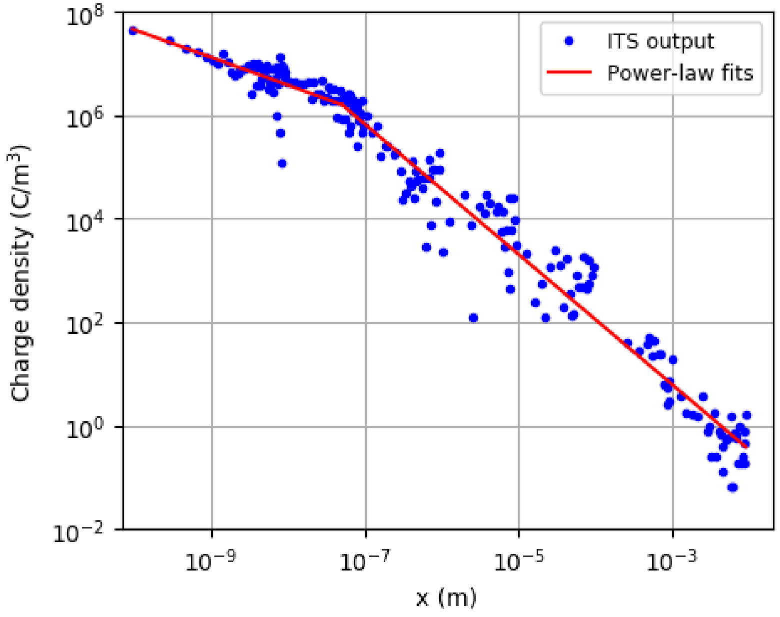
These issues were fixed in ALEGRA version 8.1.

Results after code improvements



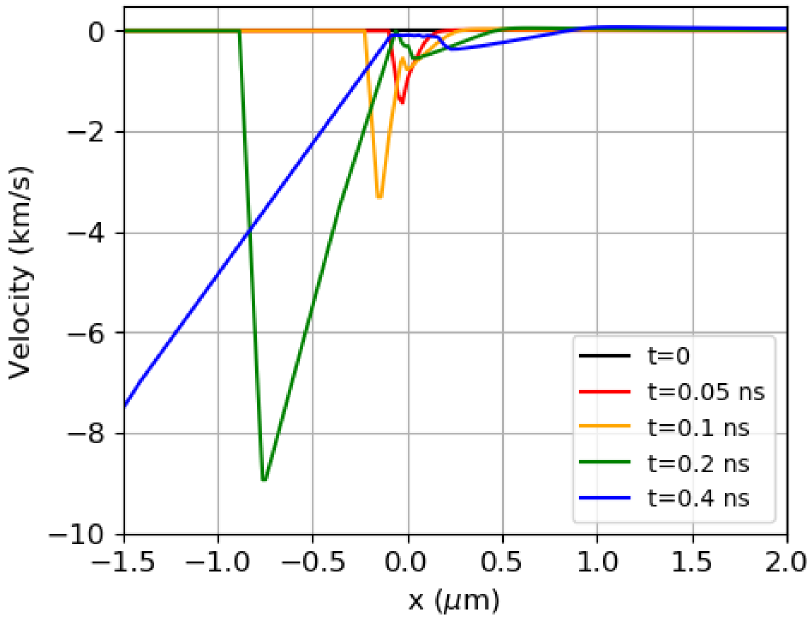


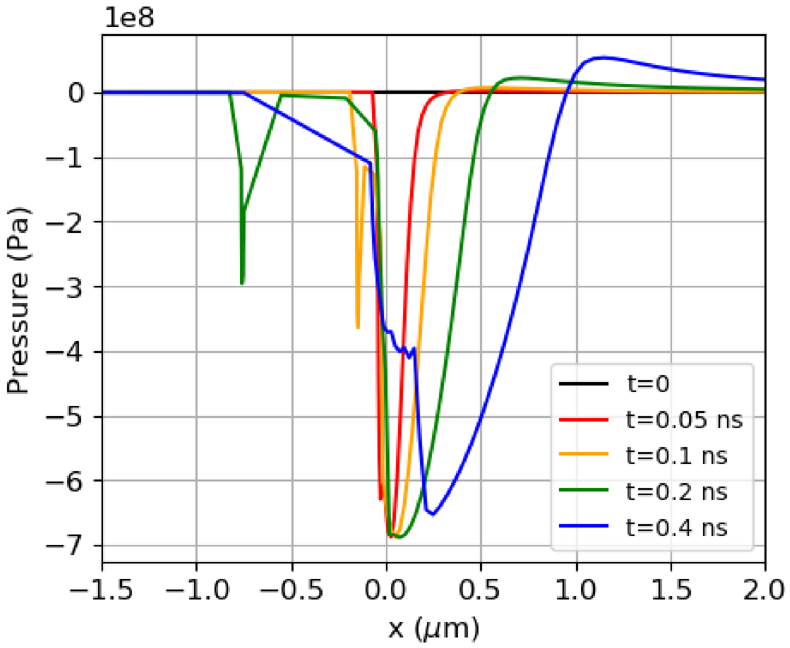
Results with real charge profile and dynamics



- Charge deposition profile in polyethylene was estimated using Monte-Carlo radiation transport code for the fluence and x-ray energy spectrum (~3 keV) generated by an argon gas puff shot on the Z accelerator
- A power-law fit to the charge profile was used to insert a positive charge profile in ALEGRA.

- Enormous electrostatic forces are computed by ALEGRA, but in a tiny thickness.
- A pressure pulse on the order of 100 MPa is transmitted to the sample.





Go to final comments

Conclusion

- ALEGRA maintains an internal repository of publications demonstrating verification, validation, and/or uncertainty quantification for its capabilities.
  - Authored by both developers and users.
  - First paper: 1997
  - Most recent paper: May 2021
  - 56 total publications

- This work builds on that legacy.

- Verification is an essential function of responsible computational science, and physicists are well-equipped to do this job.

Opportunities at Sandia

- Undergraduate summer internship program.
- HBCU undergraduate internship program.
- Graduate summer and year-round internships.
- Computer Science Research Institute internship program.
- Postdoctoral fellowships.

Questions, reach out to me at jhniede@sandia.gov, or go to https://www.sandia.gov/careers

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- Attendance at a HBCU during spring 2022 academic term

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678332	Intern - START HBCU, **Bioinformatics**, R&D Undergrad Summer
678350	Intern - START HBCU, **Physical Sciences**, R&D Undergrad Summer
678352	Intern - START HBCU, **Cyber Security**, R&D Grad Summer
678354	Intern - START HBCU, **Cyber Security**, R&D Undergrad Summer
678353	Intern - START HBCU, **Business** Undergrad Summer
678317	Intern - START HBCU, **Mechanical Engineering**, R&D Undergrad Summer
678299	Intern - START HBCU, **Electrical/Electronics Engineering**, R&D Undergrad Summer
678340	Intern - START HBCU, **Computer Science**, R&D Undergrad Summer

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THE END

Abstract

ALEGRA is a finite-element multiphysics simulation tool developed and maintained at Sandia National Laboratories. Included in its capabilities is an iterative solver for certain approximations to Maxwell's equations, allowing engineers to include transient electromagnetic fields in their computational models.

Recently, verification and validation activities have tested ALEGRA's accuracy using this solver for several practical problems in electromagnetics, including

1. the magnetic field due to a ring magnet
2. the magnetic field and self-inductance of a transformer coil, and
3. the electric field due to an arbitrary profile of positive deposited charge.

In this talk, an analytic or numerical solution from the literature is discussed for each case. ALEGRA solutions are presented for each case. Comparisons are made in order to provide a verification basis for the use of ALEGRA to model these and other related transient electromagnetics in engineering environments.

A brief overview of Sandia National Laboratories and its Center for Computing Research is also presented.

Bio

John Niederhaus is a physicist on staff in the Computational Multiphysics Department at Sandia National Laboratories. As part of the ALEGRA code development and analysis team, he conducts numerical modeling of low-frequency electromagnetics, pulsed power systems, and high-deformation solid dynamics. He holds a PhD in Engineering Physics at the University of Wisconsin (2007), an MS in Nuclear Engineering from Penn State (2003), and a BS in Physics from the Virginia Military Institute (2001).