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A 3-D Model of the Internal Charging of Spacecraft Dielectric Materials

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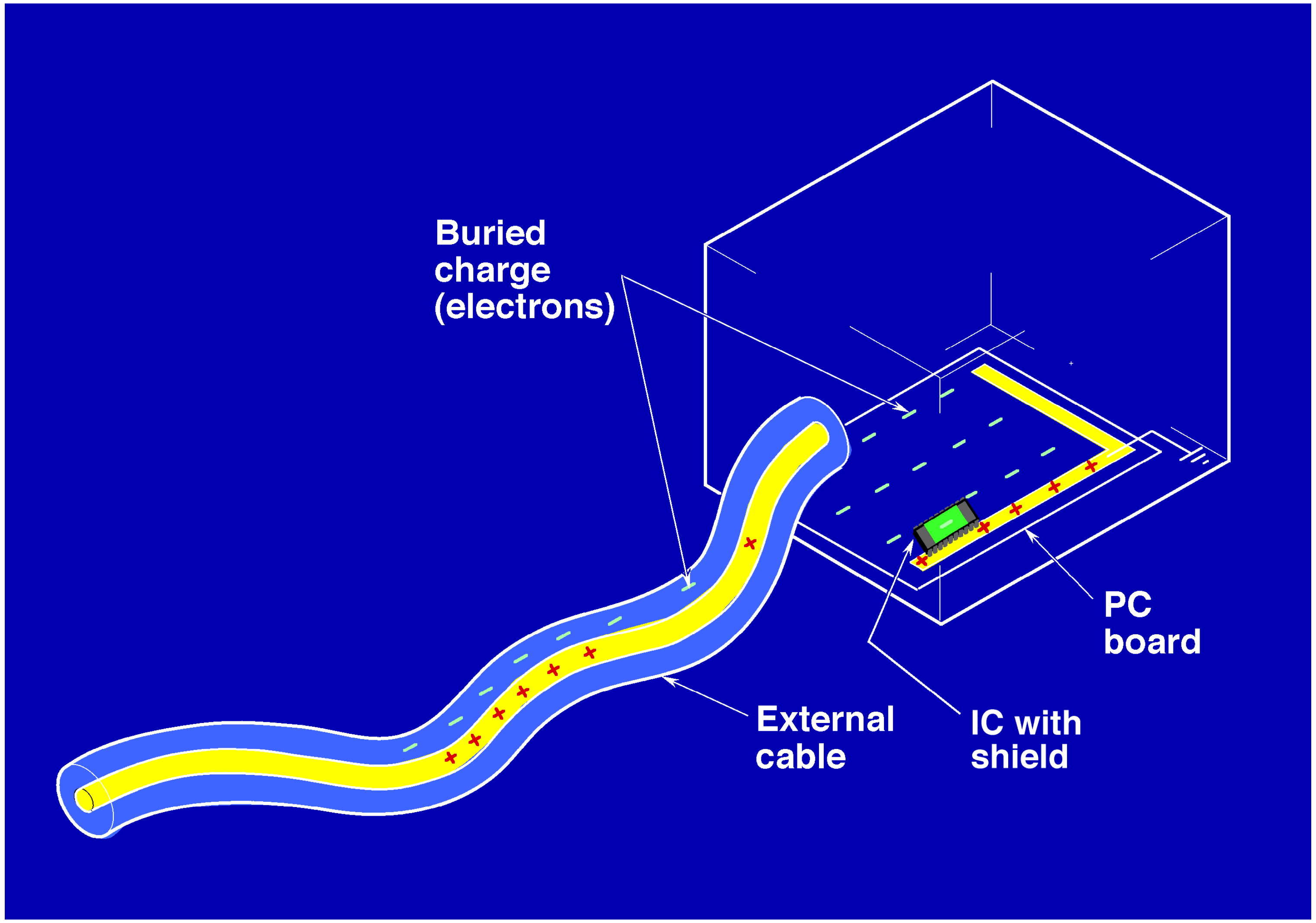
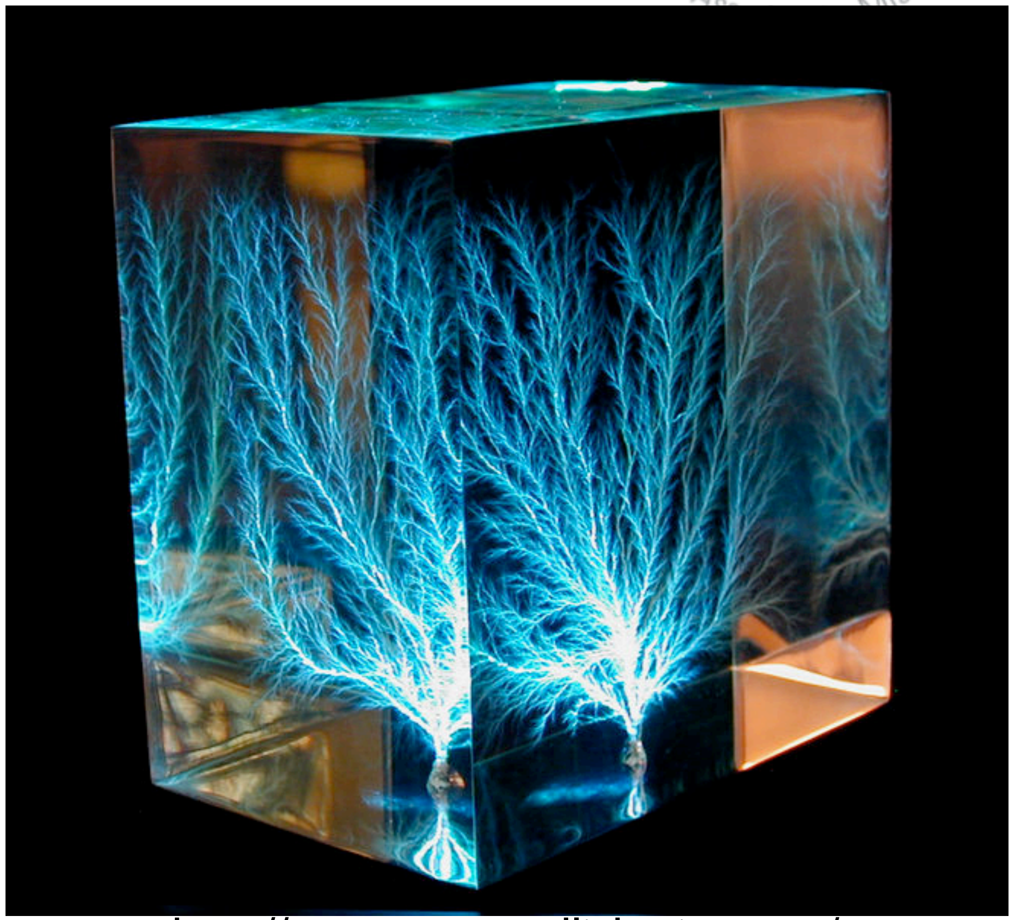
Internal Charging

- Internal charging is caused by high energy electrons that penetrate satellite material and deposit their charge within subsystems
- This charge can end up on isolated conductors, such as ungrounded radiation shields, or buried in dielectrics, such as printed circuit boards



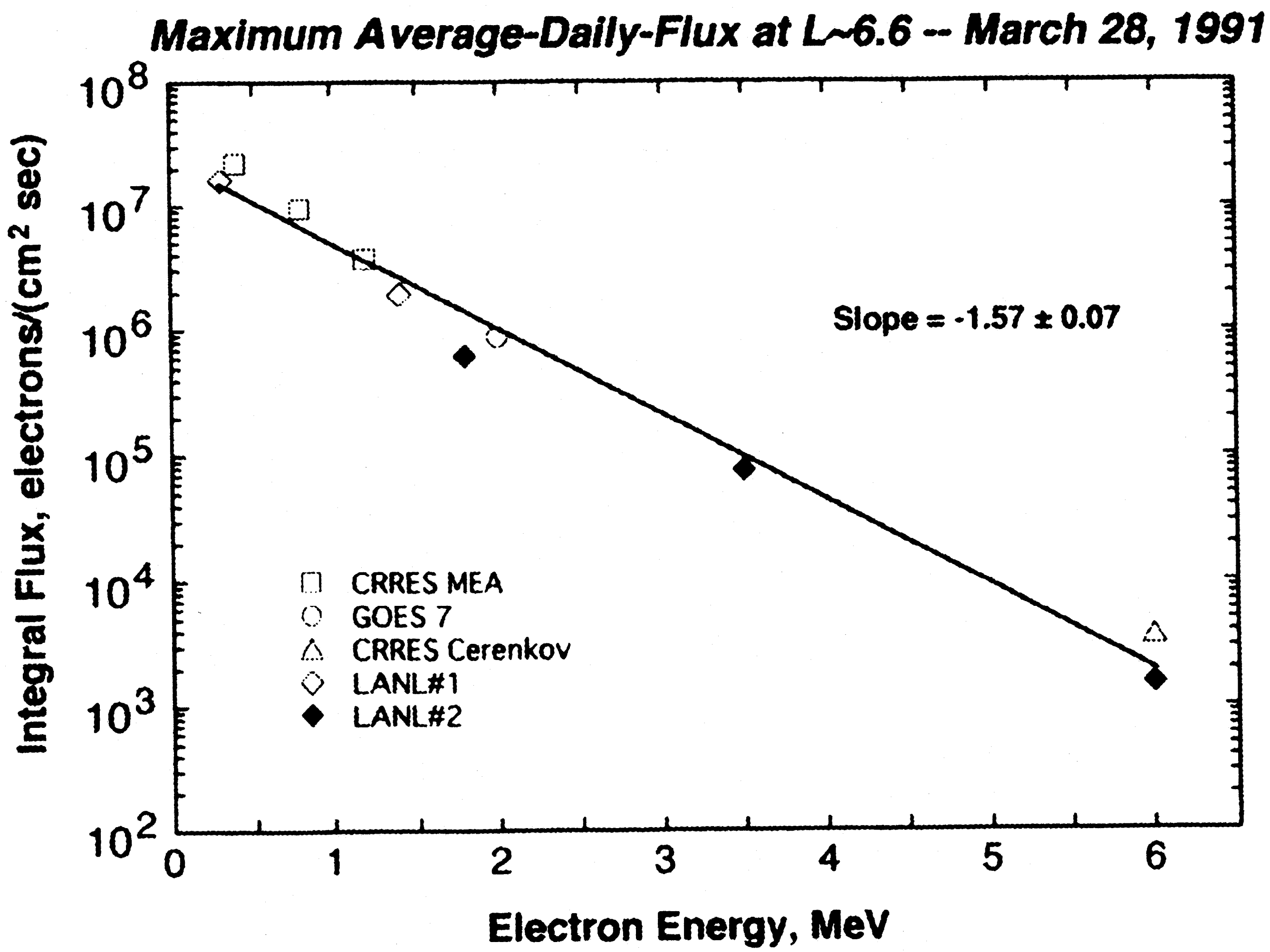


http://www.capturedlightning.com/

- The charge can build up to breakdown levels, leading to arc discharges into sensitive circuits
- Electrostatic discharges (ESD) cause on-orbit anomalies & failures

Radiation Environment

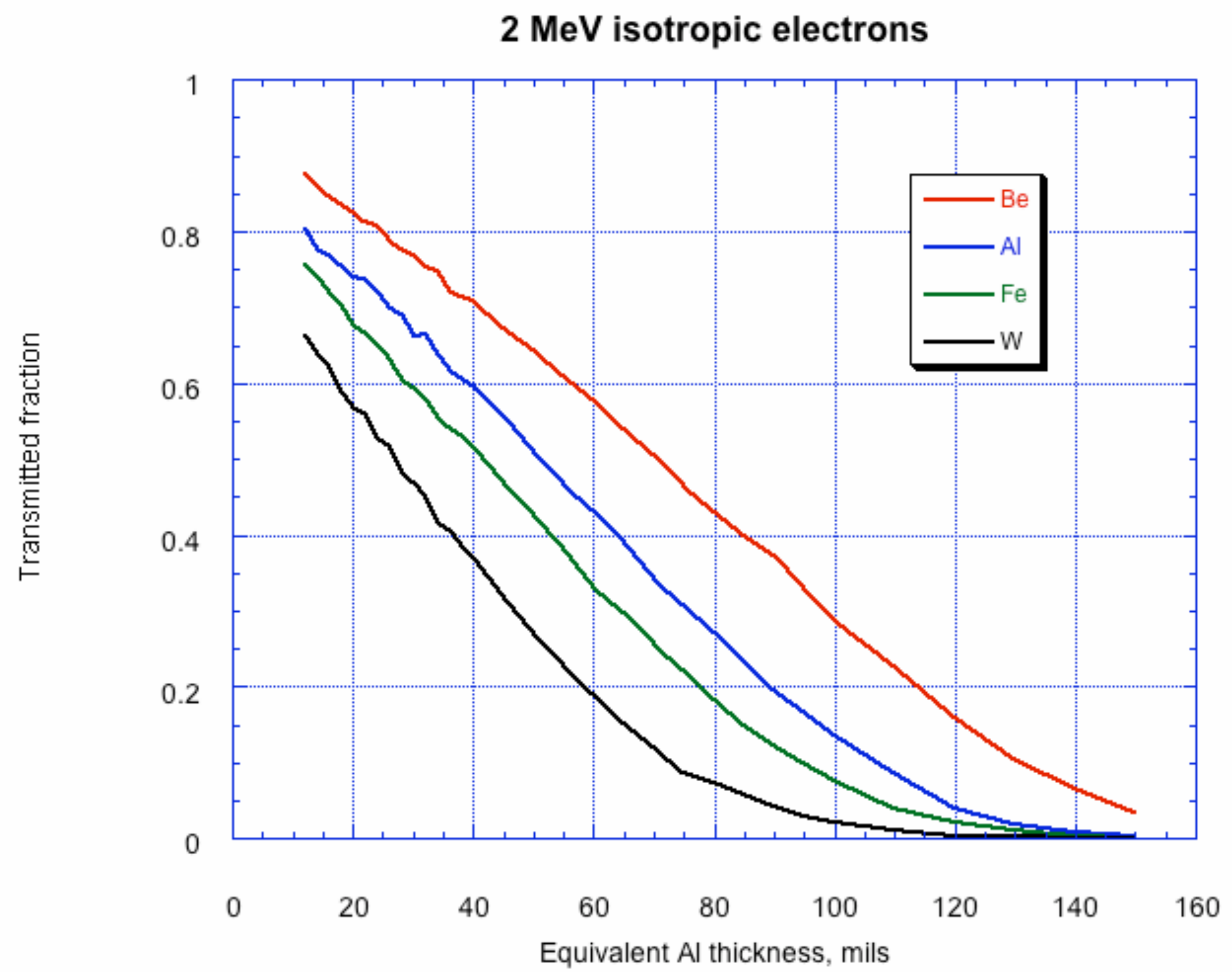
- A critical input for modeling internal charging of spacecraft subsystems is its external radiation environment
- The radiation environment experienced by the spacecraft varies both spatially (i.e. its orbit) and temporally (space weather)
- Environmental measurements obtained from on-orbit sensors are used to characterize the radiation environment



GEO worst case environment; electron flux as a function of energy on March 28, 1991 [Fennell et al., 2000, IEEE Trans. Plasma Sci.]

Physics of Radiation Transport

- electrons penetrate much deeper than ions; ions are usually neglected
- controlling for density, high-Z materials have better stopping power
- lots of secondary electrons (and holes) are generated



- angular scattering is significant; tracks are not straight
- photon secondaries travel farther than electrons, and produce new electrons and holes elsewhere

Charge Dissipation

- Modeling is a source/loss problem
  - Sources = environment
  - Losses = charge dissipation
- If material charge dissipation time constants are long relative to orbital timescales, charge can accumulate
- $J = \sigma \cdot E$
  - σ is complicated, not just "dark conductivity"
  - also depends on E and radiation dose (RIC)

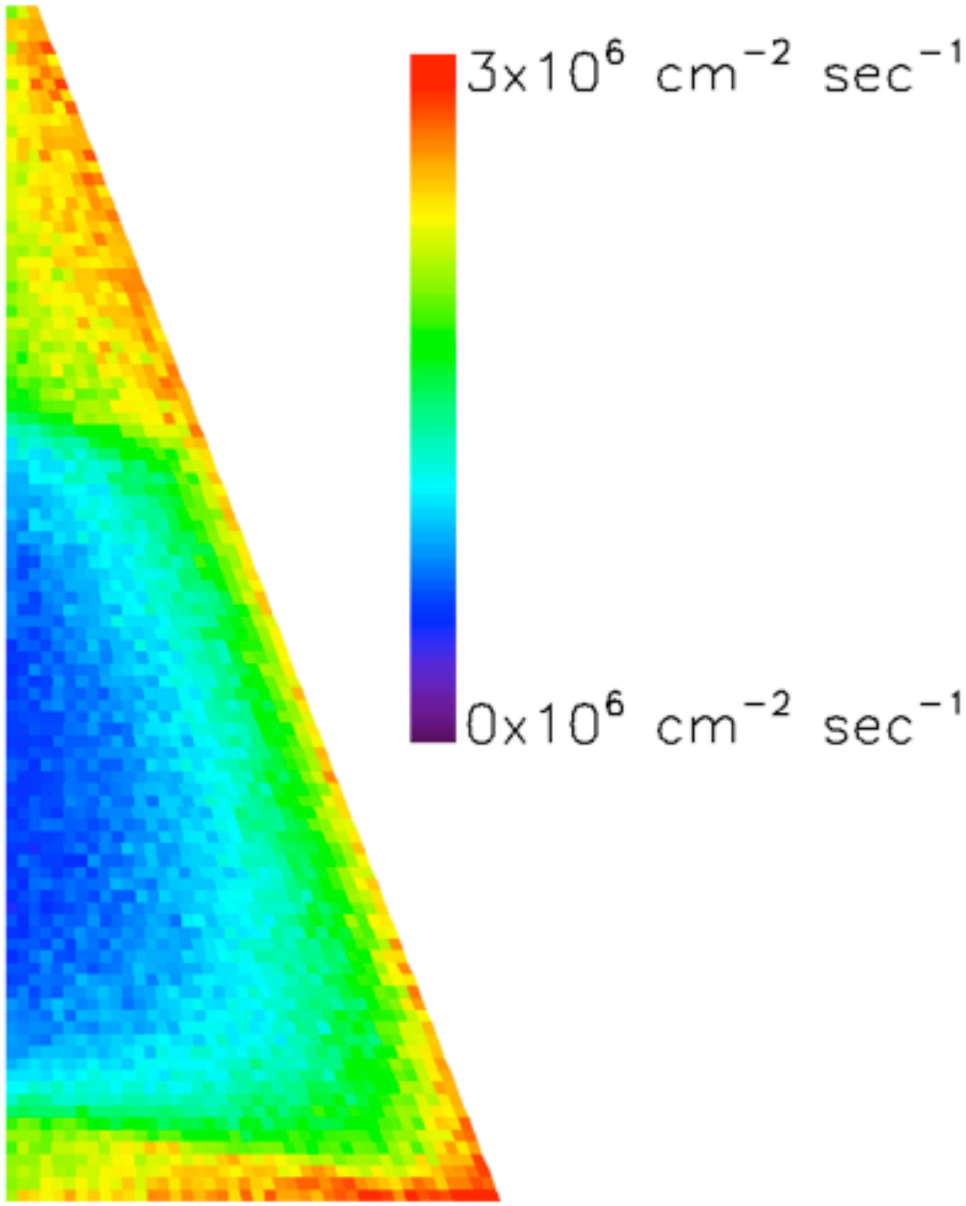
Previous Modeling Efforts

- NUMIT (Frederickson et al, 1978; Jun et al., 2008)
- ESADDC (Sobeyran et al., 1993)
- DICTAT (Sørensen et al., 2000; Rodgers et al., 2003)
- Mileev and Novikov, 2001
- ATICS (Zhong et al., 2007)
- All 1-D models; no 3-D models yet?

Why 3-D?

- Realistic problems are 3-D
- Discharges occur at corners and edges where these features cause a magnification of the field
- Improves over 1-D models that add margin to account for uncertainty
- What physical processes are really important for triggering discharges?

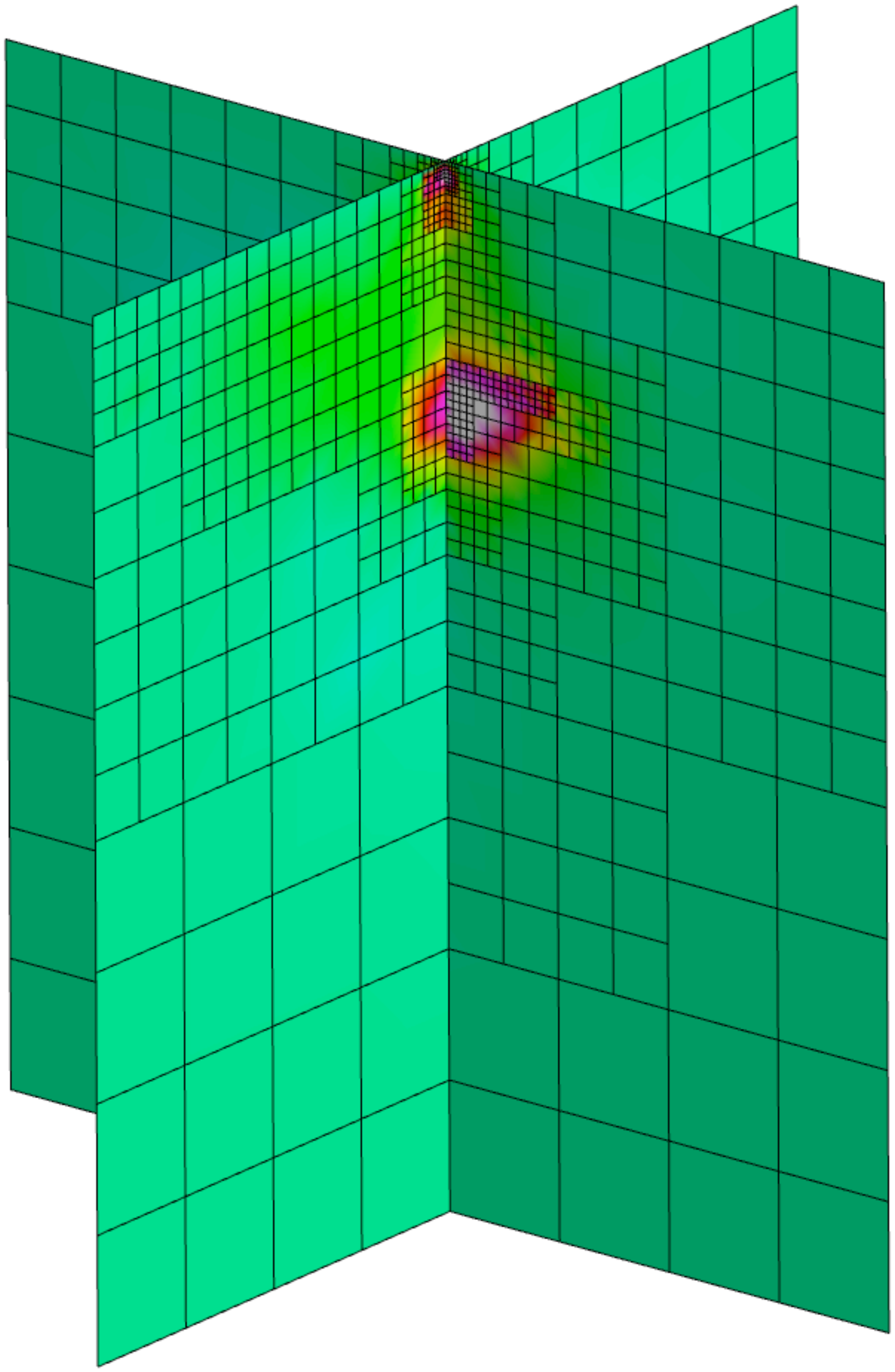
Geant4



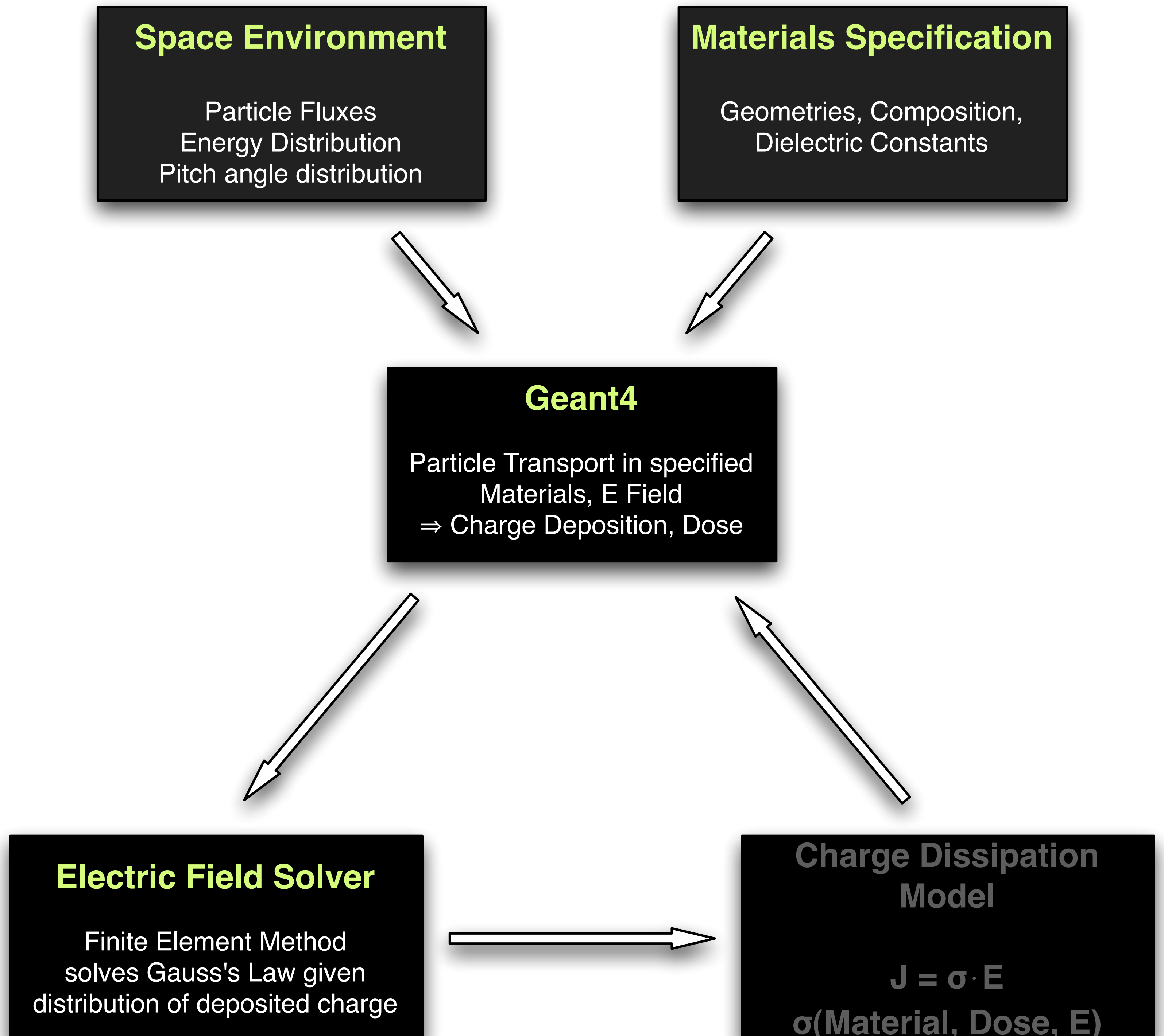
- Open-source C++ code from the high energy physics community
- Simulates transport of energetic particles and photons through matter
- Models all relevant physical processes along primary and secondary particle trajectories
- Arbitrary material geometries (CAD) can be represented
  - Either mesh geometric surfaces and create a tessellated volume in Geant4.
  - Or use Solveering to convert STL to GDML for Geant4 input

Electric Field Solver

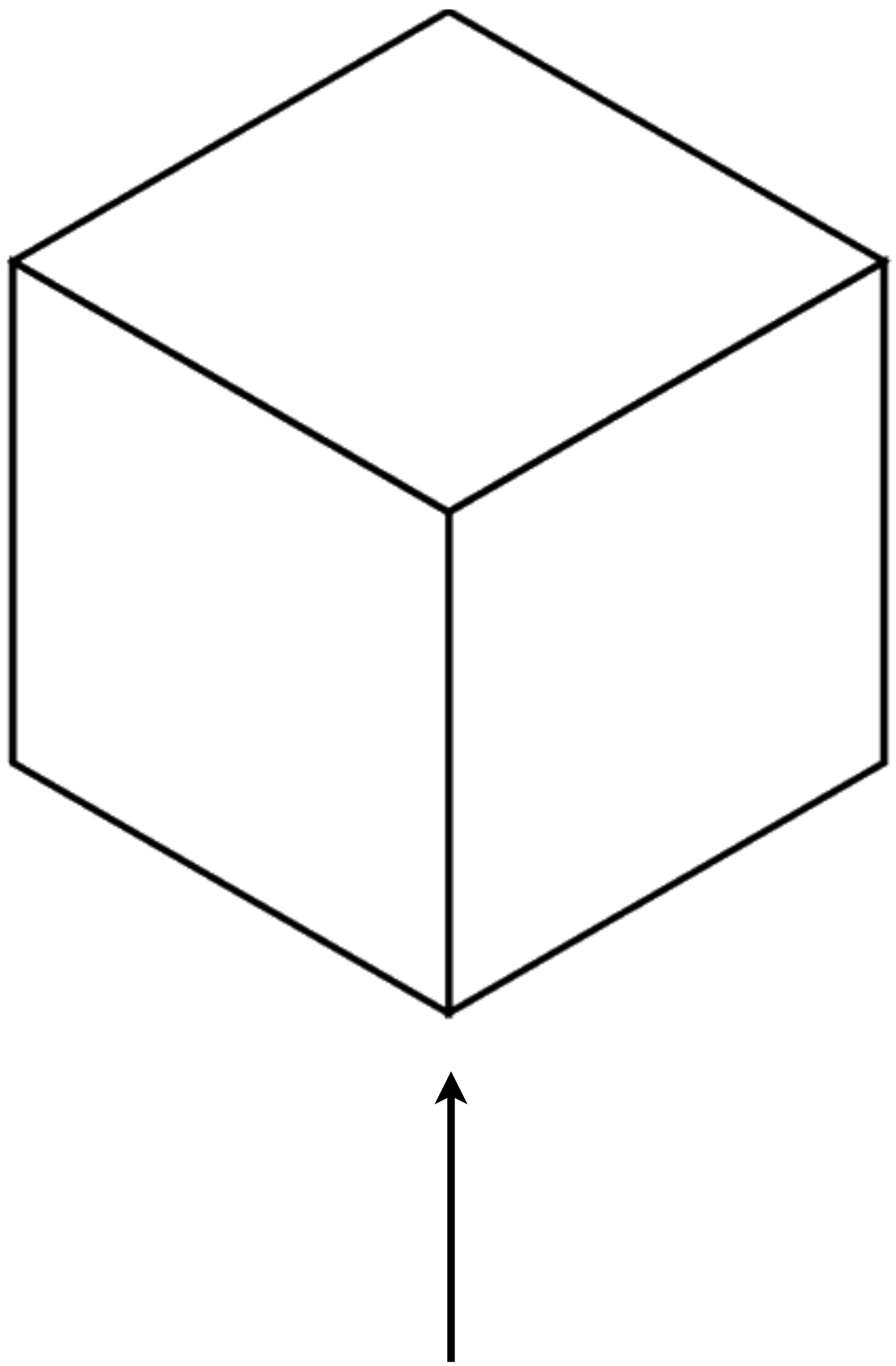
- Finite Element Method
- Open-source Libmesh FEM solver
- Adaptive Mesh Refinement
- MPI Parallel
- Solves Gauss' Law for V (Potential)
- E = -∇V



Model Organization

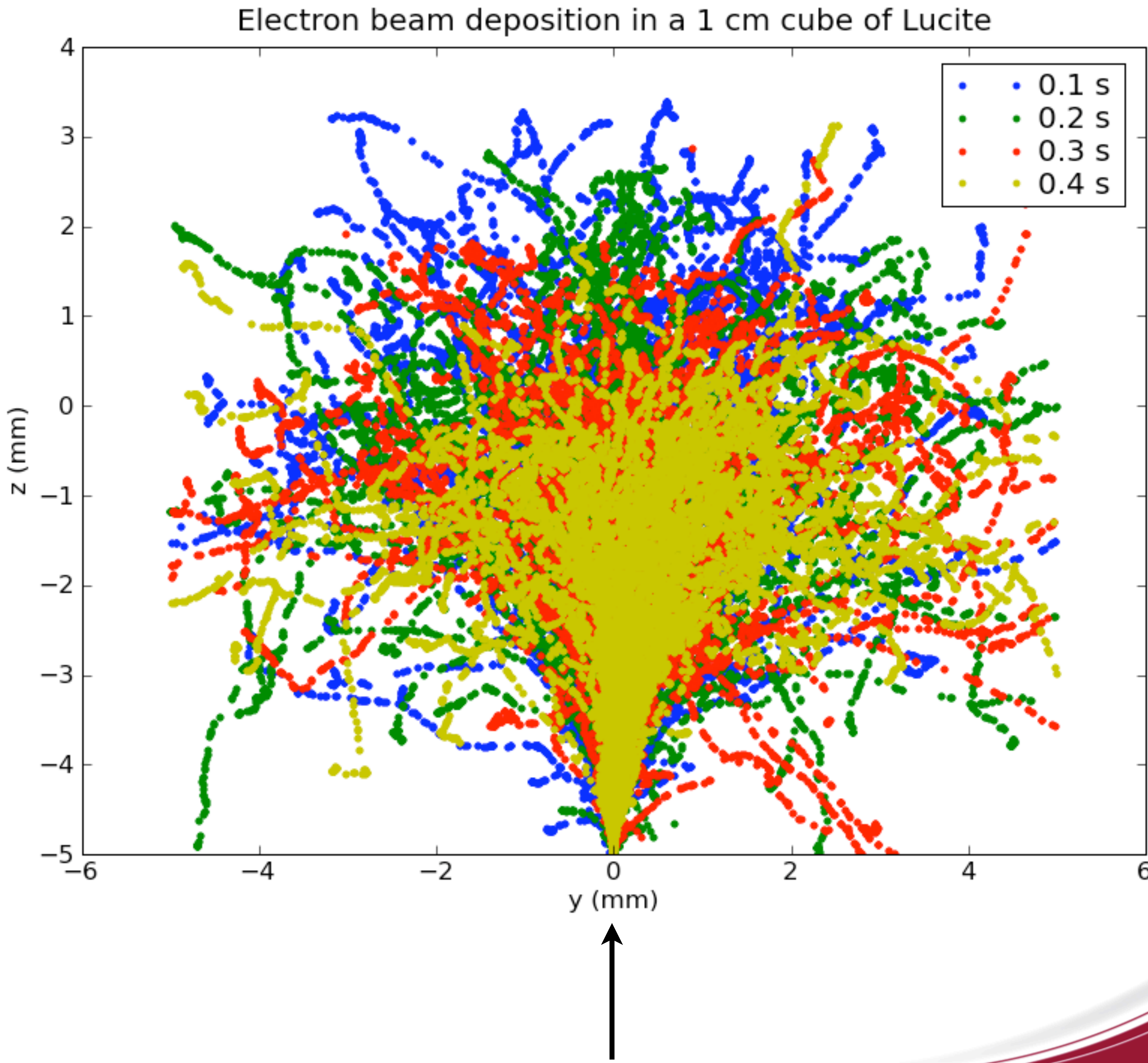


Simulation 1

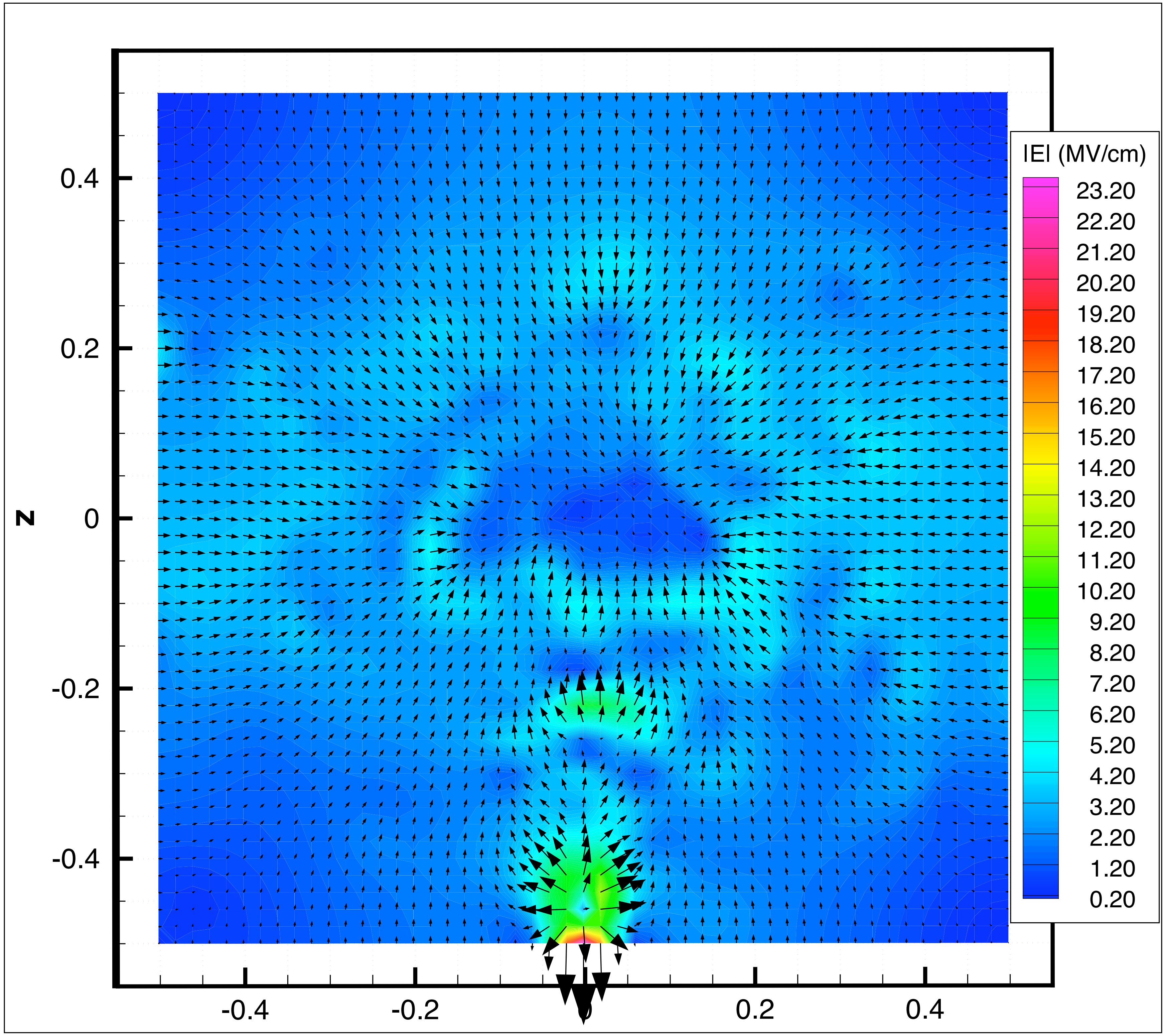


- 1 cm x 1 cm x 1 cm cube of Lucite
- 1 MeV electron pencil beam incident on center point of bottom face of the cube
- Surface is grounded with infinitesimally thin conductive layer
- Time-dependent simulation
  - (Charge→Field→Charge→Field→...)
  - Charge binned into 100 bins per dimension = 10^6 cubic bins
  - 10^6 mesh elements

Charge Deposition



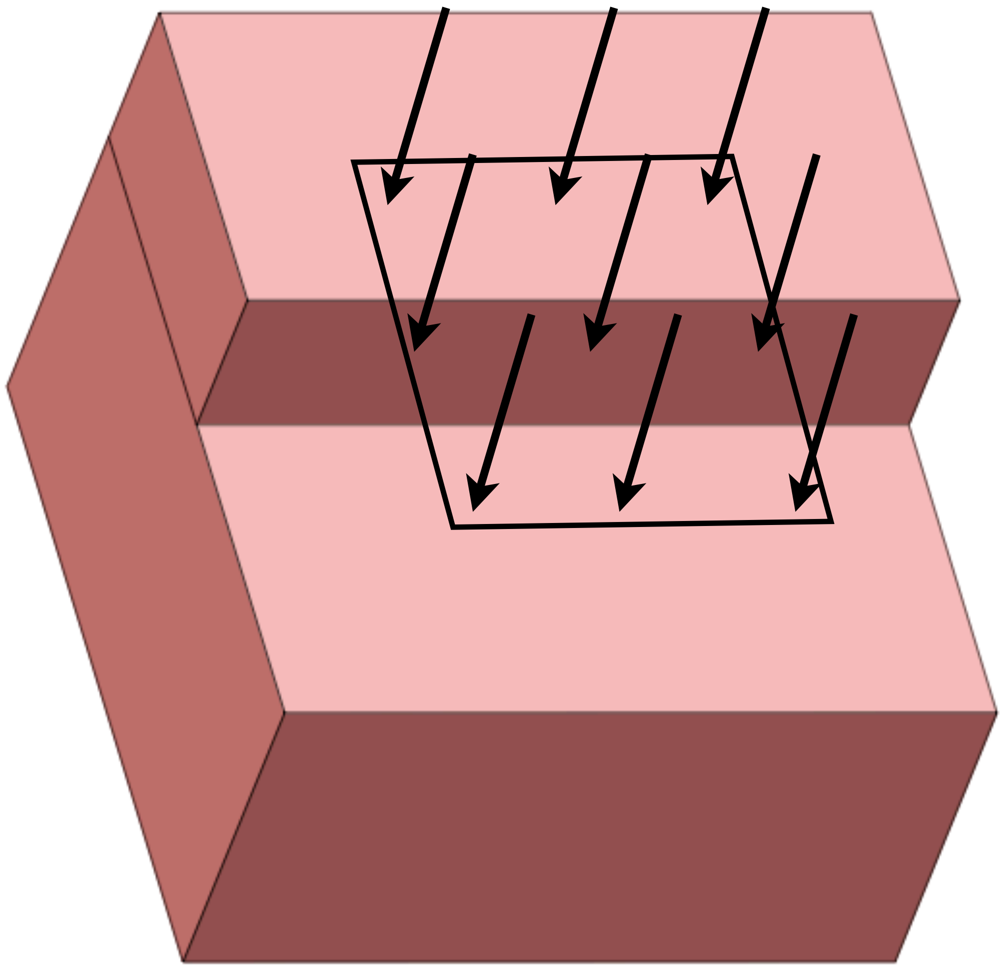
Electric Field



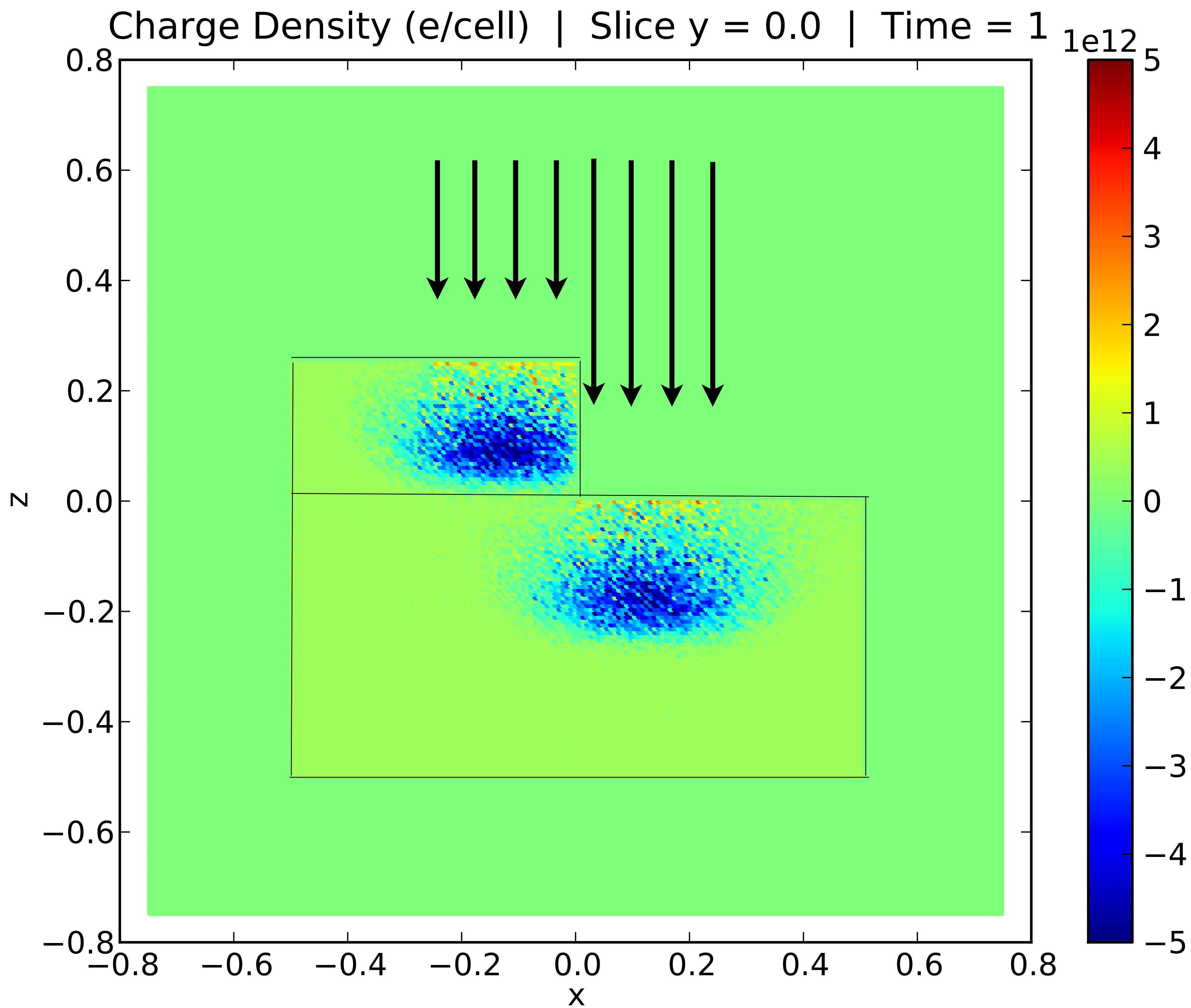
Time = 0.4 s

Simulation 2

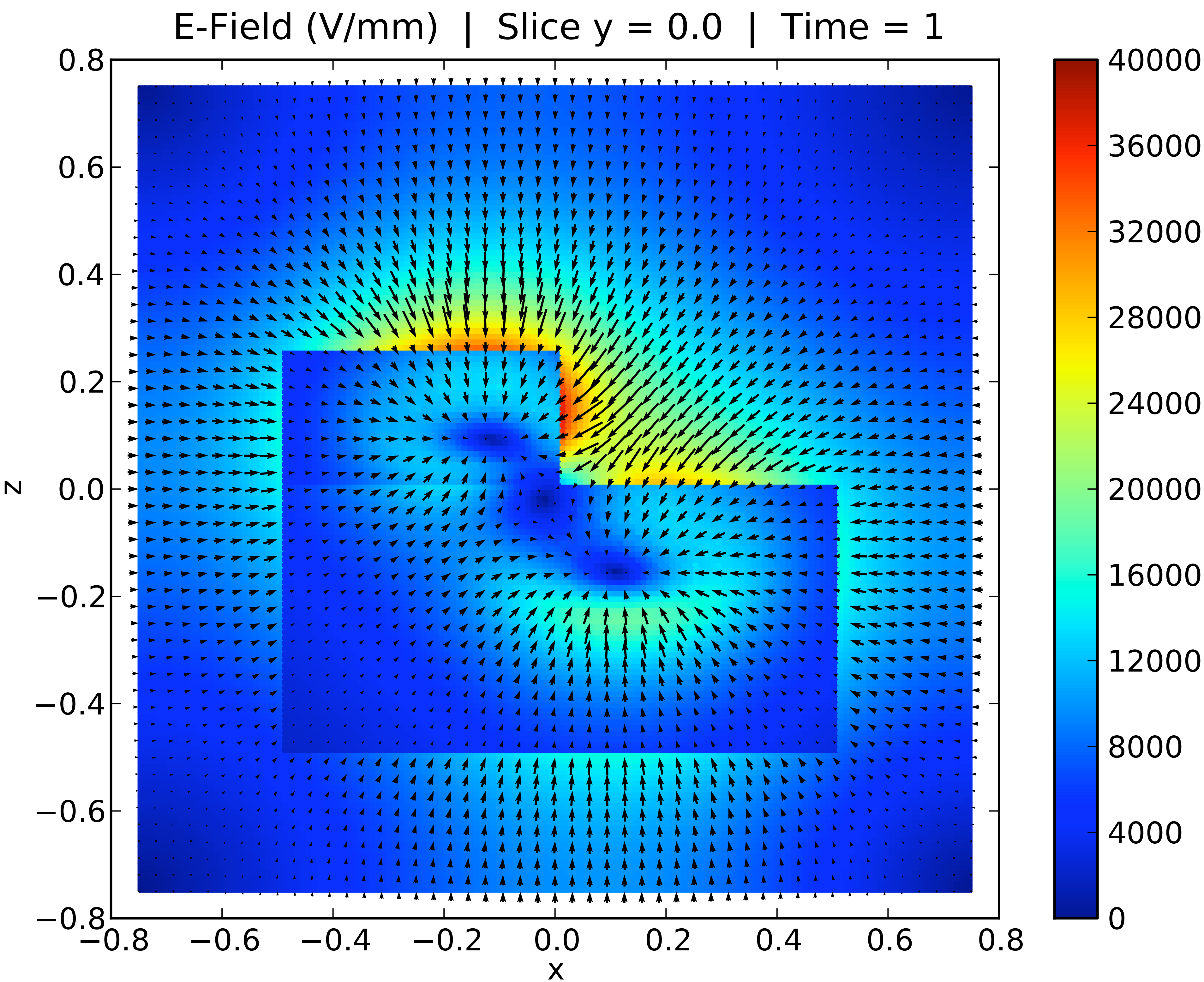
- 0.5 cm x 1 cm x 0.25 cm Mylar block on top of
- 1 cm x 1 cm x 0.5 cm Lucite block
- 0.5 cm x 0.5 cm 750 keV flood beam pointed downward toward center of the blocks; 250 $\mu A/cm^2$
- Surfaces are ungrounded
- 15×10^6 primaries simulated, deposited charge scaled by 2×10^{11}
- New field computed after 300×10^6 charges deposited (primaries, secondaries, holes)
- 216 charge bins per dimension (10^7 total)
- 72 mesh elements per dimension (3.7×10^5)



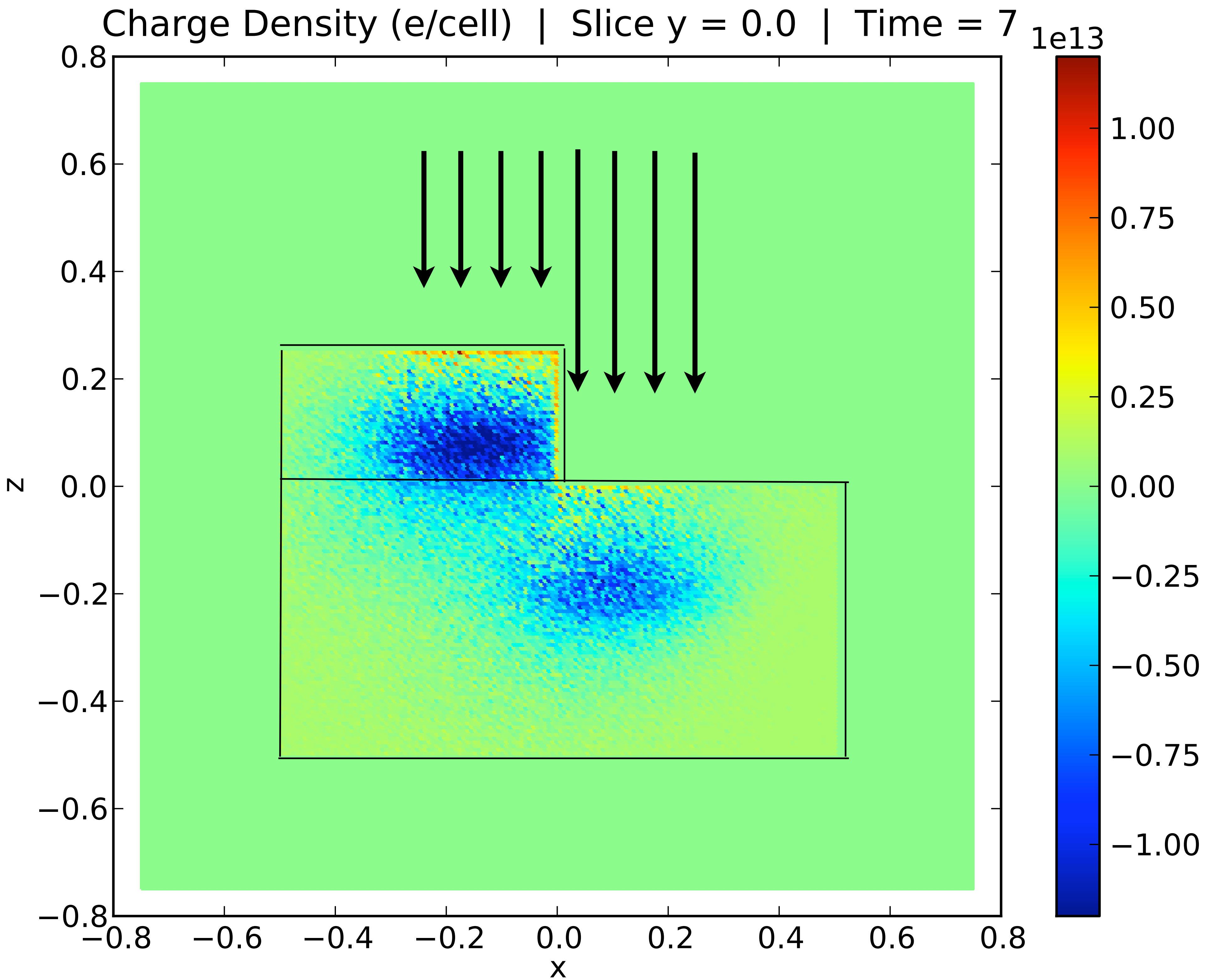
Charge Density



Electric Field



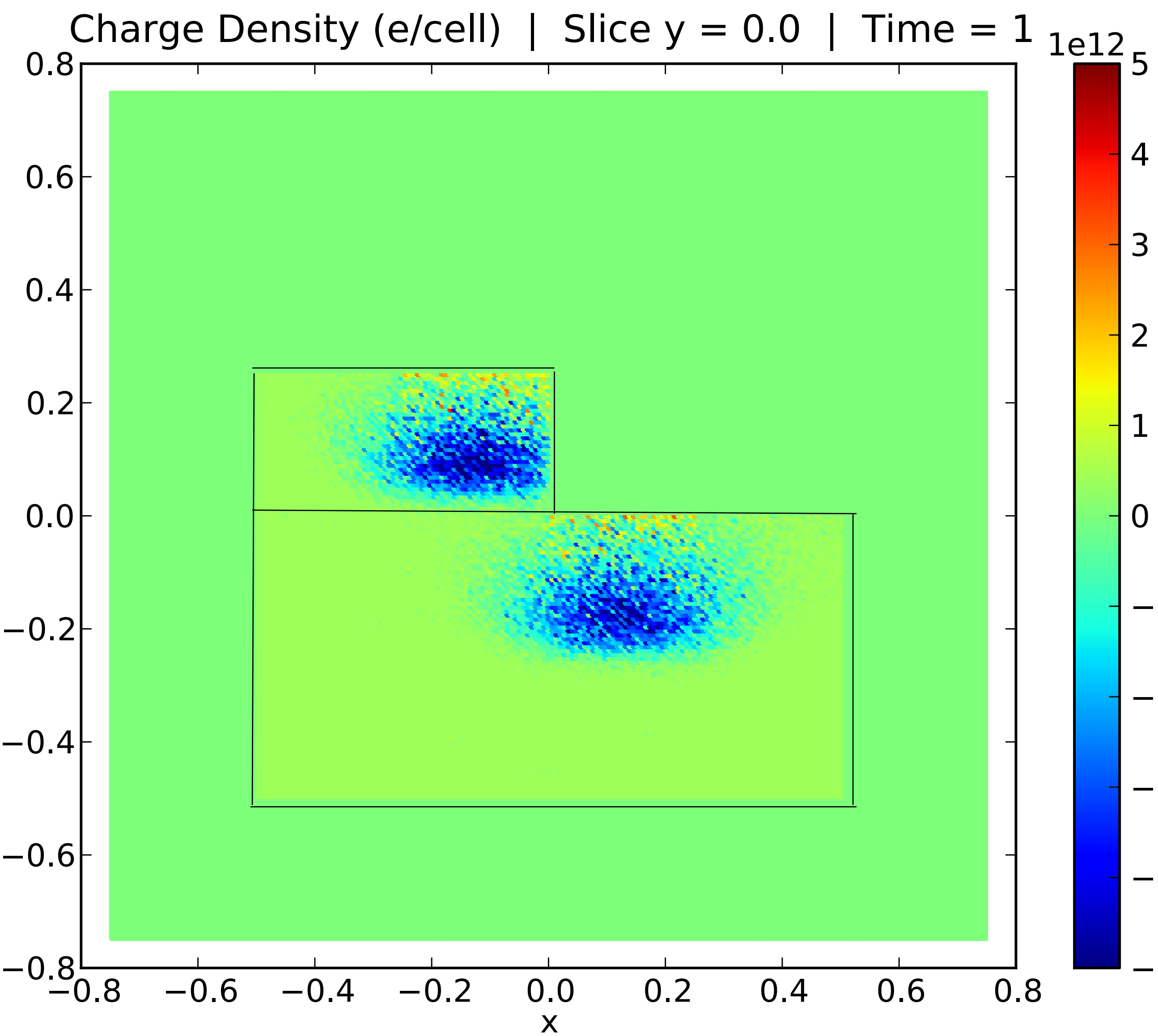
Charge Density; Time = 7 ms

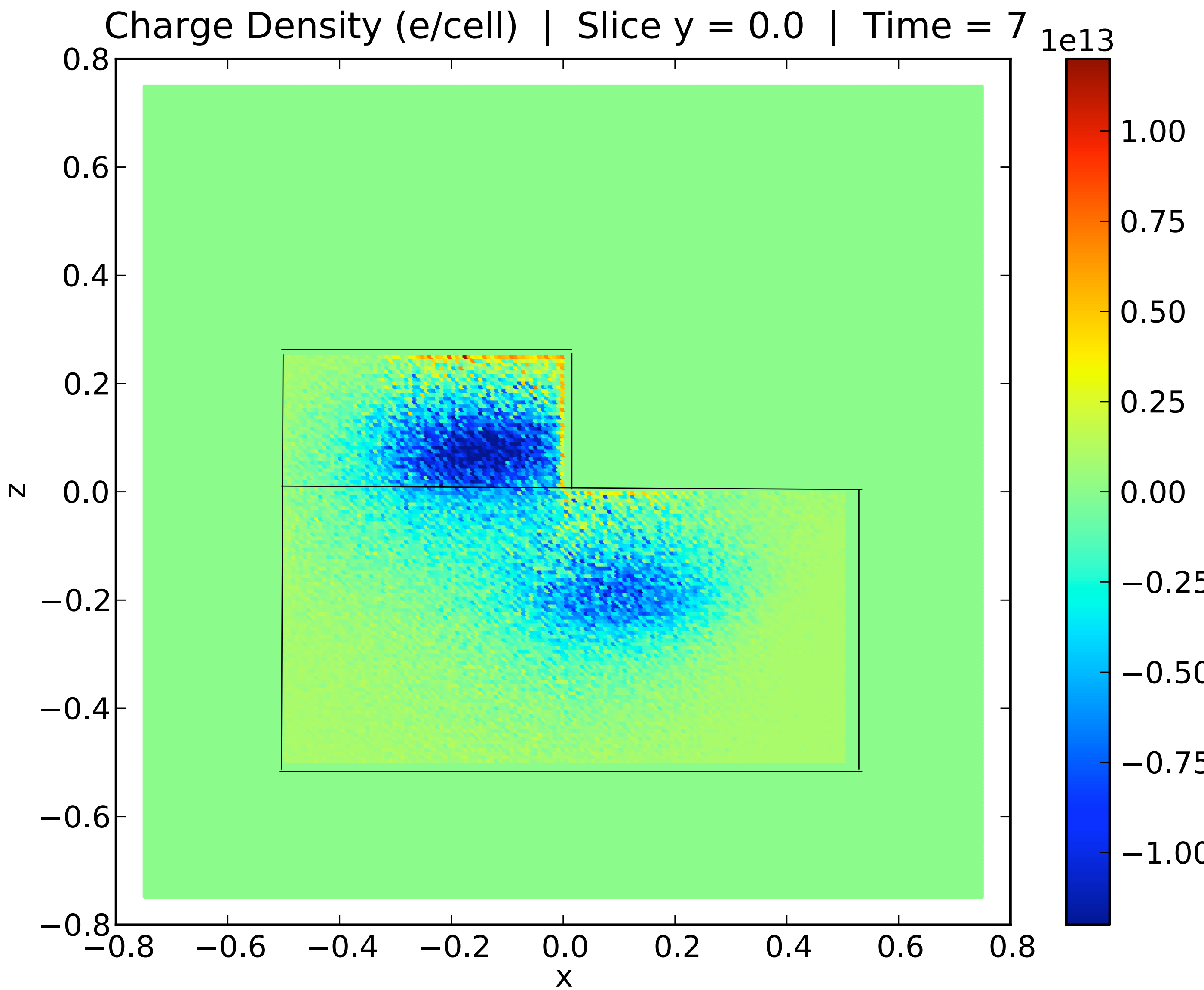


Charge Density

Time = 1 ms

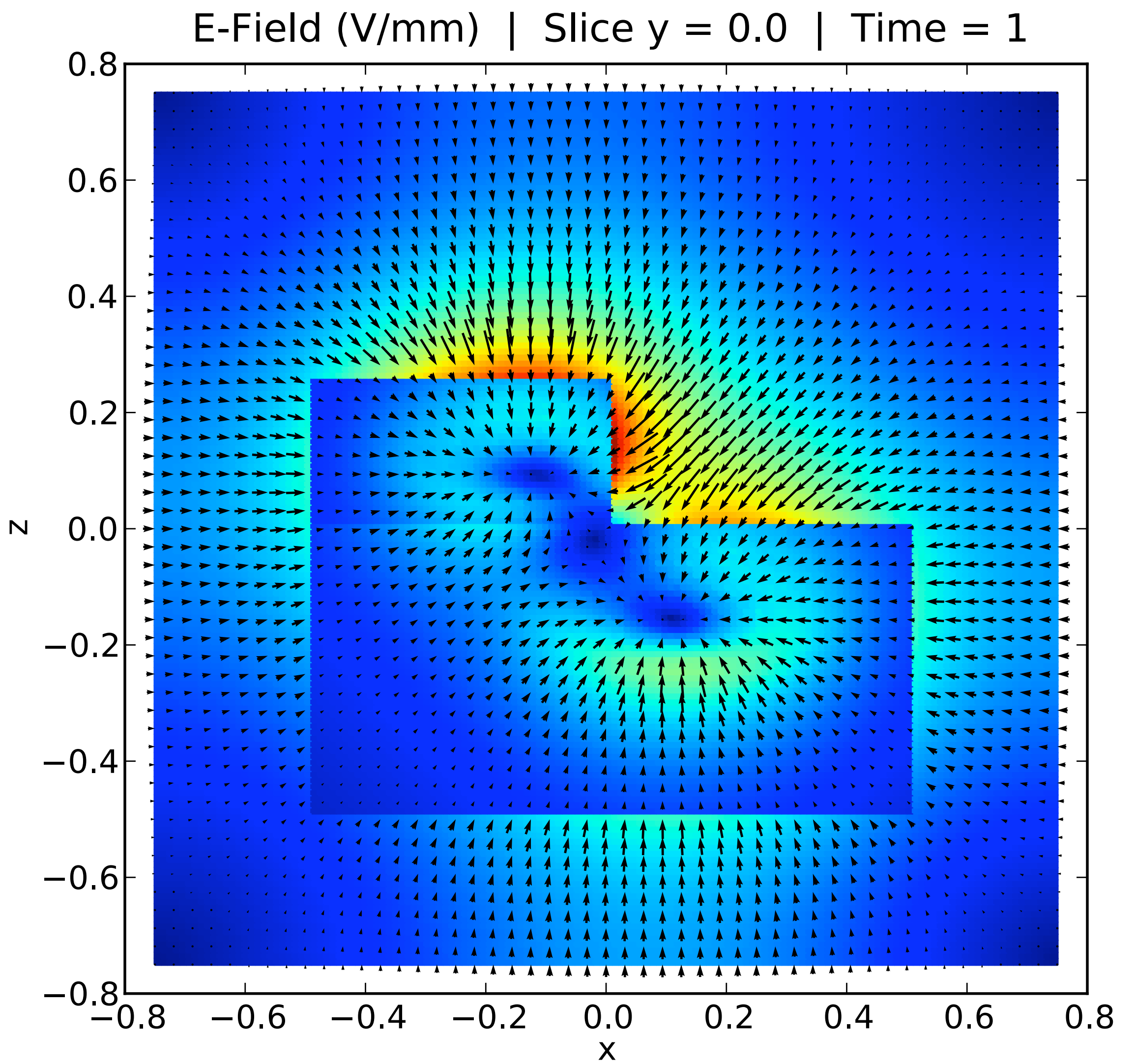
Time = 7 ms



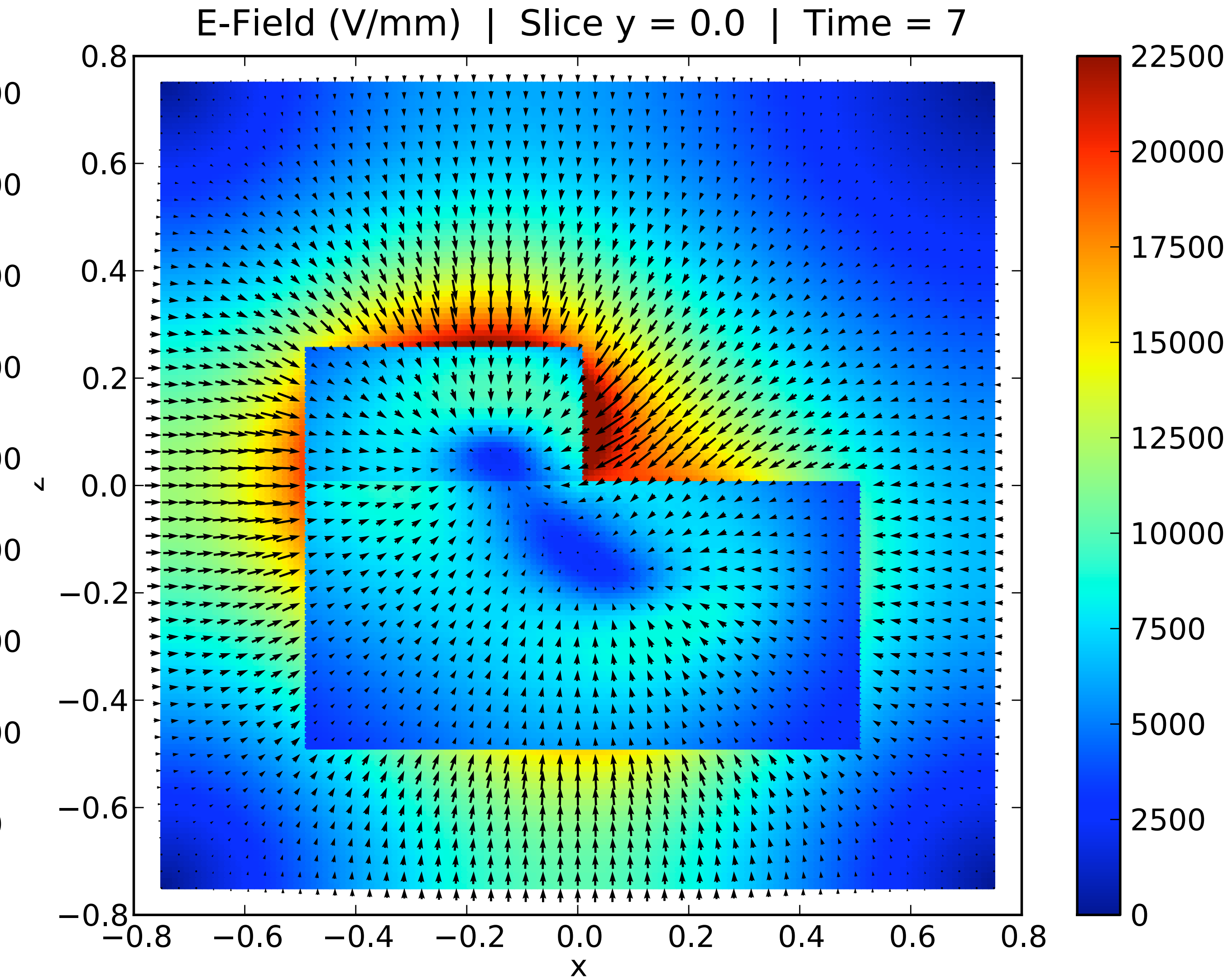


Electric Field

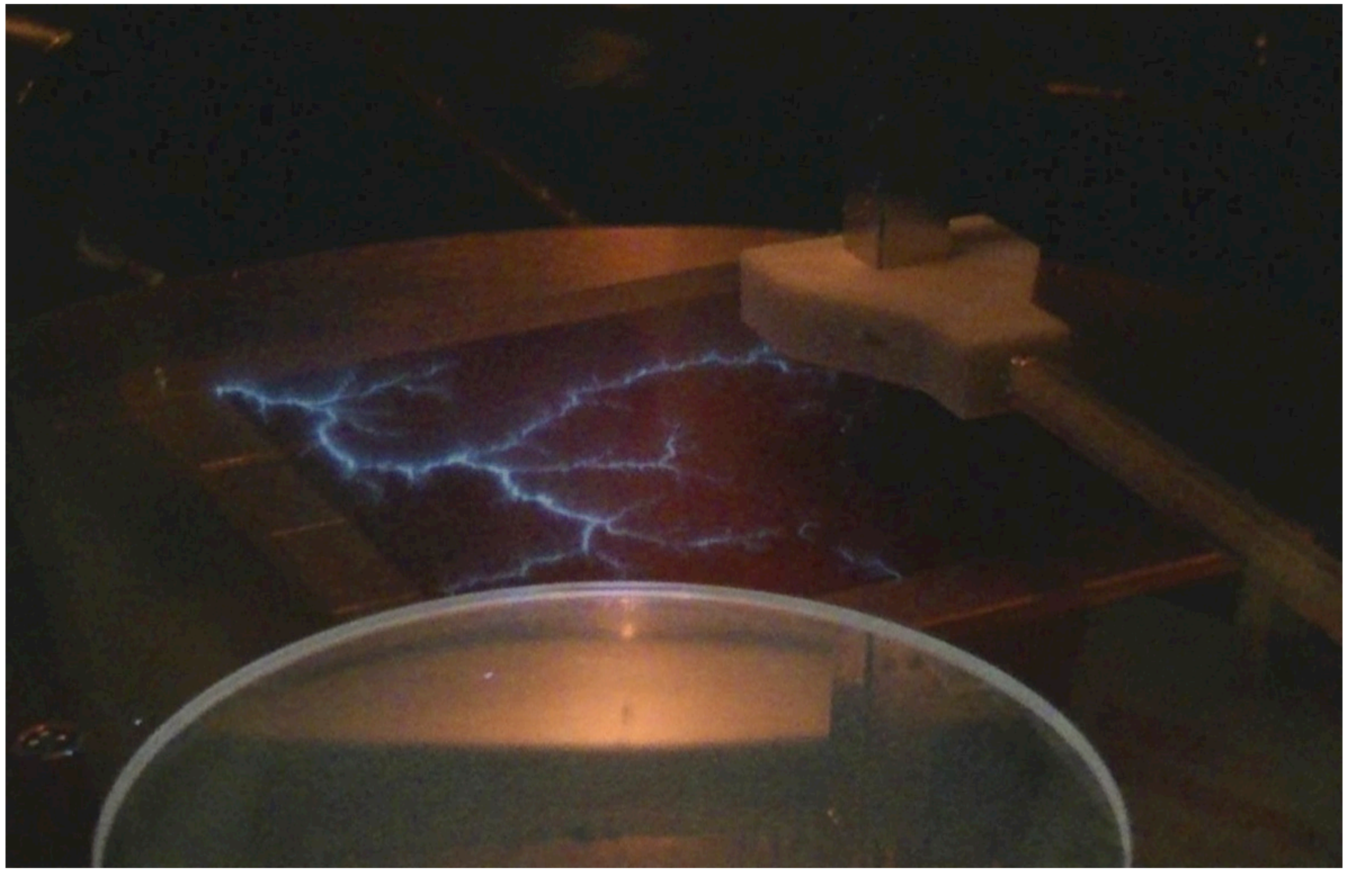
Time = 1 ms



Time = 7 ms



Model Validation



- Facility to experimentally validate the model and explore test configurations and methods
- Electron gun source (100 keV) supplies the charging current to simulate the on-orbit environment.
- This allows us to test the charge dissipation model, but higher energies will be needed to validate the full model.
- Electrostatic voltmeter senses electric field above surface to infer potential of charged material.
- Decay of potential used to derive the effective resistivity of dielectric material.
- Wideband oscilloscope detects and characterizes electrostatic discharge pulses in the material sample, in frequency range 0-2.5 GHz.

Status of Model

- ☑ Arbitrary materials
- ☑ Complex geometries
- ☑ Arbitrary source particle distributions
- Parallel solution (partial)
  - ☑ E field solver is parallelized
  - ☐ parallel comm between E solver and Geant4 is incomplete
- Adaptive meshing (partial)
  - ☑ works computationally
  - ☐ some numerical artifacts still exist in the solutions
- ☐ Charge dissipation
- ☐ Complex boundary conditions

Acknowledgements

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