FEMLAB 3
Multiphysics Modeling

Microwave Applications: Electromagnetic and Thermal Modeling in FEMLAB

Monterey

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IMMG 7th Seminar
Computer Modeling and Microwave Power Industry

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COMSOL

- Spin-off from The Royal Institute of Technology, KTH, Sweden, 1986
- Delivering modeling solutions for problems based on partial differential equations (PDEs)
- Developed the PDE Toolbox in 1995
- Developers of FEMLAB®, interfaces with MATLAB® (1998-present)
- Offices in USA, UK, Germany, France, Nordic countries
- Distributor network covering the rest of the world

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What is FEMLAB?

- A tool that makes it possible to express the laws of physics, using the language of mathematics, and get these translated into a numerical code

Philosophy and the Development of FEMLAB

- ***Usability*** to allow you to concentrate on the problem and not on the software
- ***Flexibility*** to maximize the family of problems that you can formulate in FEMLAB
- ***Extensibility*** to allow you, as an advanced user, to implement your own code in FEMLAB and to change the built-in code
- ***Platform Independence*** choose between Windows, Linux, HP-UX, Sun Solaris, or Mac OSX, and several 64-bit platforms

Who uses FEMLAB?

- NPS Electrical Engineering
- UC X
  - X ε {LA,SB,SD,D,SF,SC,R, I}
- Caltech, University of Washington, Stanford
- UNLV, CU Boulder, UU
- MIT, Harvard, Princeton, …
- Y NL
  - Y ε {B,LA,LL,LB,PN,S}
- NASA research centers
- NIST, NREL, USGS, SWRI
- NIH
- ARL, AFRL, NRL

- Northrop-Grumman, Raytheon
- Boeing, Lockheed-Martin
- Applied Materials, Agilent
- GE, 3M, Motorola
- MedRad, Medtronic, St. Jude Medical
- Merck, Roche
- Procter and Gamble, Gillette
- Energizer, Eveready
- Hewlett-Packard, Microsoft, Intel
- Nissan, Sony, Toshiba
- ABB, Volkswagen, GlaxoSmithKline
- PARC, Osram-Sylvania

How is FEMLAB Used?

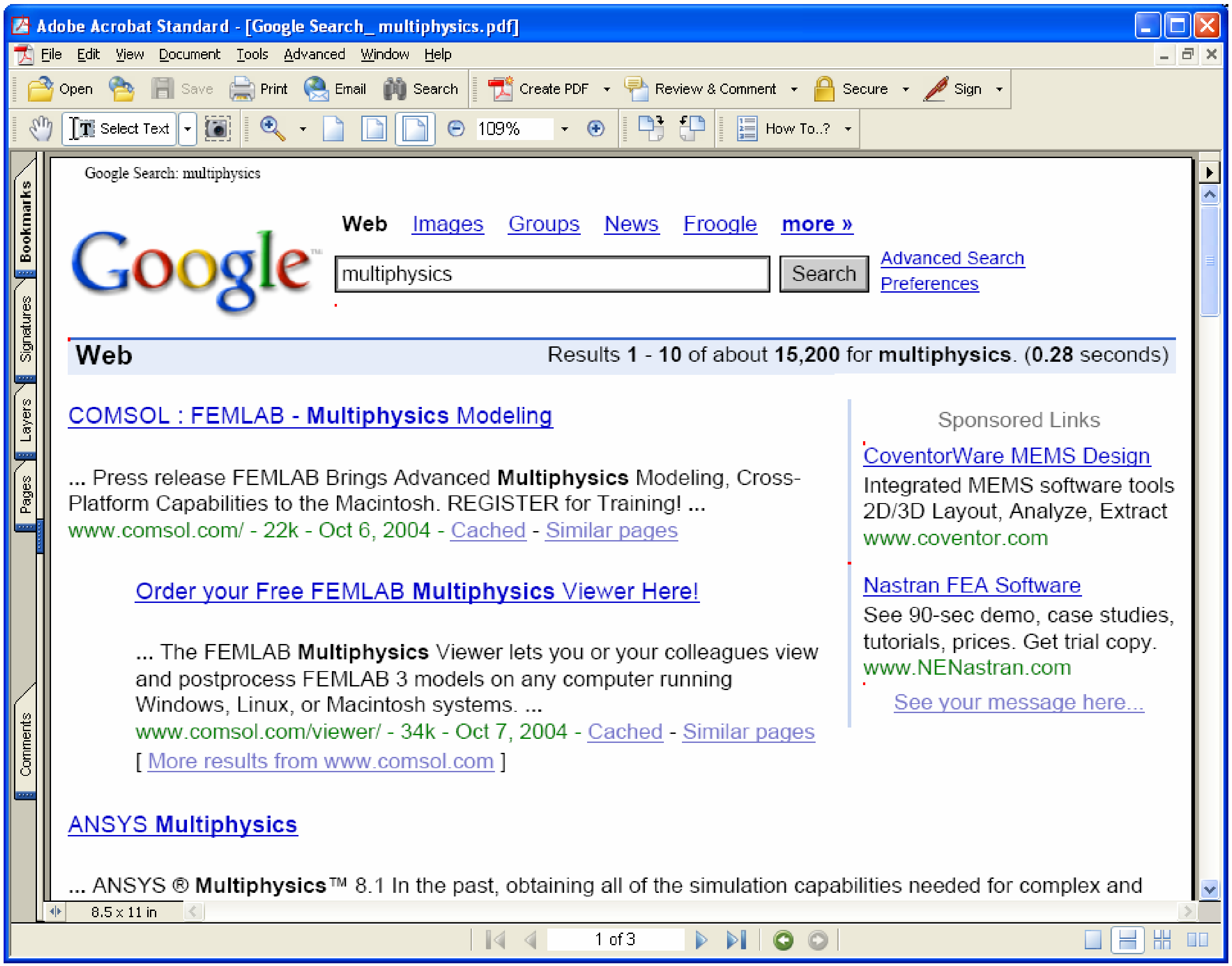
- Teaching
  - Course work (e.g., transport phenomena, electromagnetics, heat transfer, MEMS analysis)
  - Thesis research
- Research
  - Product designers (prototyping and what-if analysis)
  - Experimentalists (design, computational complements)
  - Theoreticians (insight into physics or equations)
  - Computational scientists (algorithm design)

Current press and news

- New book featuring FEMLAB
  - *Elements of Chemical Reaction Engineering*, by H. Scott Fogler
- Articles
  - "Smoothing out the wrinkles", from *Desktop Engineering* featuring Thermage, Inc.
  - "Software tunes up microwave weapon", from *Machine Design* featuring SARA, Inc.

- Press releases
  - FEMLAB 3.1 released
  - COMSOL News, Issue no. 1
  - FEMLAB Multiphysics Viewer released
  - Benchmark of FEMLAB vs. Ansys and Fluent
  - Mac OS 10.3 platform added
  - Site licenses purchased at Stanford and Chalmers
  - For more see www.comsol.com

Multiphysics Modeling



What is Multiphysics Modeling?

- Similar system of PDEs is valid for a large number of physical phenomena
- Describing a single physical system often requires the combination of multiple such phenomena, coupled or not

Current flows in a structure

↓

Structure heats up

↓

Structure expands

= Decoupled Multiphysics

Current flows in a structure

↓

Structure heats up

↓

Conductivity of structure is temperature dependent ↑

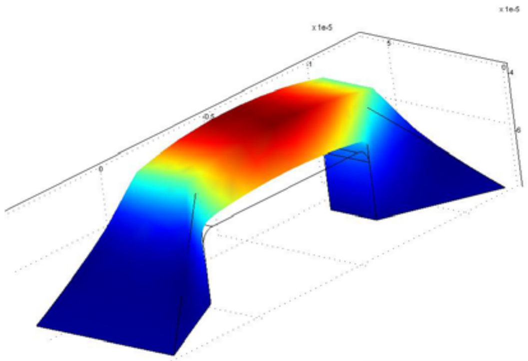
↓

Structure expands

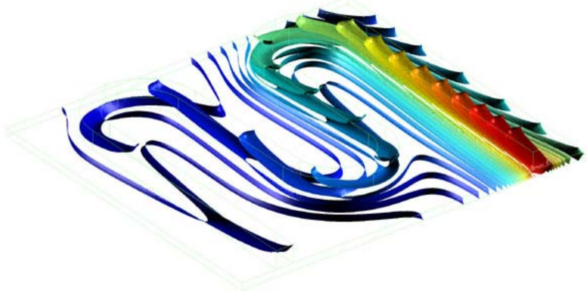
= Coupled Multiphysics

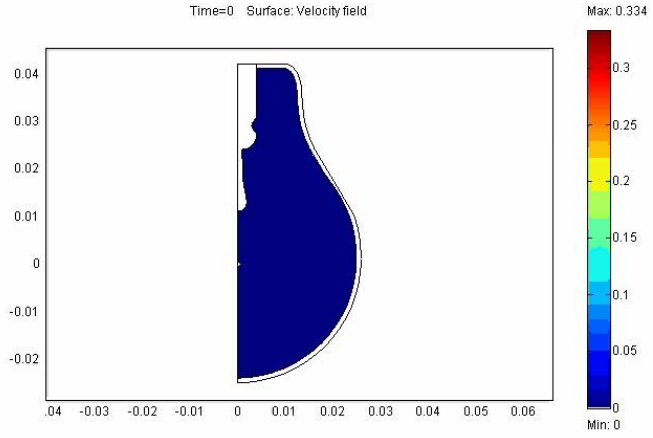
Multiphysics Examples

A MEMS device deforms due to thermal strains when a potential is applied to it



A fuel cell produces power due to chemical reactions





Argon flows due to natural convection in a light bulb as the filament heat it up

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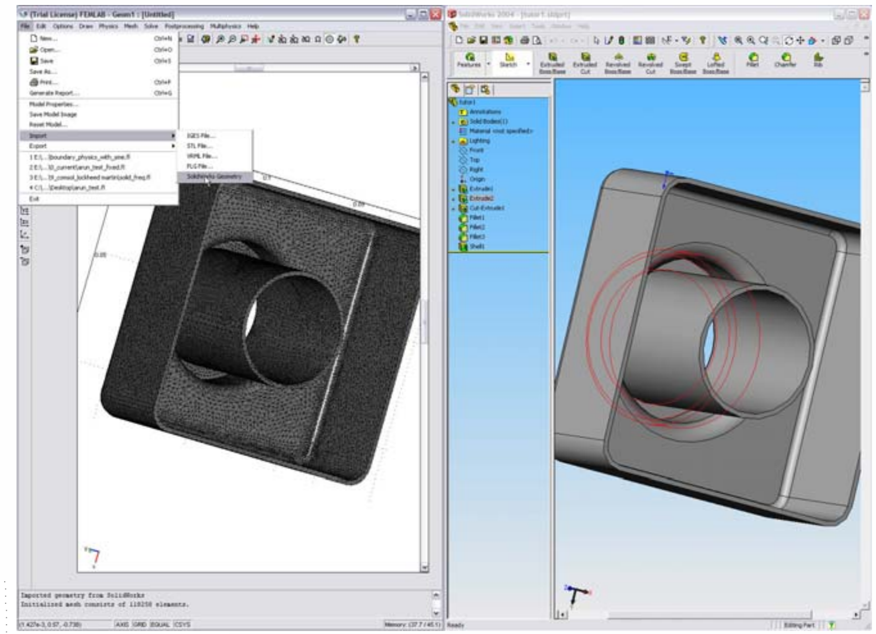
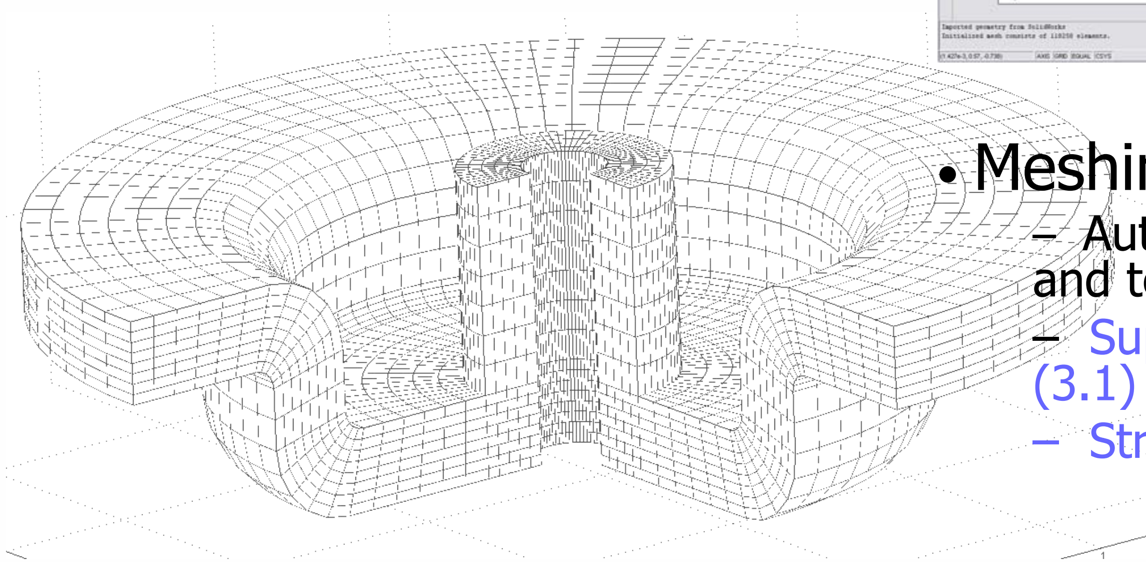
FEMLAB Overview

- FEMLAB's Core Capabilities
  - Numerical solutions to physics models based on differential equations
  - Coupled equations/physics (Multiphysics)
- FEMLAB Modules
  - Predefined equations and an extensive library of models covering specific fields
- FEMLAB Compatibilities
  - MATLAB, Simulink, Control Systems Toolbox
  - Solidworks
  - CAD import (DXF, IGES, STL)
  - Image import (MRI, jpeg, tiff, etc.)

FEMLAB Features

- Geometry
  - Integrated CAD tools
  - External geometry files import
  - Live connection to SolidWorks (3.1)





- Meshing
  - Automatic mesher for triangle and tetrahedron element
  - Support for Quad/Brick/Prism (3.1)
  - Structured meshes (3.1)

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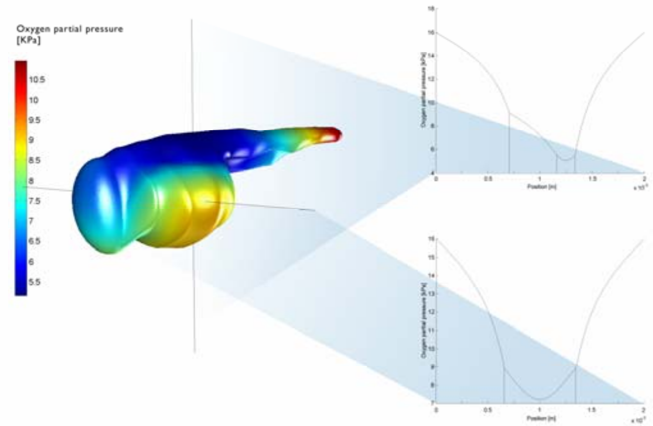
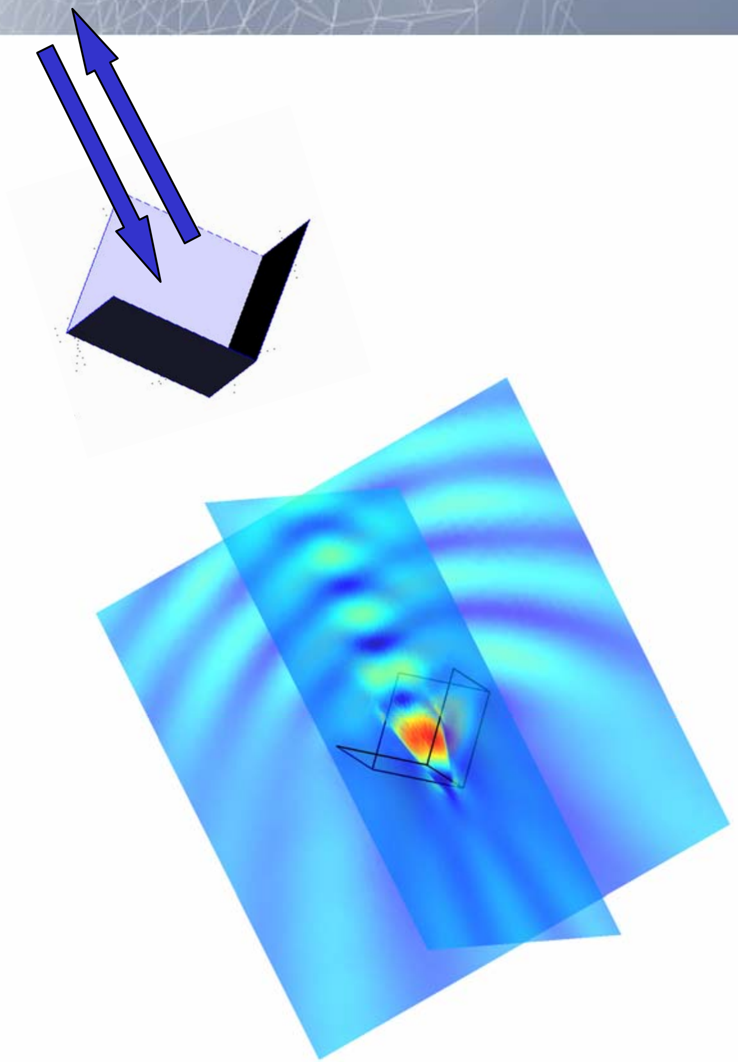
FEMLAB Features

- Solvers
  - Direct and iterative solvers
  - Stationary linear/nonlinear; transient; eigenvalue and parametric analysis
  - Adaptive mesh
  - Direct and sequential coupling
  - New geometric multigrid preconditioner (3.1)
- Postprocessing
  - Plot any expression of results as a slice, contour, subdomain, isosurface, deformed plot…
  - Plot cross-sections
  - Evaluate line, surface, volume integrals
  - Export results as an ASCII file
  - Make movies of your solutions
  - Fully integrated with MATLAB for further analysis



64-bit FEMLAB 3.1

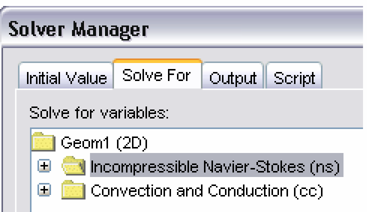


- Supported platforms
  - HP-UX/PA-RISC
  - Solaris/UltraSparc
  - Linux/AMD64/EM64T
  - Linux/Itanium
- Electromagnetic waves reflected by a metallic corner cube
- 31 times larger than before...
  - 7.1 M degrees of freedom (before 113 K)
  - 9.5 GB memory
  - 1 hour 13 minutes solution time
  - New GMG solver used

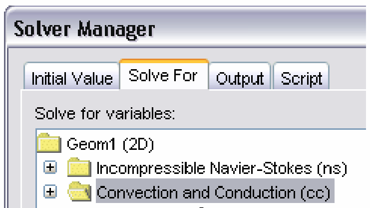
Additional FEMLAB 3.1 Features

- Record a solution procedure (scripting)

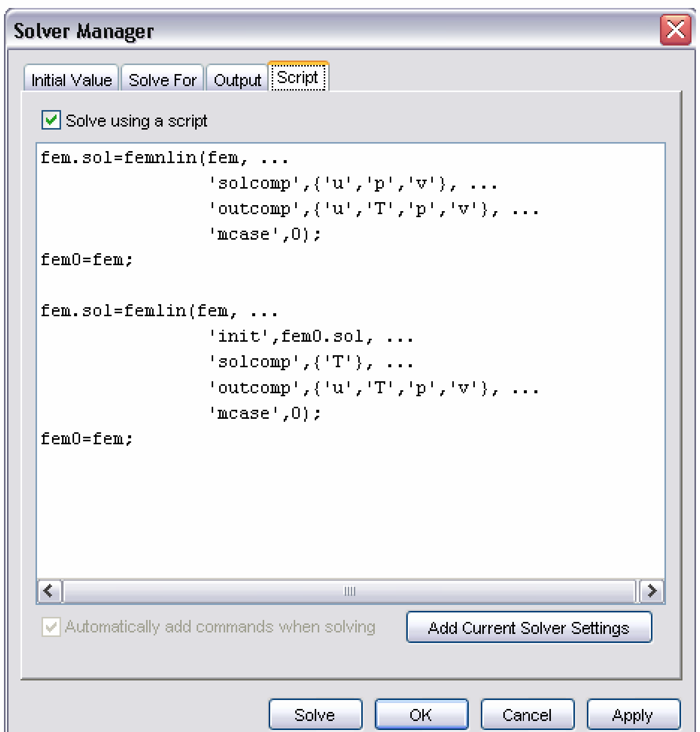
1. Fluid



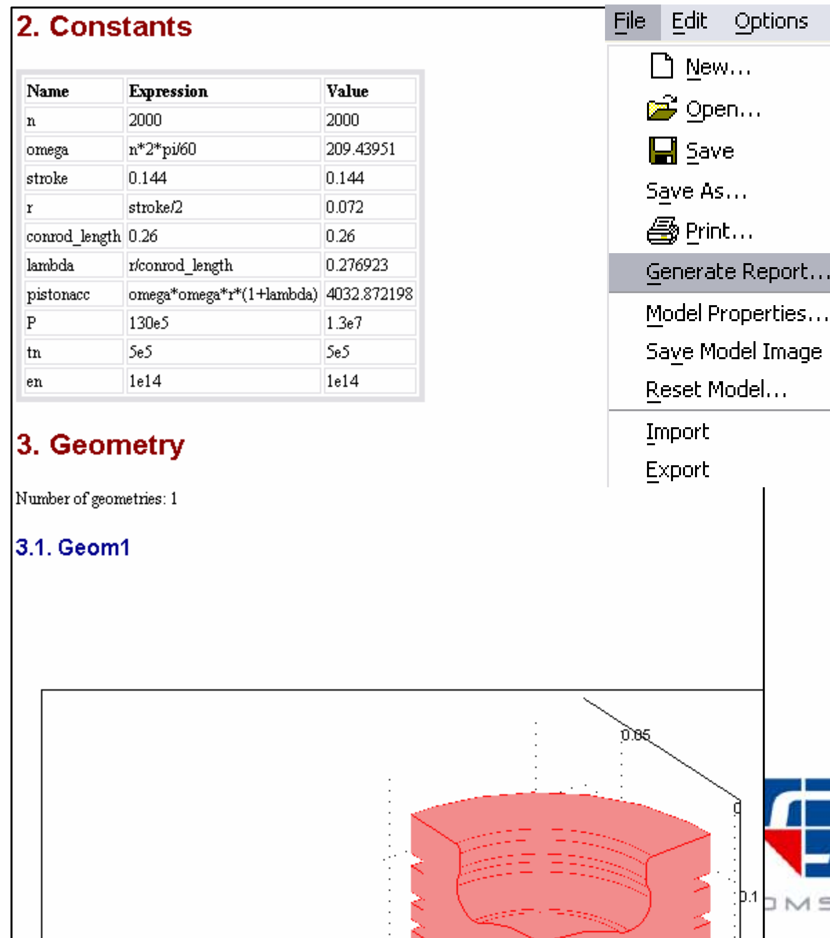
2. Thermal



Language script generated :



- Generate reports automatically



2. Constants

Name	Expression	Value
n	2000	2000
omega	n*2*pi/60	209.43951
stroke	0.144	0.144
r	stroke/2	0.072
conrod_length	0.26	0.26
lambda	r/conrod_length	0.276923
pistonacc	omega*omega*r*(1+lambda)	4032.872198
P	130e5	1.3e7
tn	5e5	5e5
en	1e14	1e14

3. Geometry

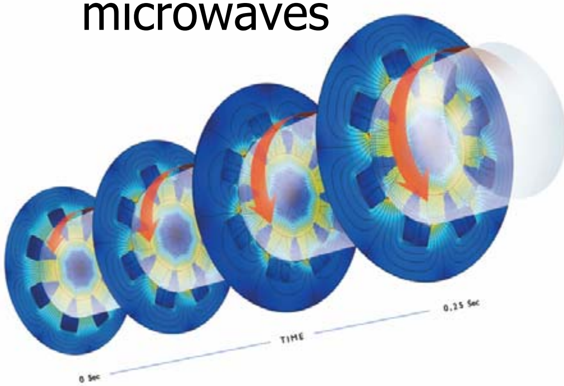
Number of geometries: 1

3.1. Geom1

FEMLAB Modules

Electromagnetics

- Electrostatics
- Magnetostatics
- Eddy currents
- Electromagnetic waves, with applications in photonics and microwaves

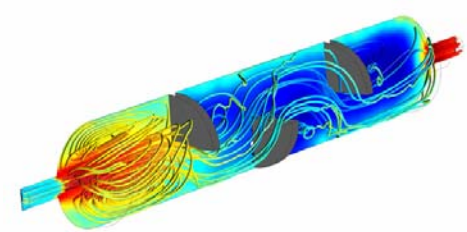


Structural Mechanics

- Solids, beams, plates, and shells
- Thermal stresses
- Large deformations
- Piezoelectric material

Chemical Engineering

- Incompressible Navier-Stokes
- Flow in porous media
- Non-Newtonian fluids
- Electrokinetic flow
- Maxwell diffusion
- Convection and conduction



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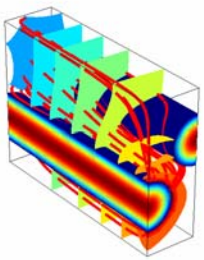
New Modules in FEMLAB 3.1

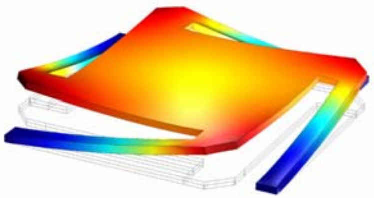
Heat Transfer

- General Heat Transfer including radiation boundary conditions
- Highly conductive layer (shell)
- Bioheat equation
- Non-isothermal flow



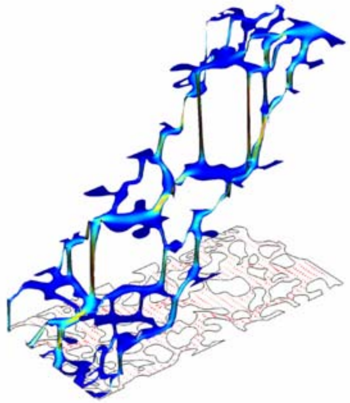
MEMS

- Combination of Structural Mechanics, Fluid Dynamics
- Electromagnetics
- Model library
  - Actuator models
  - Sensor models
  - Microfluidics models



Earth Science

- Richard’s equation
- Darcy's law
- Brinkman equations
- Saturated solute transport
- Variably saturated solute transport



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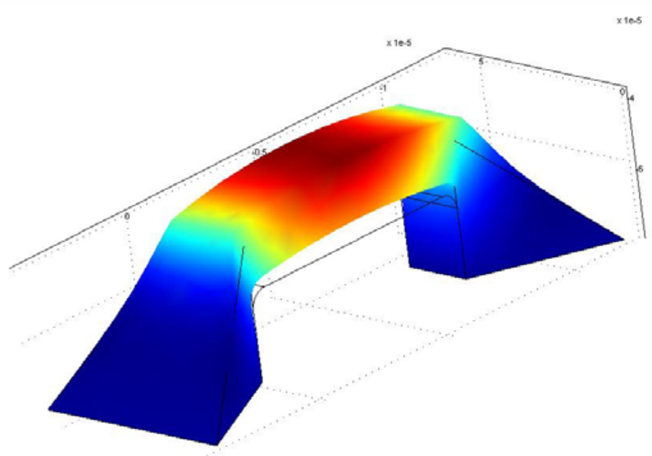
Introductory Example

Titanium microresistor beam

- Combination of electrical, thermal and structural analysis in a single model
- Current flows in a microbeam, and generates heat
- Heat generation induces thermal stresses which deform the beam
- Steady-state solution



- Possible alterations
  - Temperature dependent coefficients
  - Several subdomains
  - Parametric study
  - Transient analysis
  - Much, much more!

Specify geometry

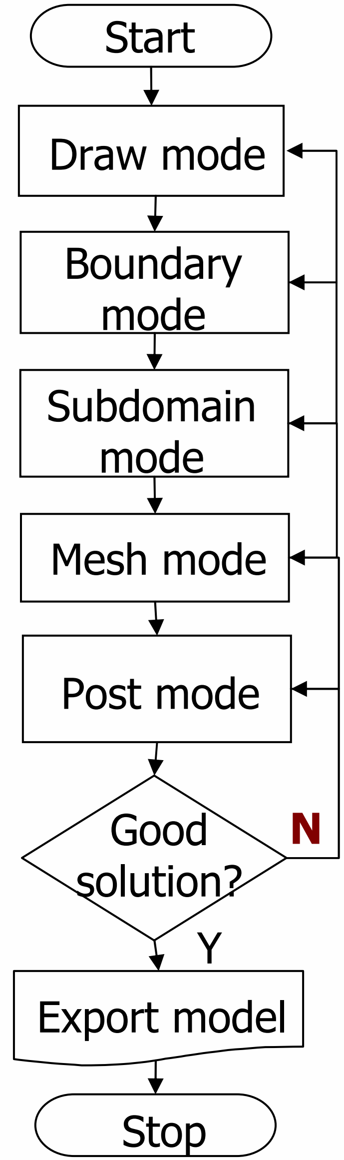
External interactions

Internal properties

Discrete mesh

Visualization / data representation

Simulink / Matlab / other programs

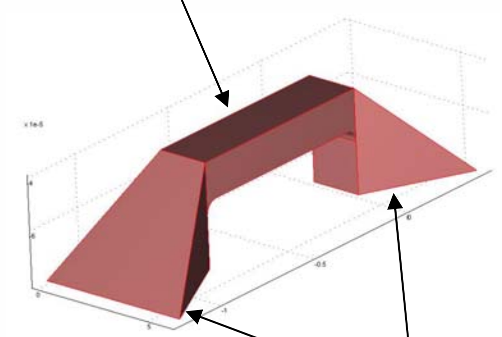


Set up solver(s)

Problem Definition

DC current

DC current balance for conductive media

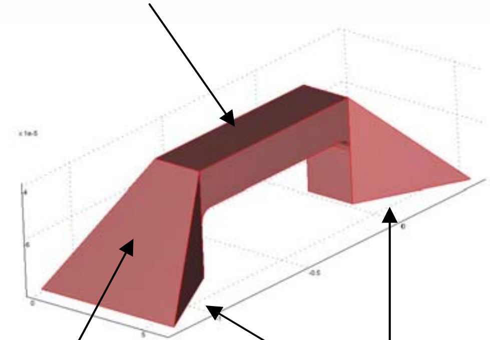


Fixed potentials generate potential difference $\Delta V = .2V$

Heat Transfer

Thermal flux balance with the electric heating as source:

$$Q = \sigma |\nabla V|^2$$

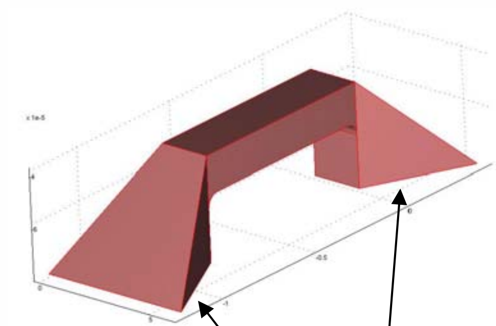


Convection: $h(T - T_{amb})$

$T = T_0 = 323^{o}K$

Structural Analysis

Force balance with the thermally induced stress as volume load



Fixed to the base plate

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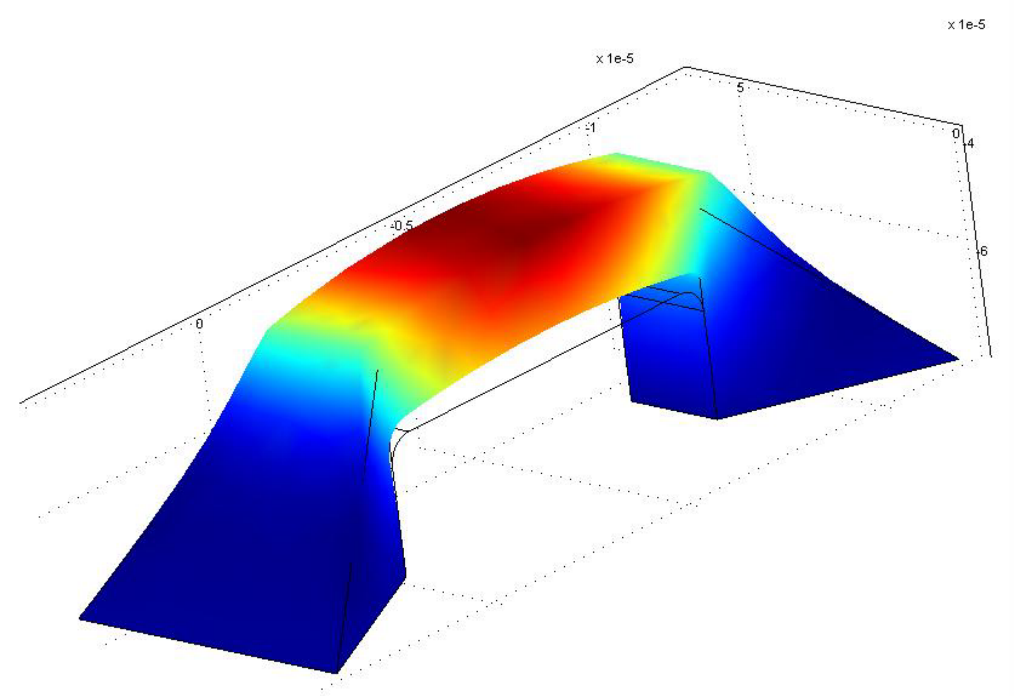
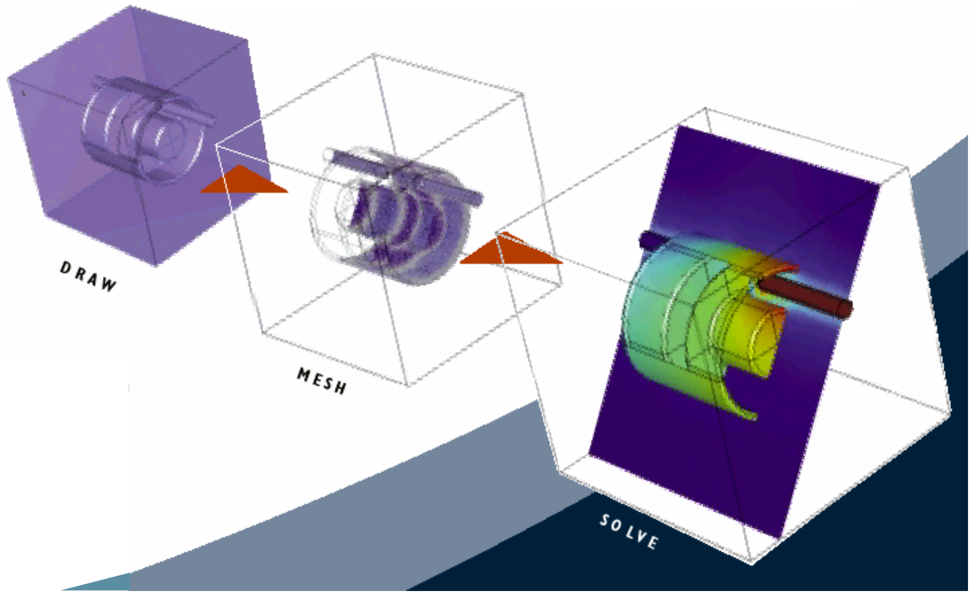
Results

- Maximum temperature and displacement can be evaluated
- An optimization problem can easily be set up
- Model built from scratch in less than an hour!



Summary of the modeling process

- Draw Mode
- Boundary Mode
- Subdomain Mode
- Mesh Mode
- Solve!
- Post Mode



Learn more!

"Because of what I learned in today's FEMLAB course, I saved at least a month of work," Professor Carl Meinhart, UCSB

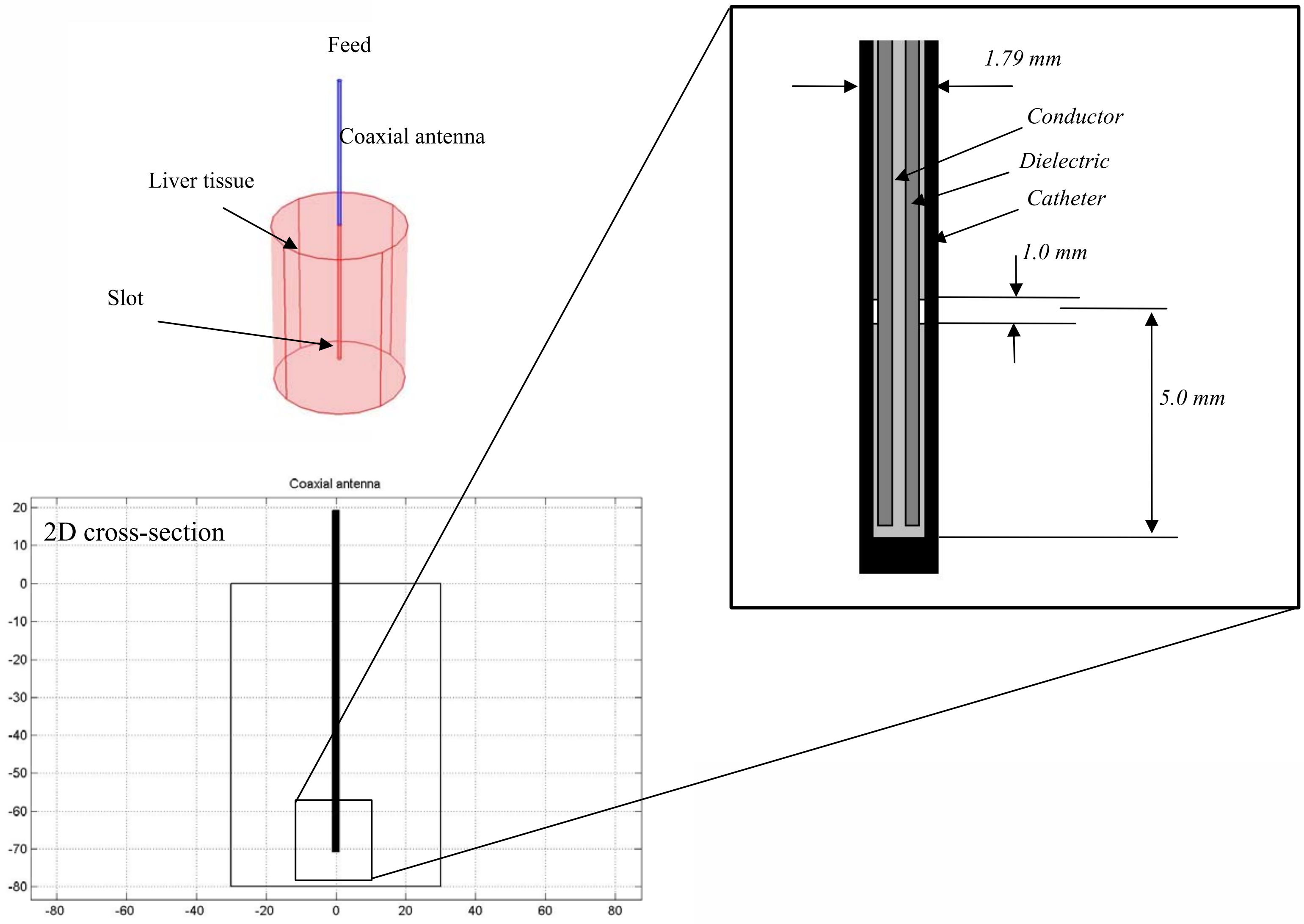
- FEMLAB Hands-on Modeling Courses
  - Training at several locations including Ne
    Vancouver, Austin, Denver, and San Jose
- Visit www.comsol.com/training
  - For more information, including courses and locations

Microwave Cancer Therapy

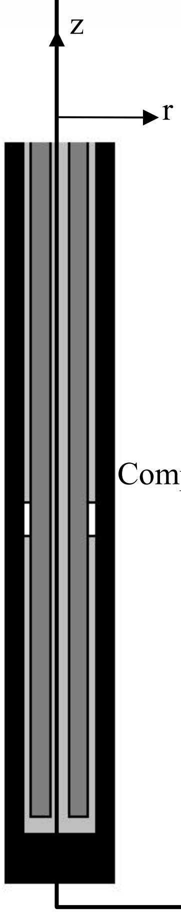
Introduction

- Cancer is treated by applying localized heating to the tumor tissue
- Microwave heating is applied by inserting a thin microwave antenna into the tumor
- Challenges associated with the selective heating of deep-seated tumors without damaging surrounding tissue are:
  - control of heating power and spatial distribution
  - design and placement of temperature sensors
- Computer simulation is an important tool
- The purpose of this model is to compute the radiation field and the specific absorption rate (SAR) in liver tissue for a thin coaxial slot antenna used in Microwave Cancer Therapy

Problem definition



2D Geometry and domain equations



$$\nabla \times \left(\frac{1}{\varepsilon_c} \nabla \times \mathbf{H} \right) - \mu\omega^2 \mathbf{H} = 0$$

$$\mathbf{H} = H_\varphi \hat{\mathbf{e}}_\varphi$$

$$\varepsilon_c = \varepsilon - j\sigma / \omega$$

$$\omega = 2\pi f$$

$$f = 2.45[\mathrm{GHz}]$$

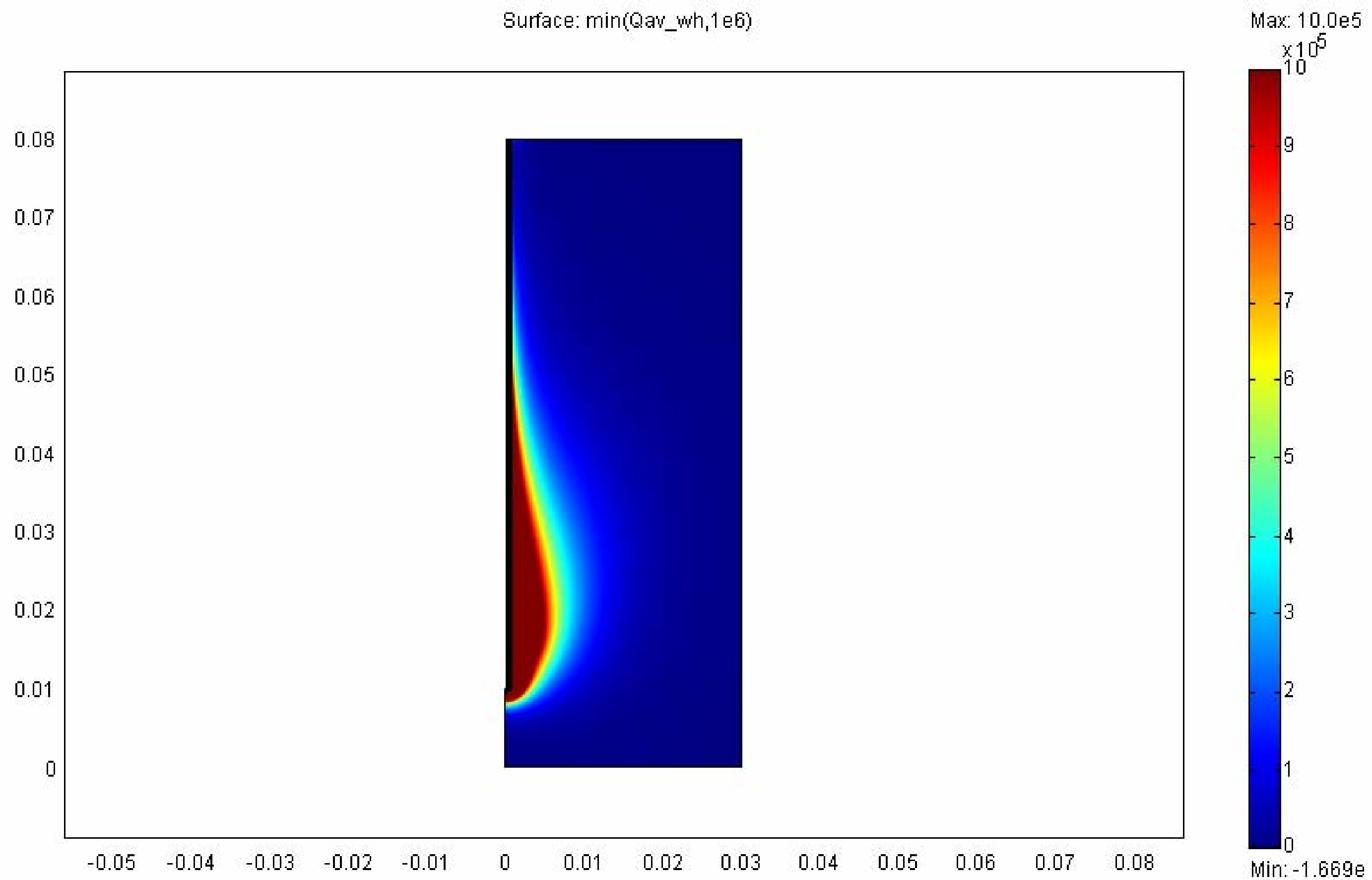
Material Parameters

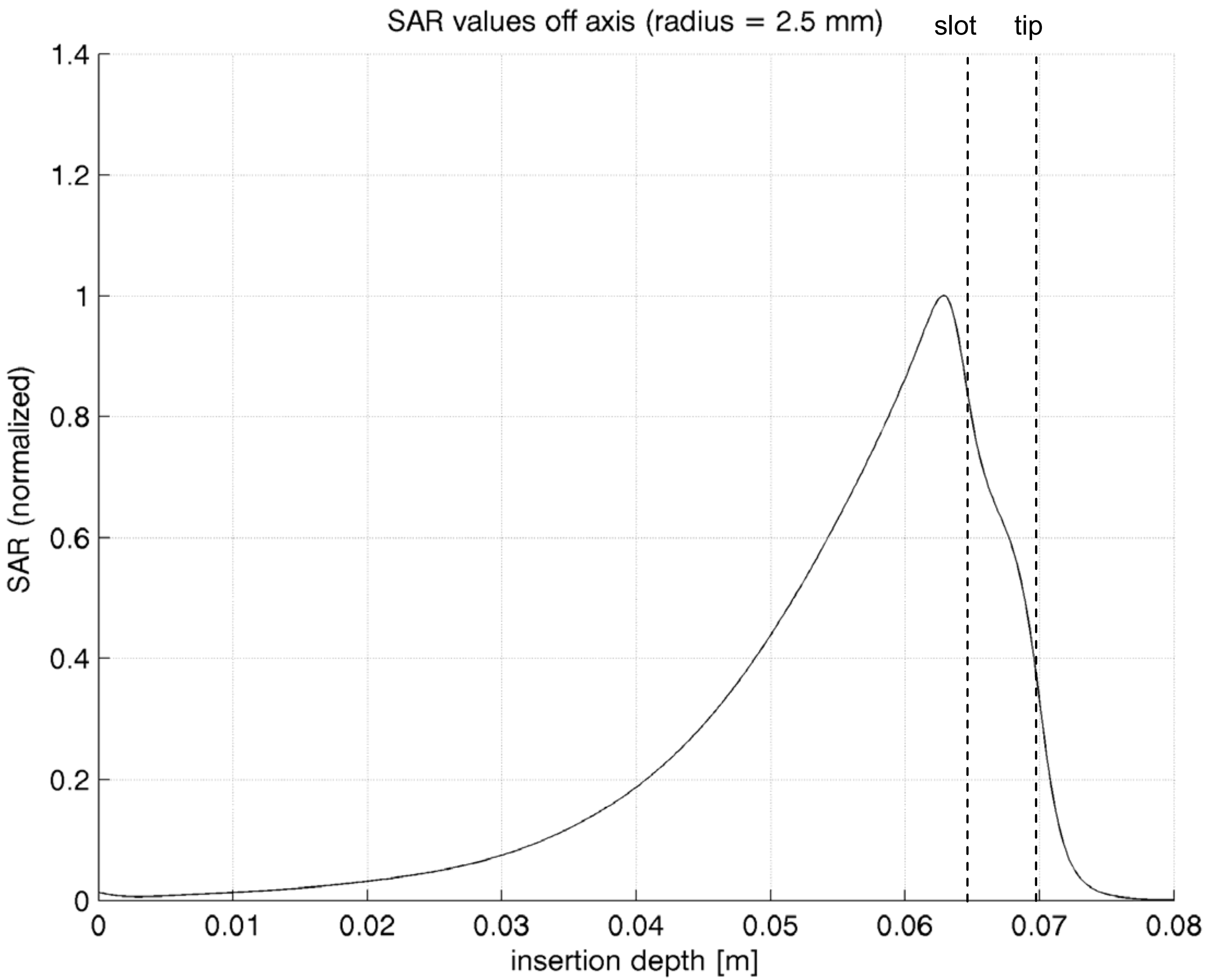
Relative permittivity	
inner dielectric of the coaxial cable	2.03
catheter	2.60
liver tissue	43.03
Conductivity [S/m]	
liver tissue	1.69

Boundary Conditions

- Metallic boundaries: $$\mathbf{n} \times \mathbf{E} = \mathbf{0}$$
- Symmetry axis: $$\begin{cases} E_r = 0 \\ \dfrac{\partial E_z}{\partial r} = 0 \end{cases}$$
- Feed (10 W): $$\begin{cases} \mathbf{n} \times \sqrt{\varepsilon_c}\,\mathbf{E} - \sqrt{\mu} H_\varphi = -2\sqrt{\mu} H_{\varphi 0} \\ H_{\varphi 0} = \dfrac{0.1012}{r} \end{cases}$$
- Mesh truncation: $$\mathbf{n} \times \sqrt{\varepsilon_c}\,\mathbf{E} - \sqrt{\mu} H_\varphi = 0$$

Microwave Heating





SAR values off axis (radius = 2.5 mm)
slot
tip
SAR (normalized)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
insertion depth [m]

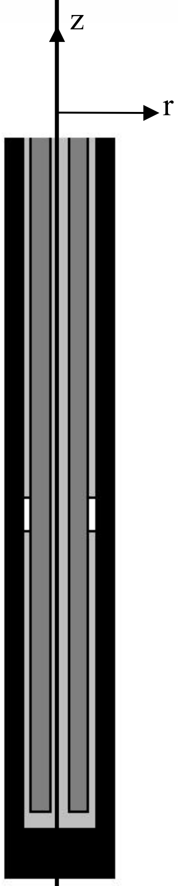
Notes

- SAR values are highest near the slot.
- The absolute microwave power inflow can be computed using boundary integration and evaluates to 9.94 W, i.e. <1% of the input power of 10 W is reflected.
- A natural extension of the model is to include a heat transfer analysis.

Thermal analysis

- Microwaves are heating the tissue
- The dominating heat loss is due to blood perfusion
- The purpose of modeling is to compute the temperature field near the microwave antenna

Domain Equations: Thermal analysis



$$-\nabla \cdot k\nabla T = Q_{microwave} - W_b C_p (T - T_0)$$

$$k = 0.56 \ [\mathrm{W\ m^{-1} K^{-1}}]$$

$$W_b = 3.6 \ [\mathrm{kg\ m^{-3} s^{-1}}]$$

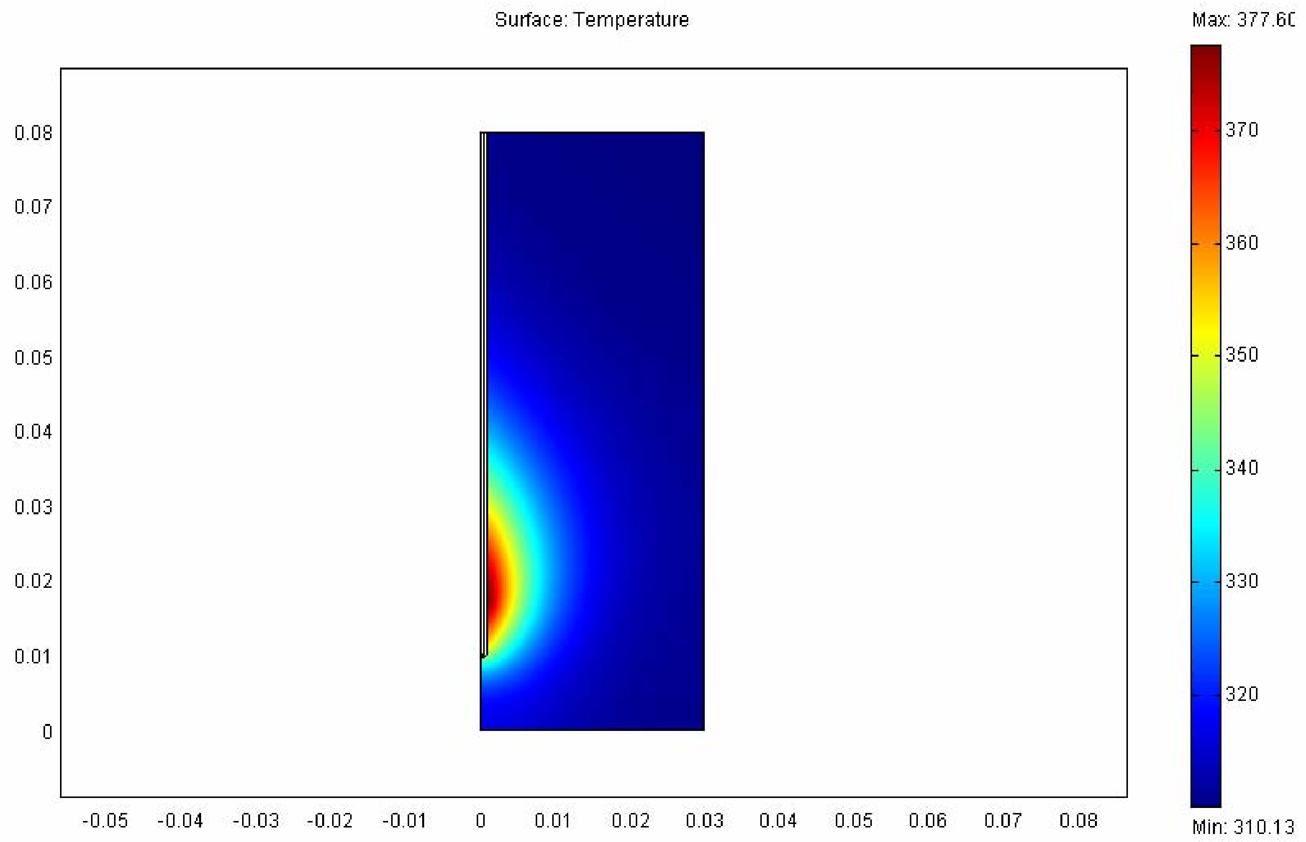
$$C_p = 3639 \ [\mathrm{J\ kg^{-1} K^{-1}}]$$

$$T_0 = 310 \ [\mathrm{K}]$$

Boundary Conditions:
Thermal analysis

- All boundaries: $$\mathbf{n} \cdot k \nabla T = 0$$
- Input microwave power: 10 W

Temperature Distribution



Conclusions: Thermal analysis

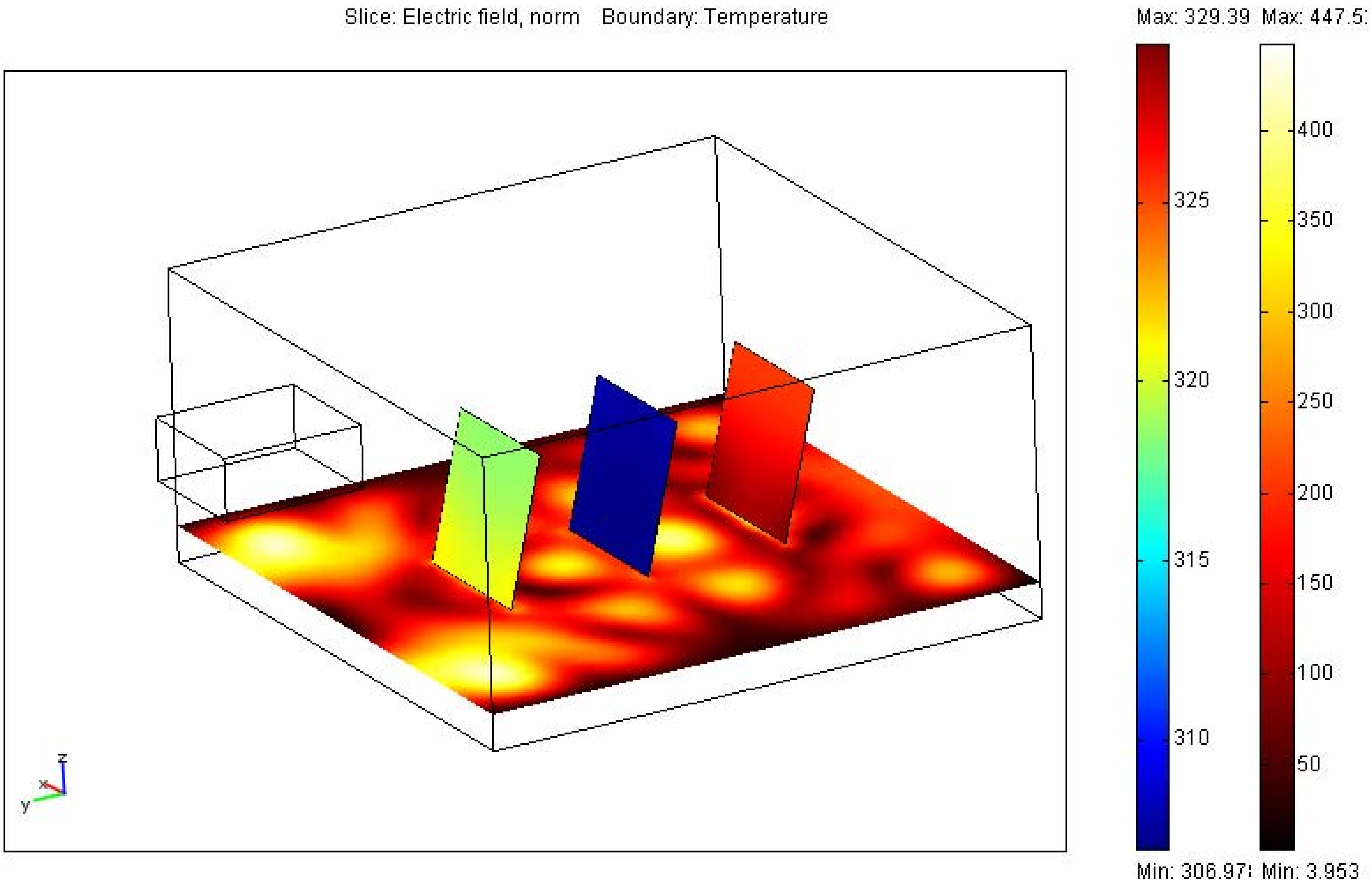
- The temperature is highest near the slot
- For an input microwave power of 10 W, the calculated maximum temperature is about 100°C
- Including heat conduction effects in the antenna will decrease this value.

Microwave Oven with Face Absorbers

Model comments

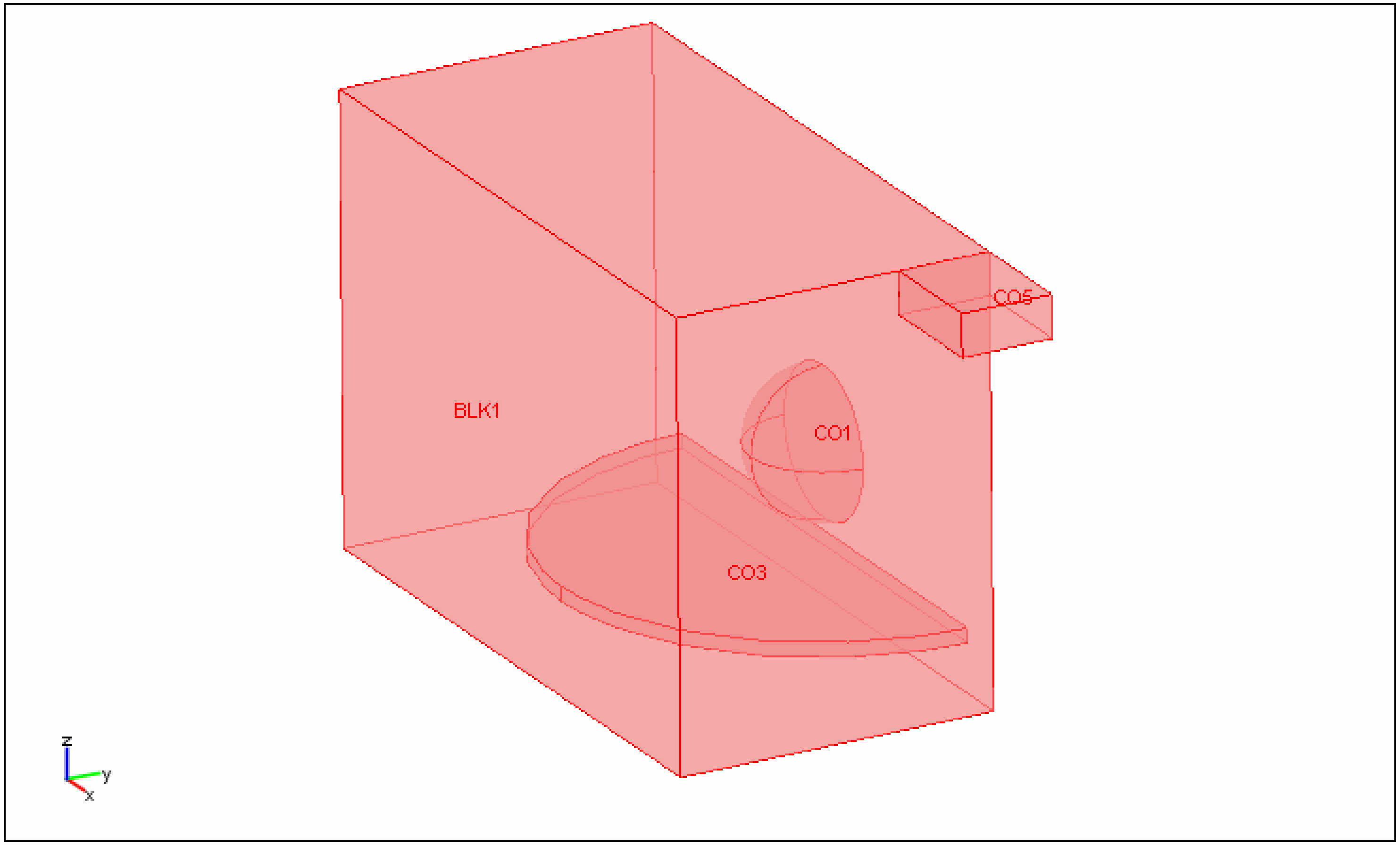
- Uses two application modes
  - 3D EM waves
  - Thin conducting shells
- Face absorbers
  - Transition boundary condition with surface impedance is used on the faces
  - Heat source is an expression involving surface current density

3D EM Waves + Shell Heat Transfer



Microwave Heating of a Potato

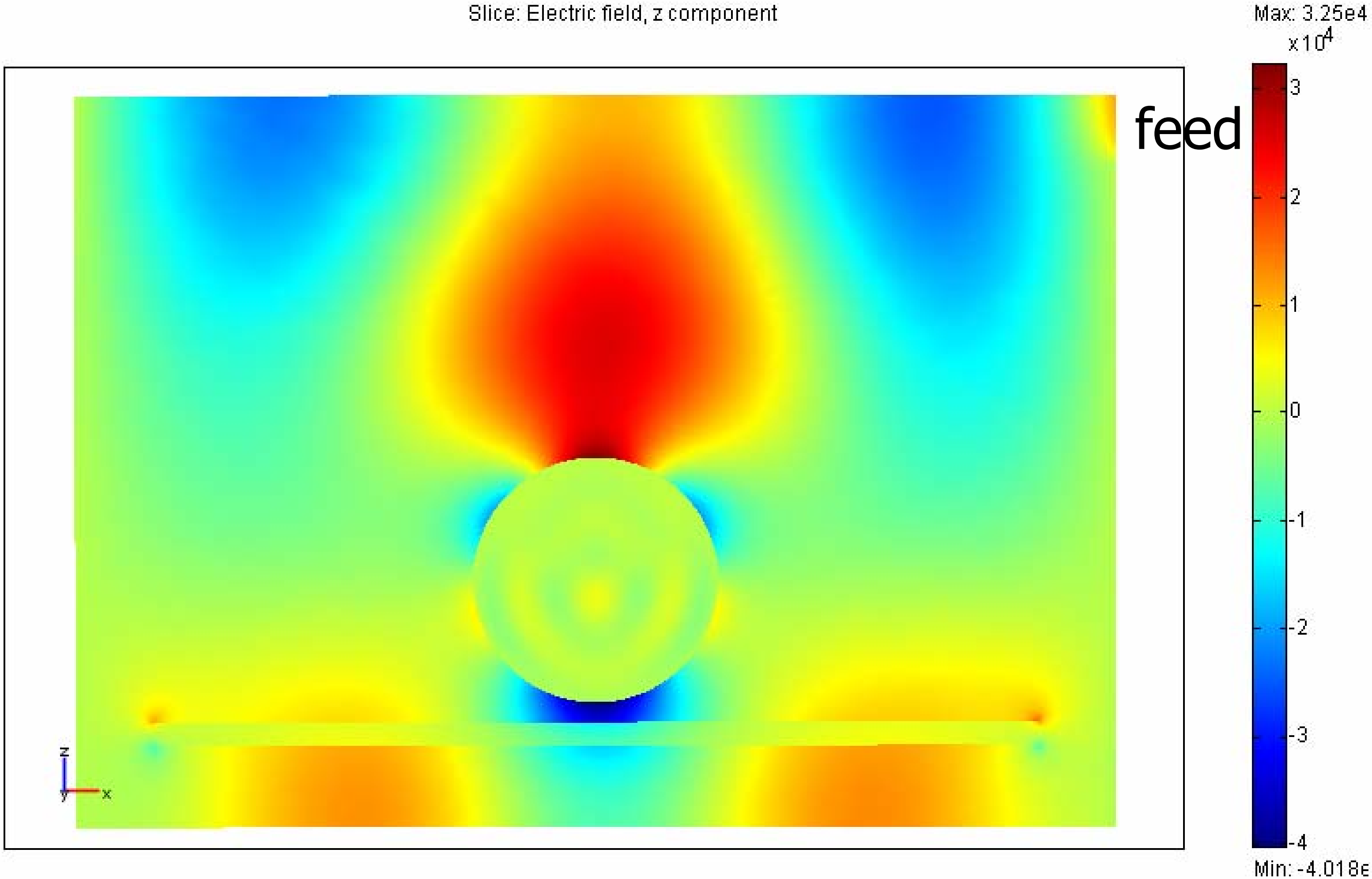
3D Geometry



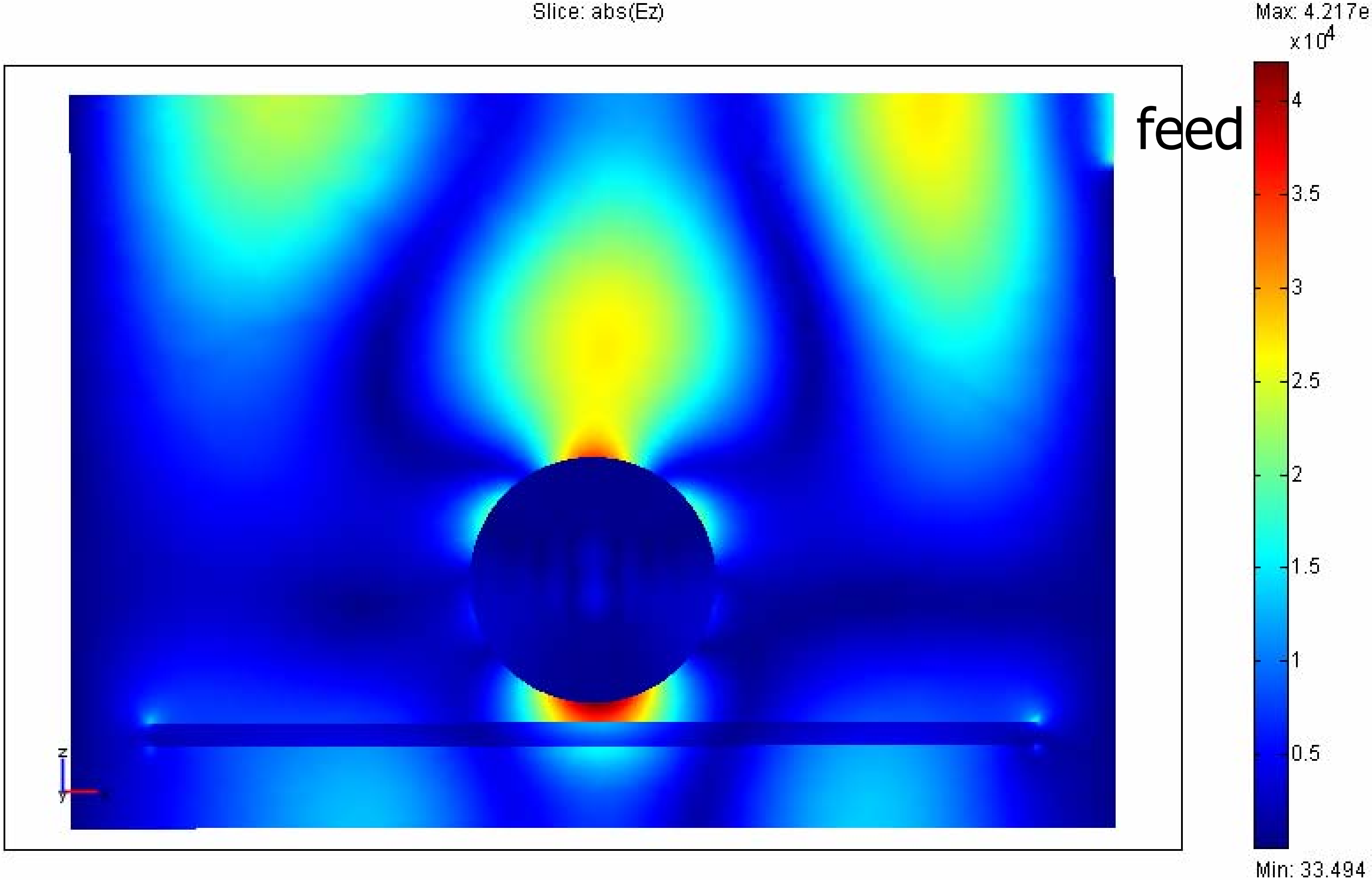
Model Notes

- To reduce problem size, only half of the geometry is modeled
- 3.2 M DOFs (real valued) and used about 4.5 GB peak memory
- Computer specs
  - 64 bit dual processor Itanium with 12 Gb RAM

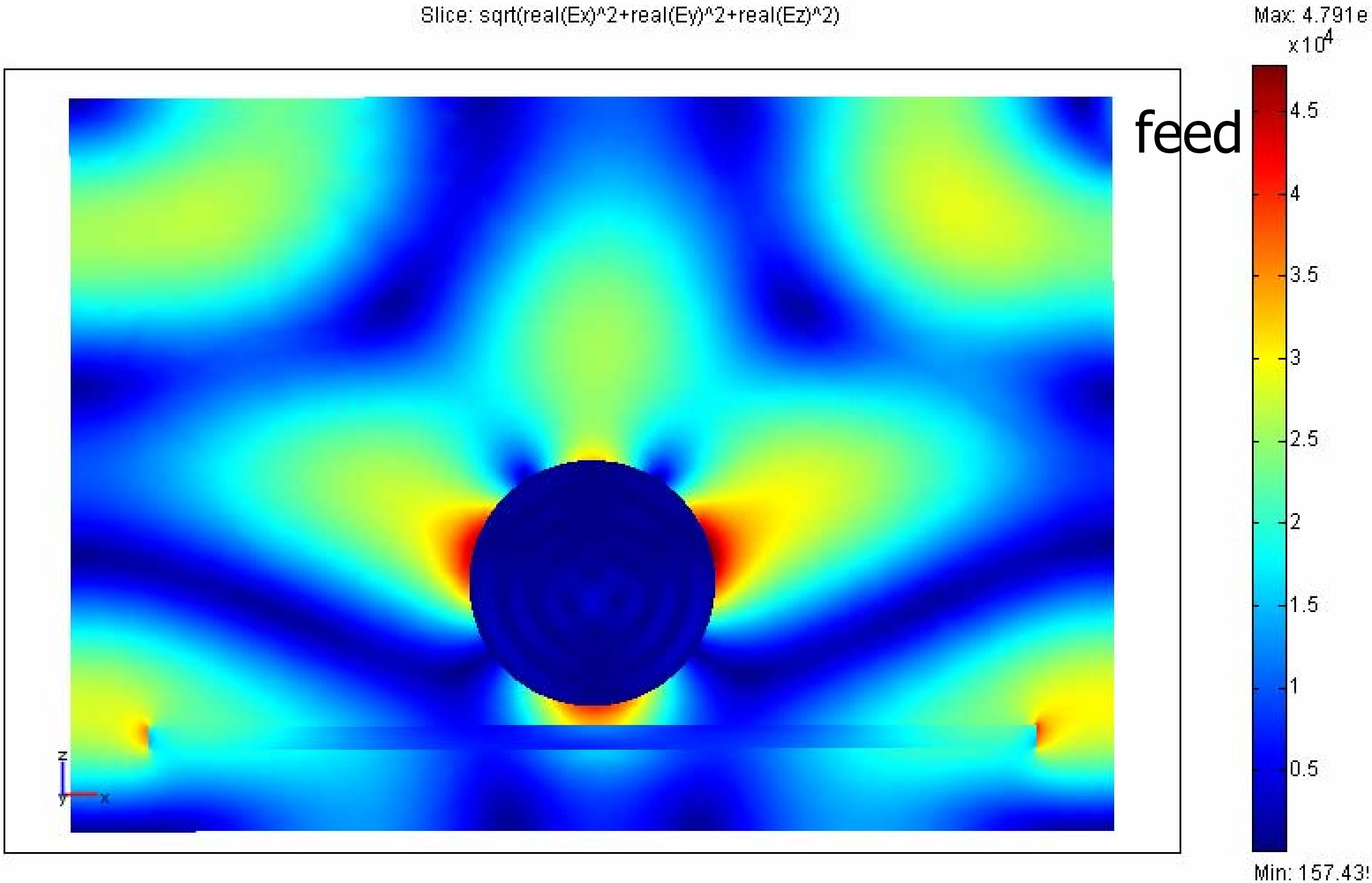
Electric field, Ez(0): xz-plane



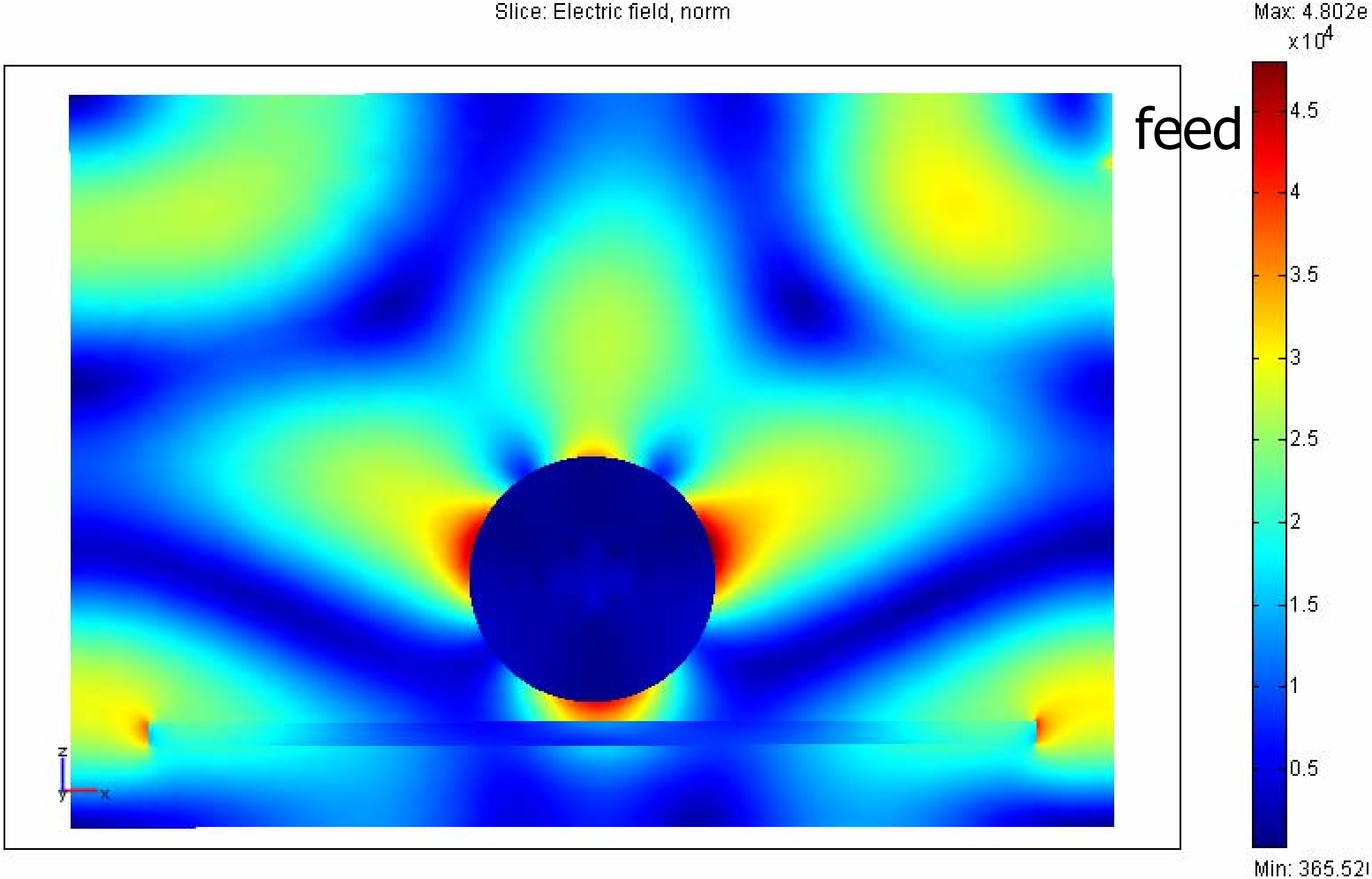
Electric field, |Ez|: xz-plane



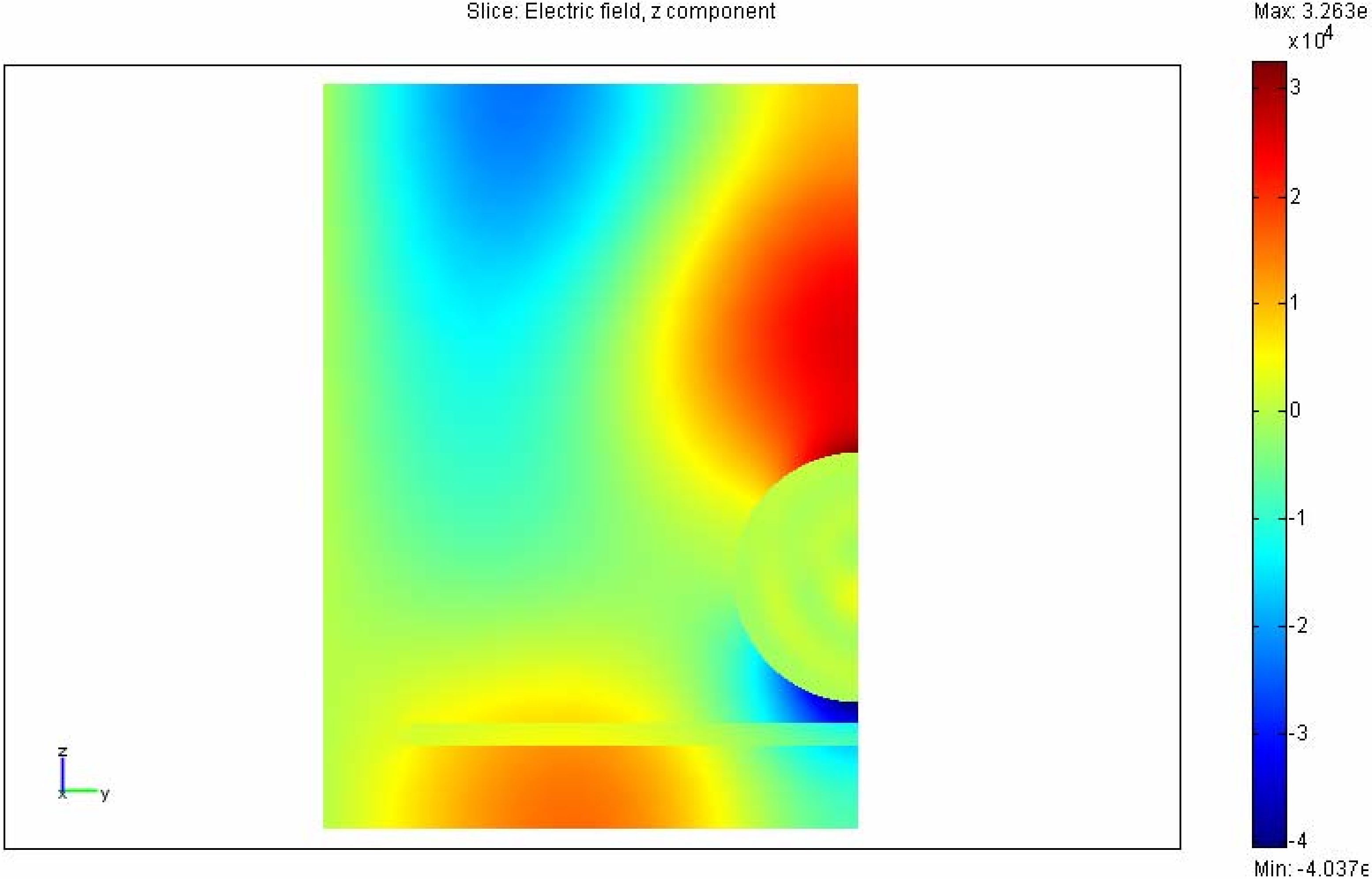
Electric field, E(0): xz-plane



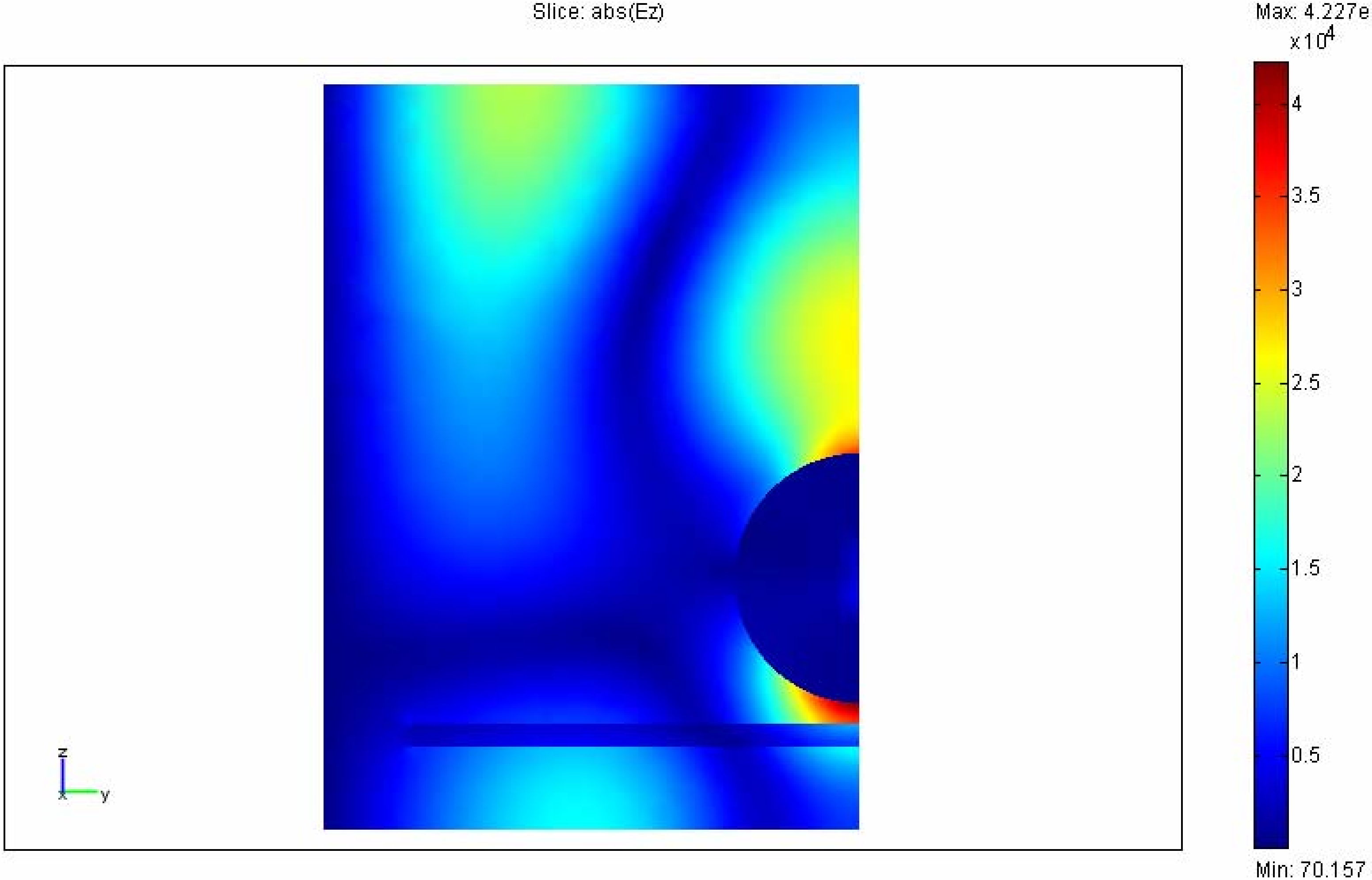
Electric field, |E|: xz-plane



Electric field, Ez(0): yz-plane



Electric field, |Ez|: yz-plane



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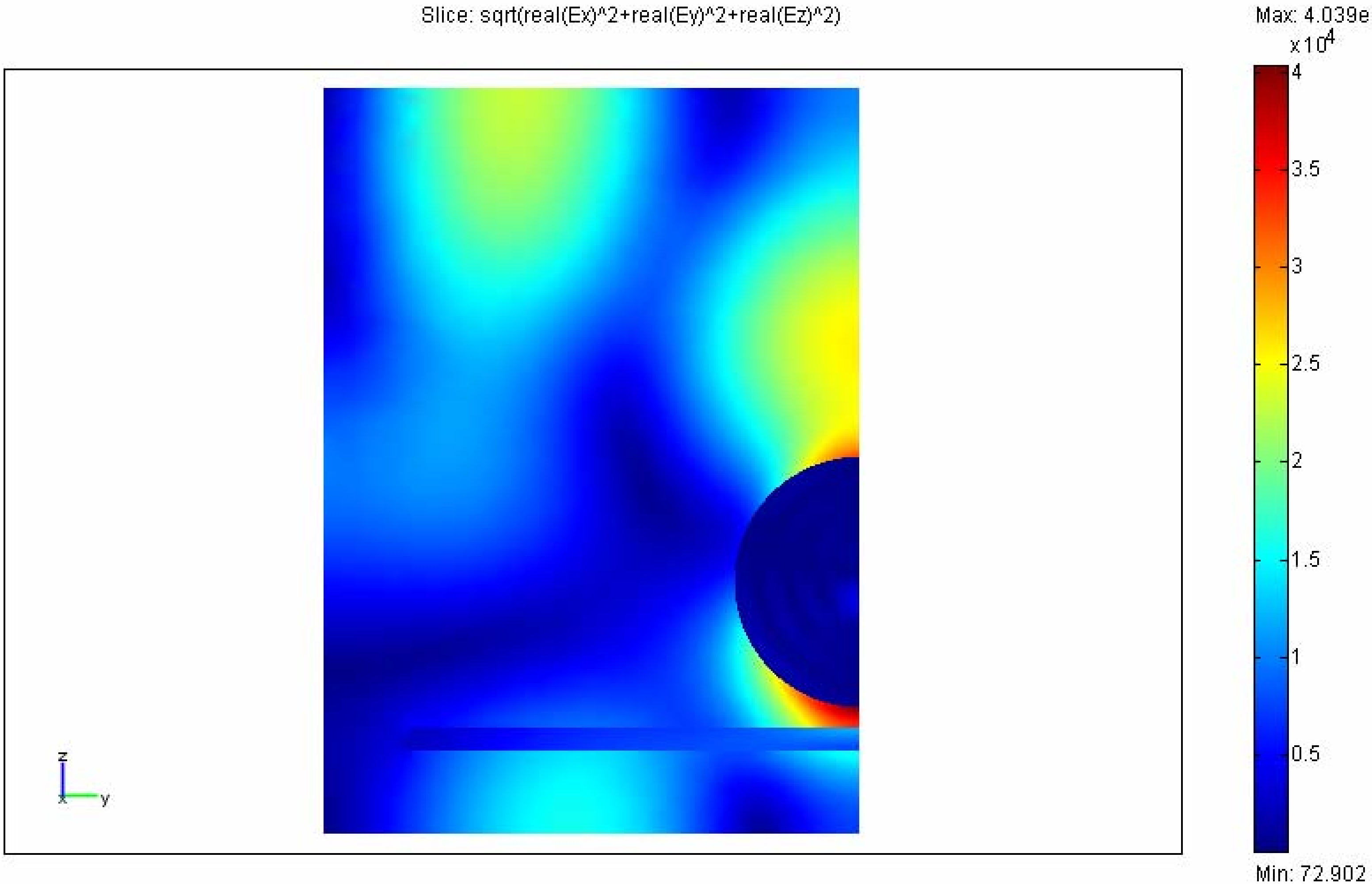
Electric field, E(0): yz-plane



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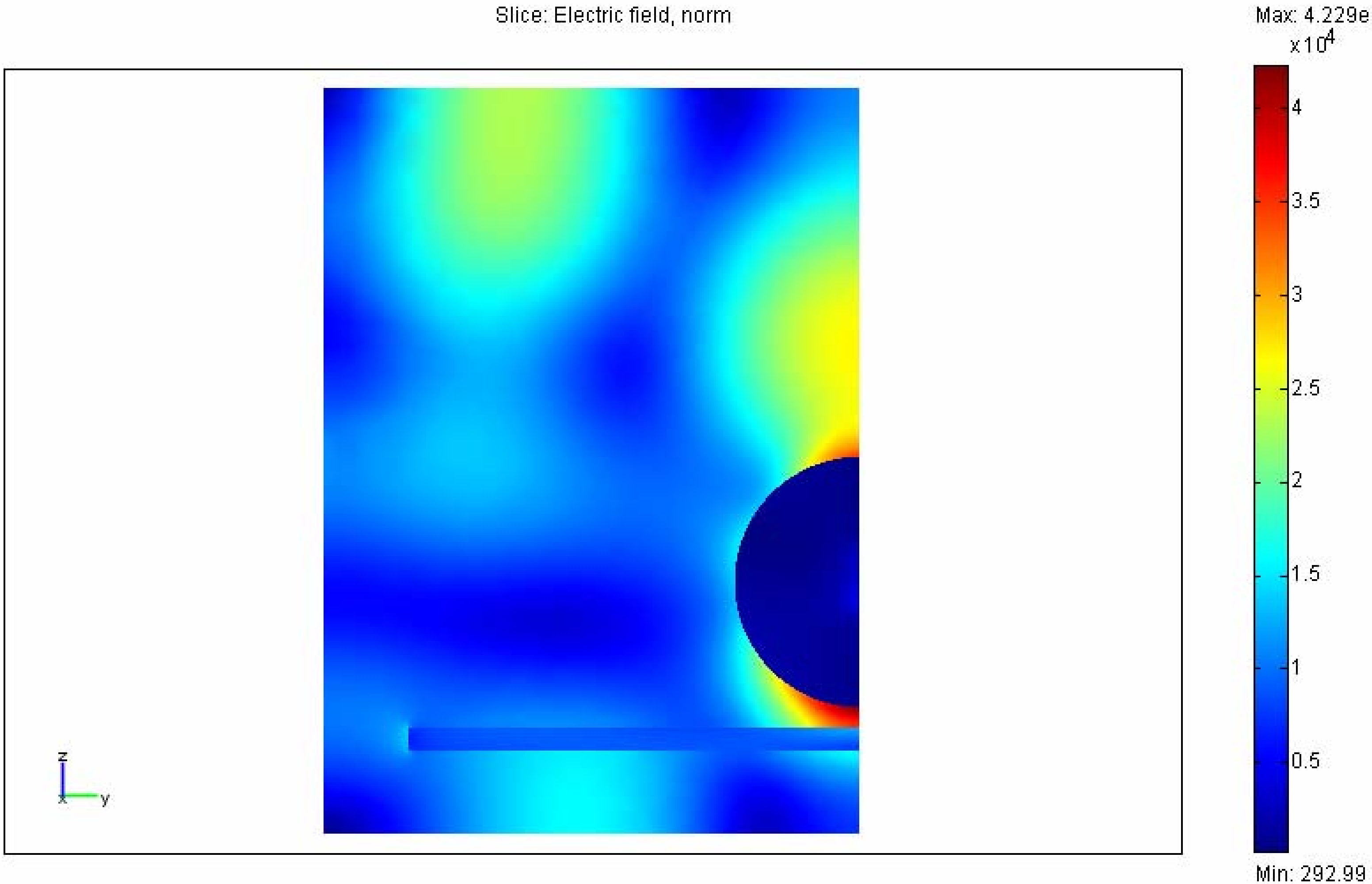
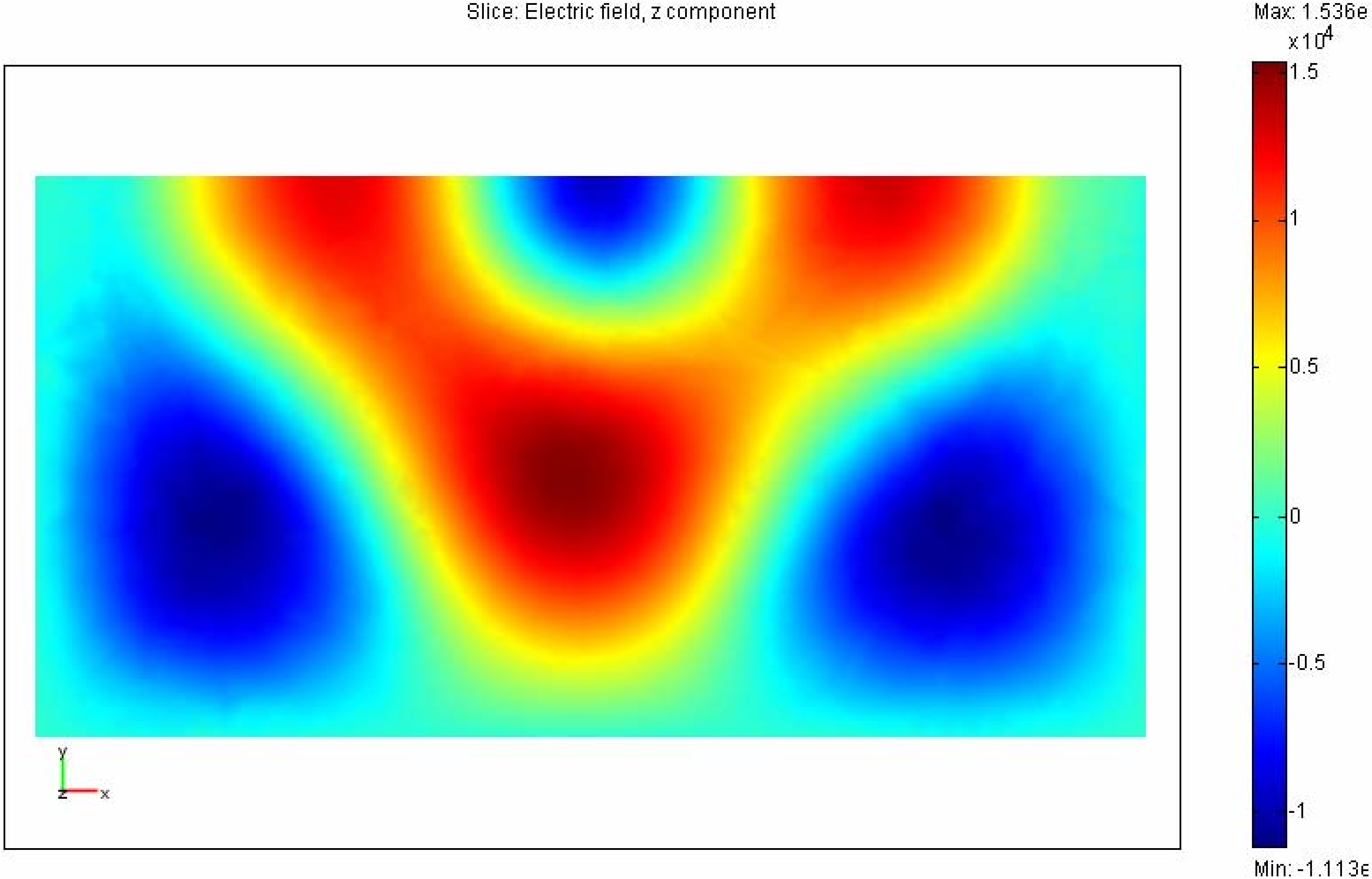
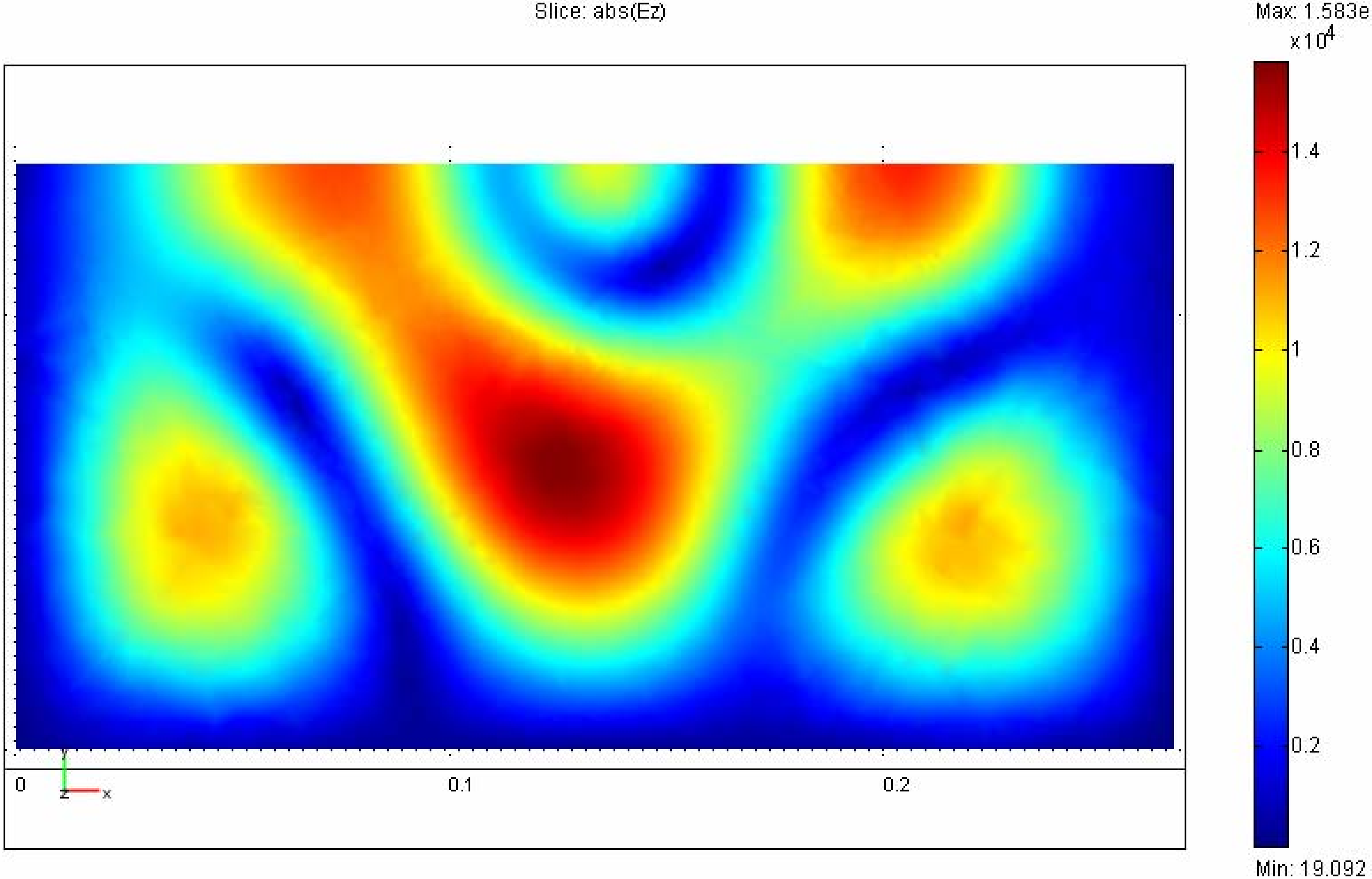
Electric field, |E|: yz-plane



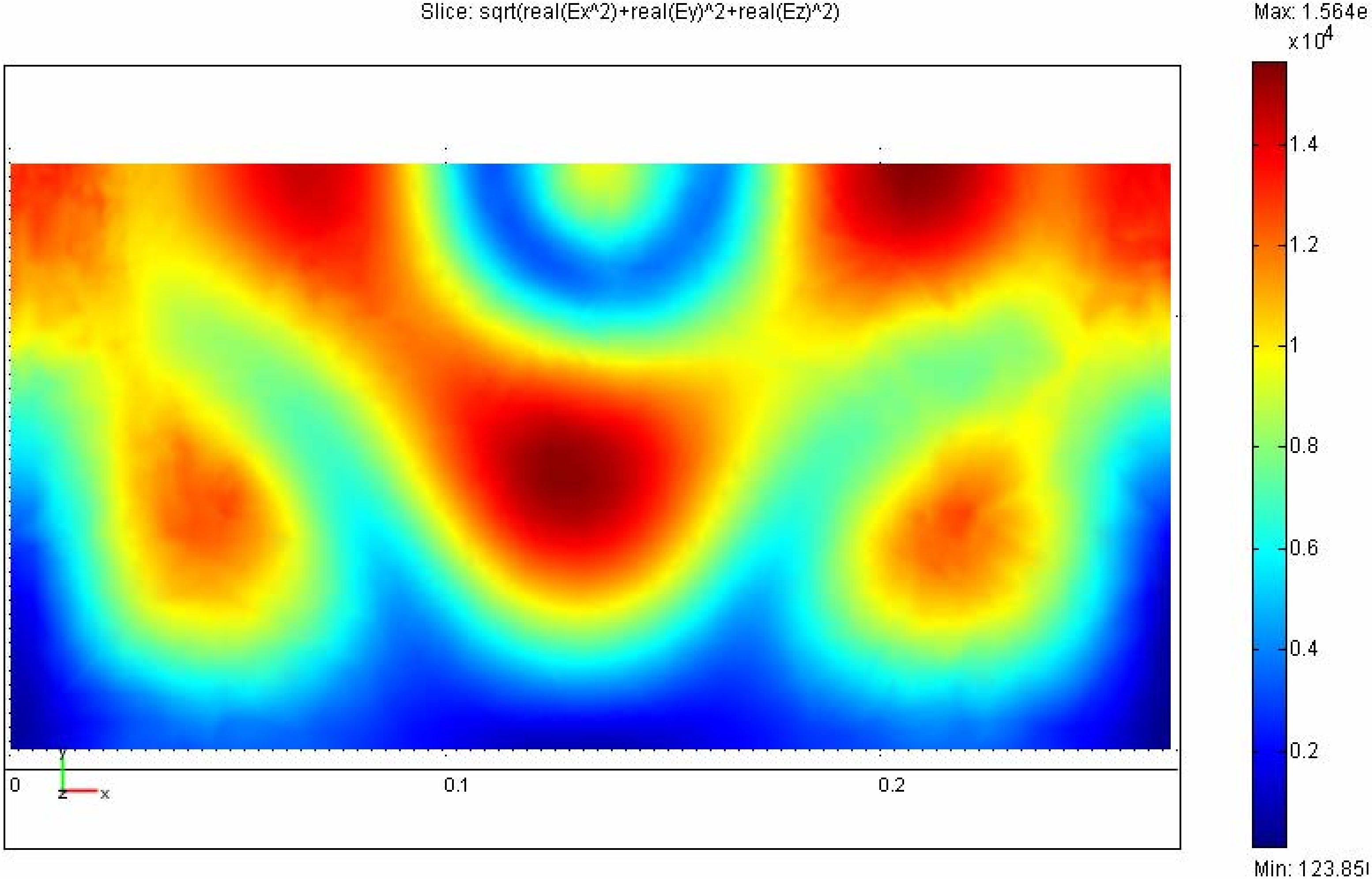
Electric field, Ez(0): xy-plane (z=10mm)



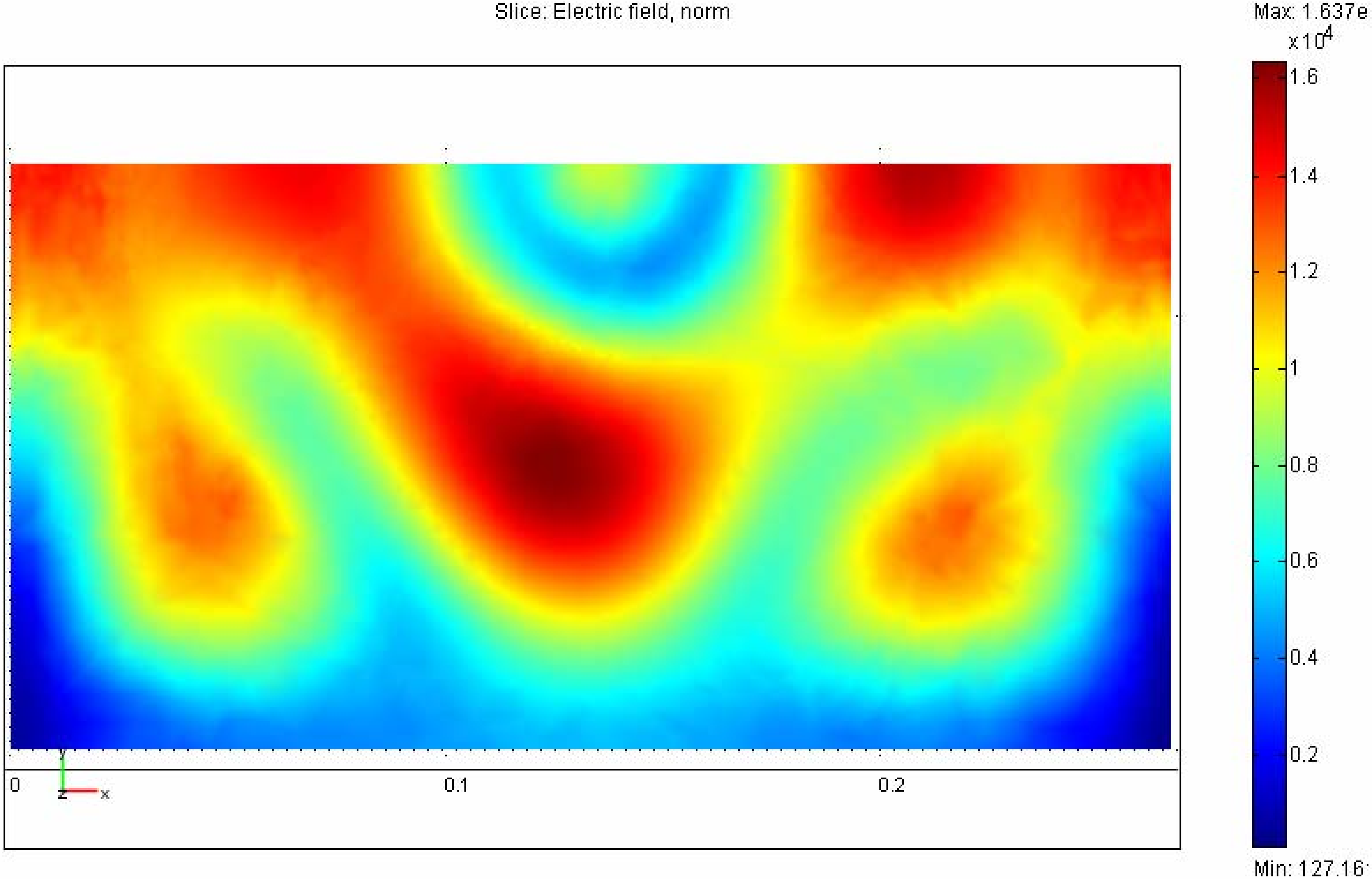
Electric field, |Ez|: xy-plane (z=10mm)



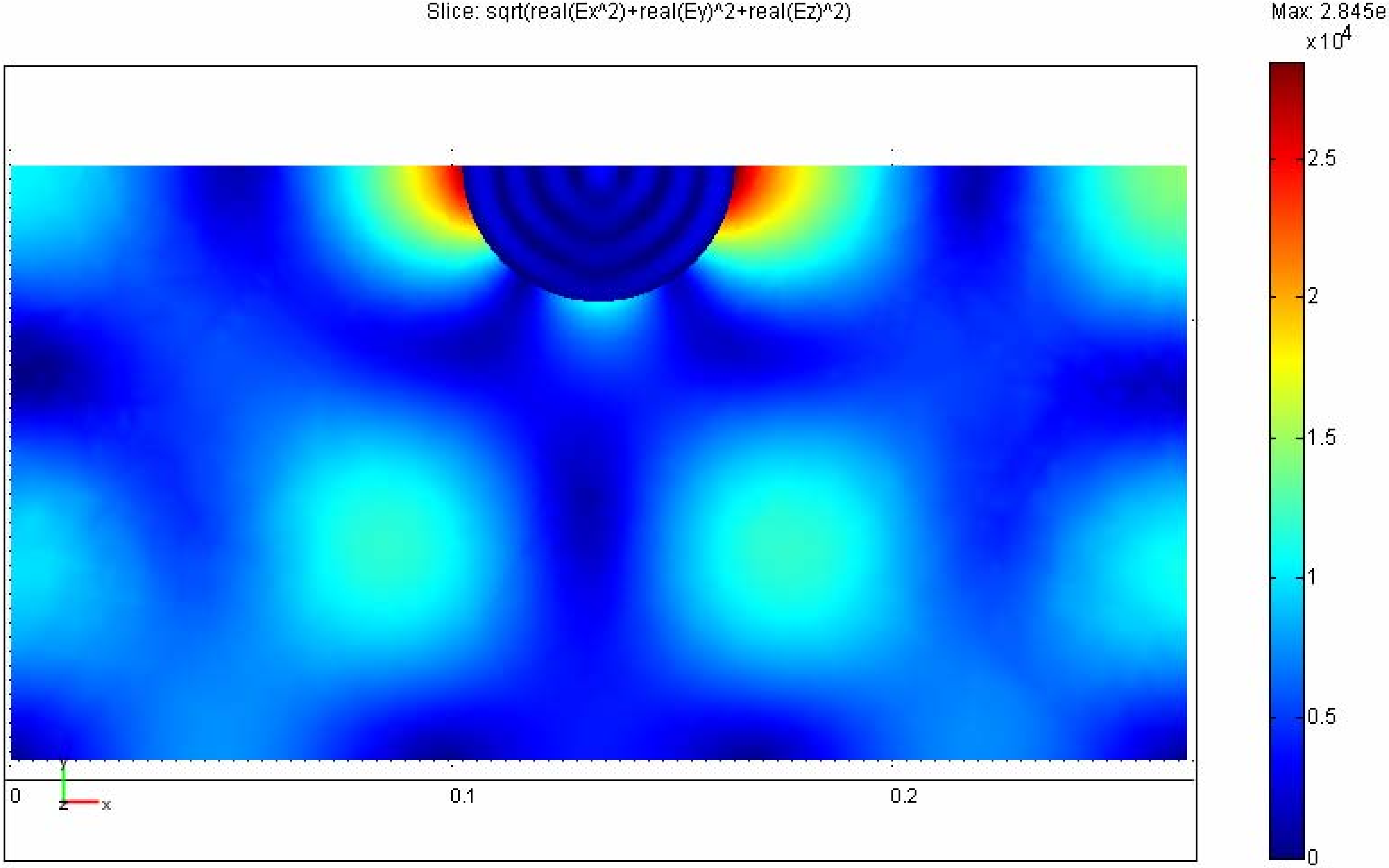
Electric field, E(0): xy-plane (z=10mm)



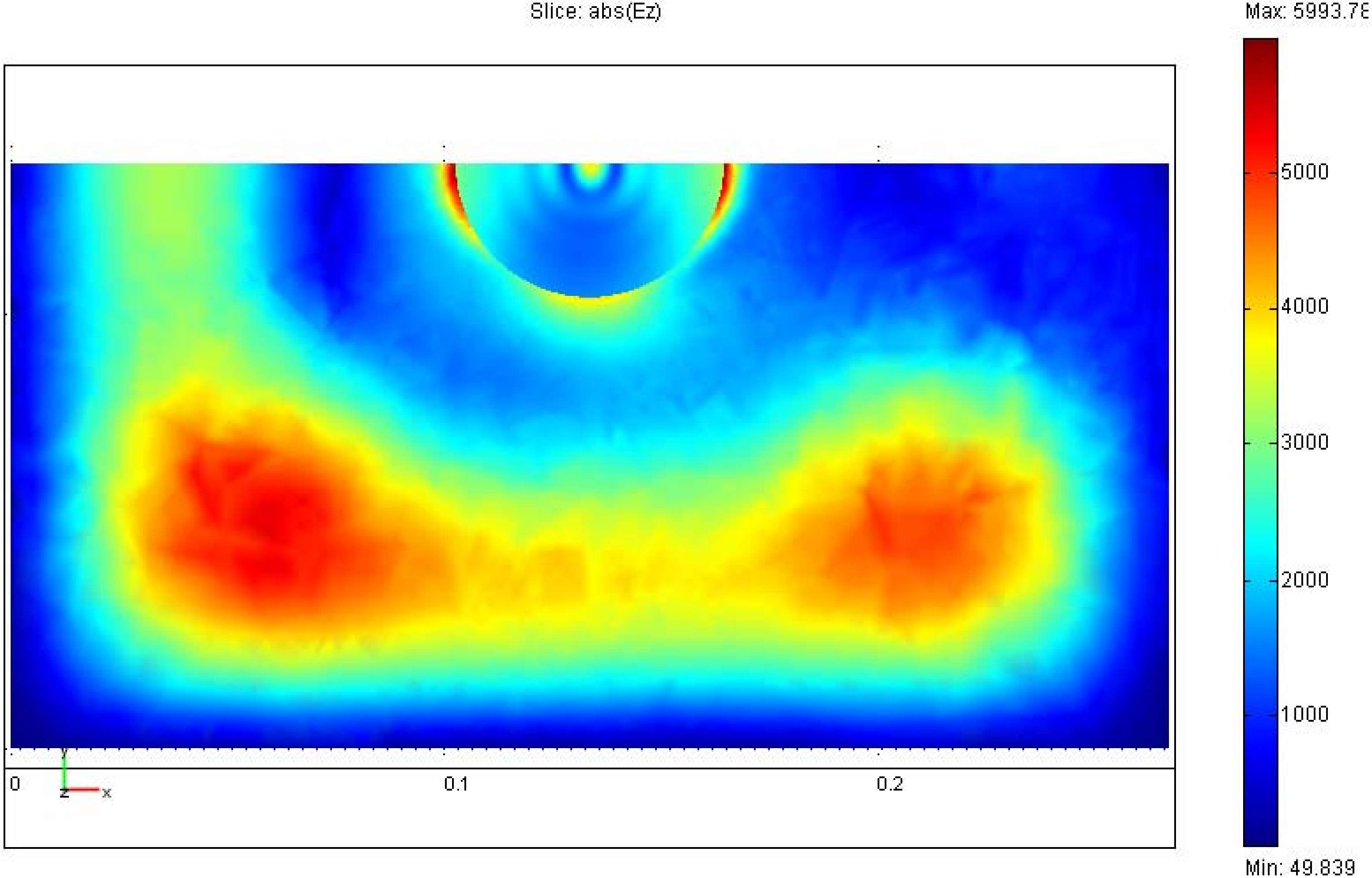
Electric field, |E|: xy-plane (z=10mm)



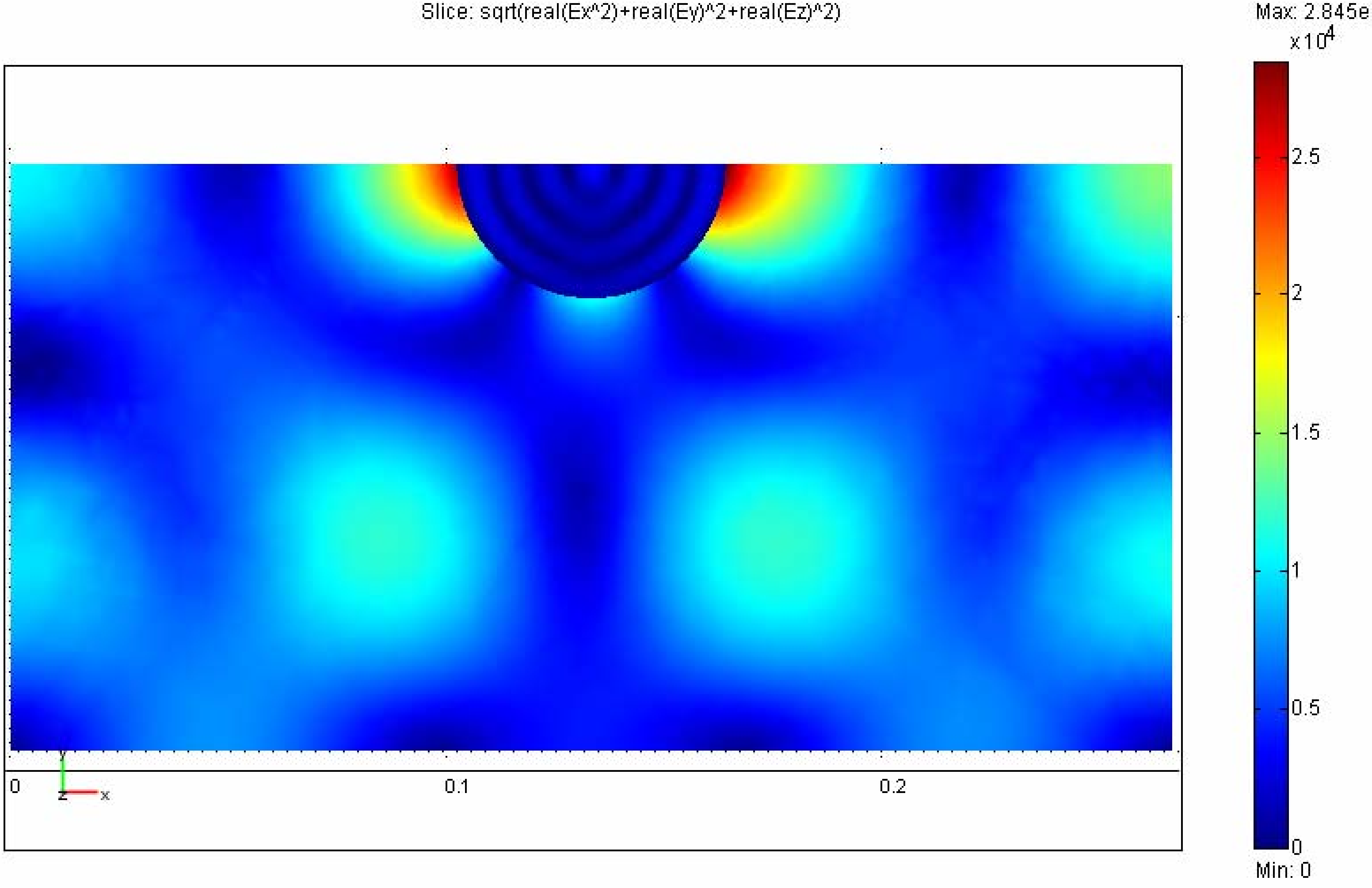
Electric field, Ez(0): xy-plane (z=57.5mm)



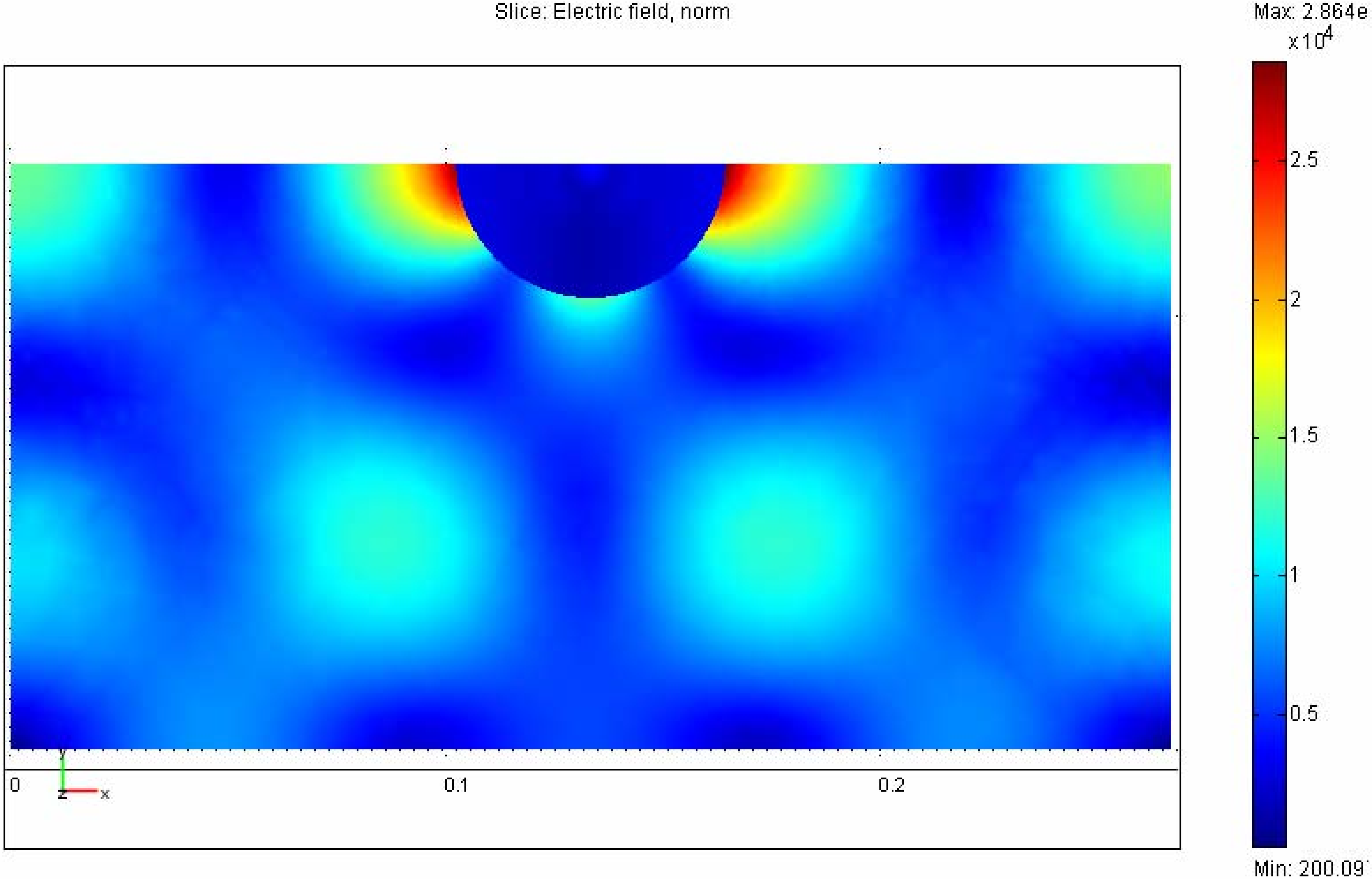
Electric field, |Ez|: xy-plane (z=57.5mm)



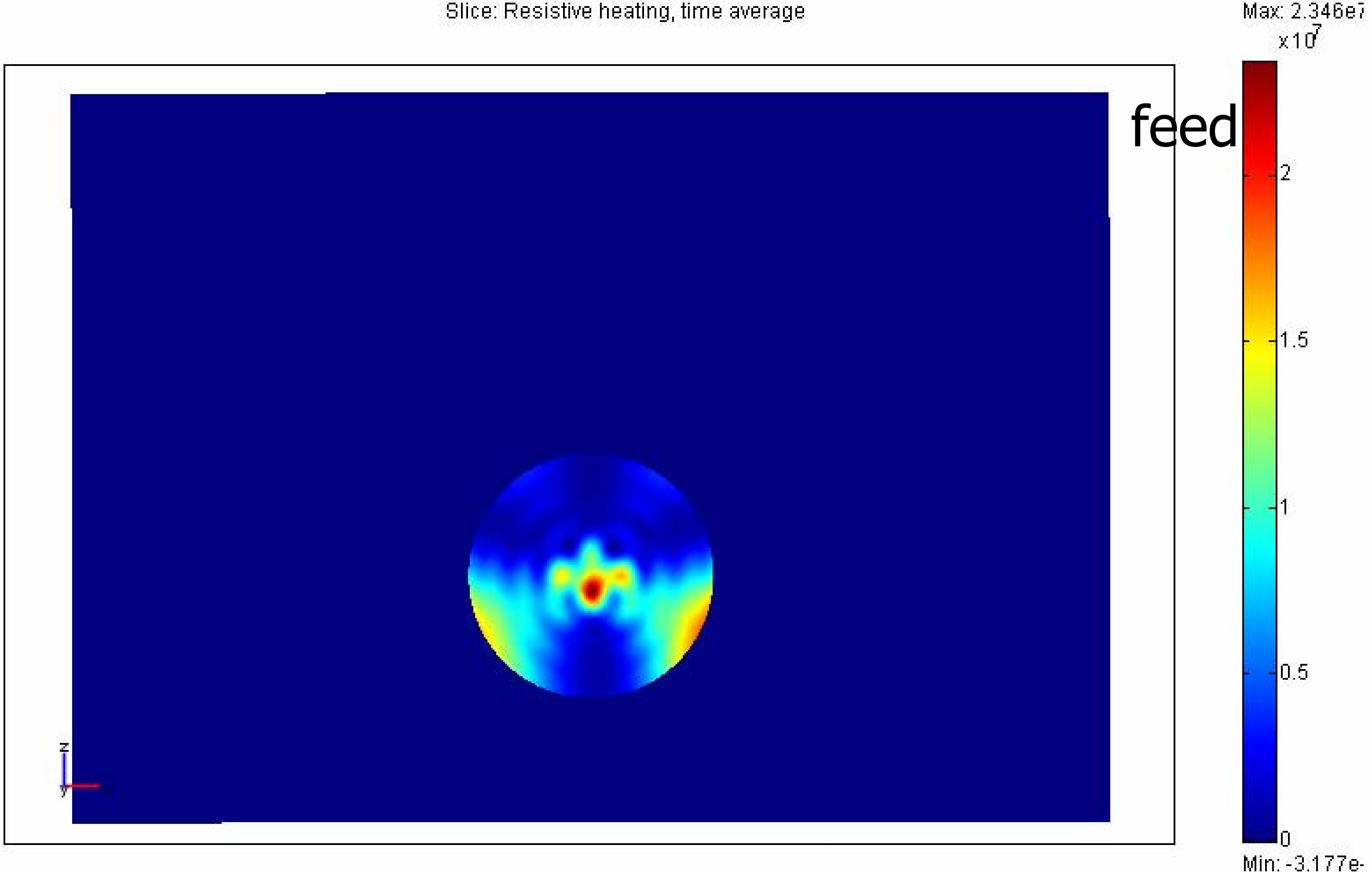
Electric field, E(0): xy-plane (z=57.5mm)



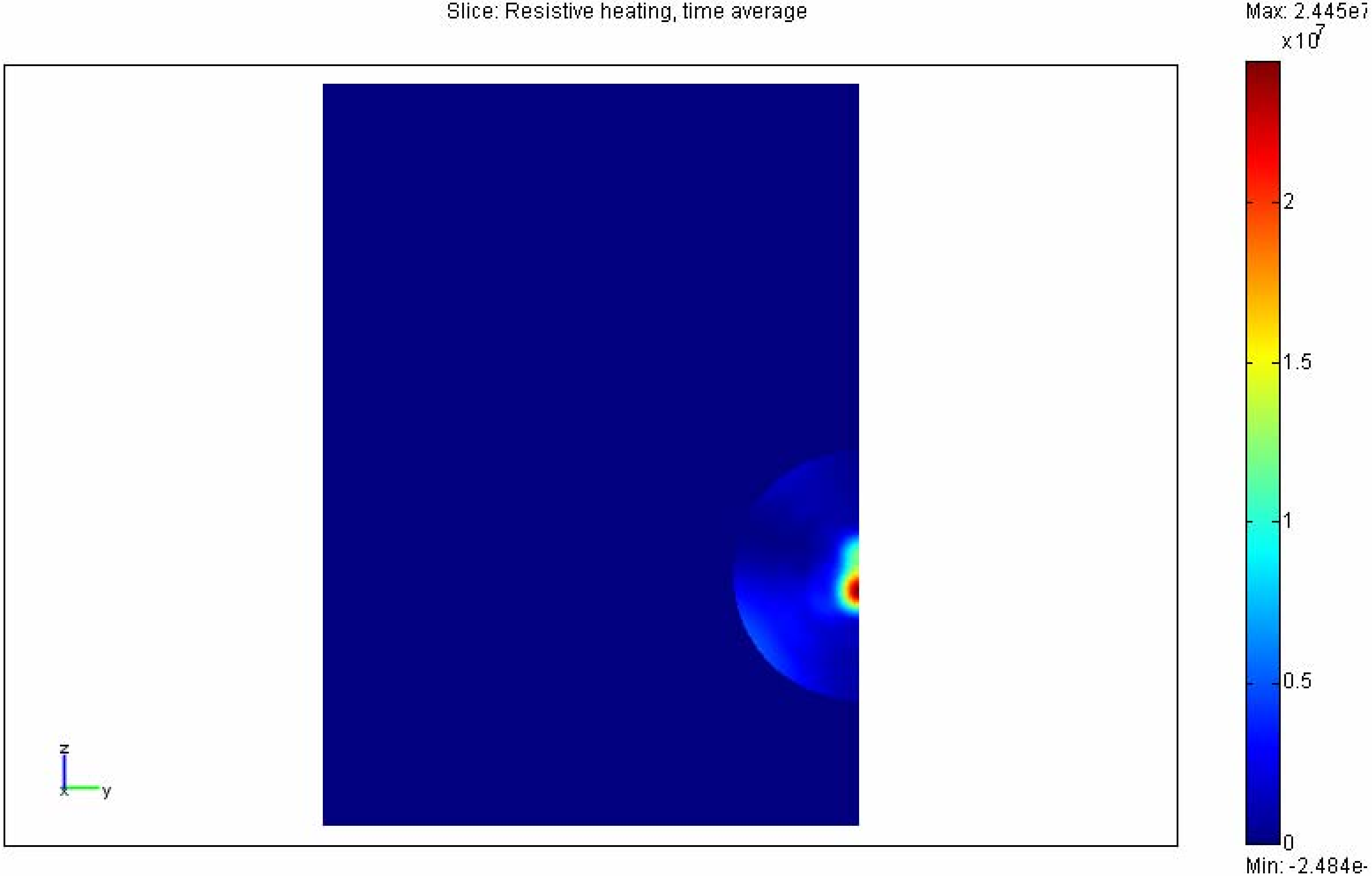
Electric field, |E|: xy-plane (z=57.5mm)



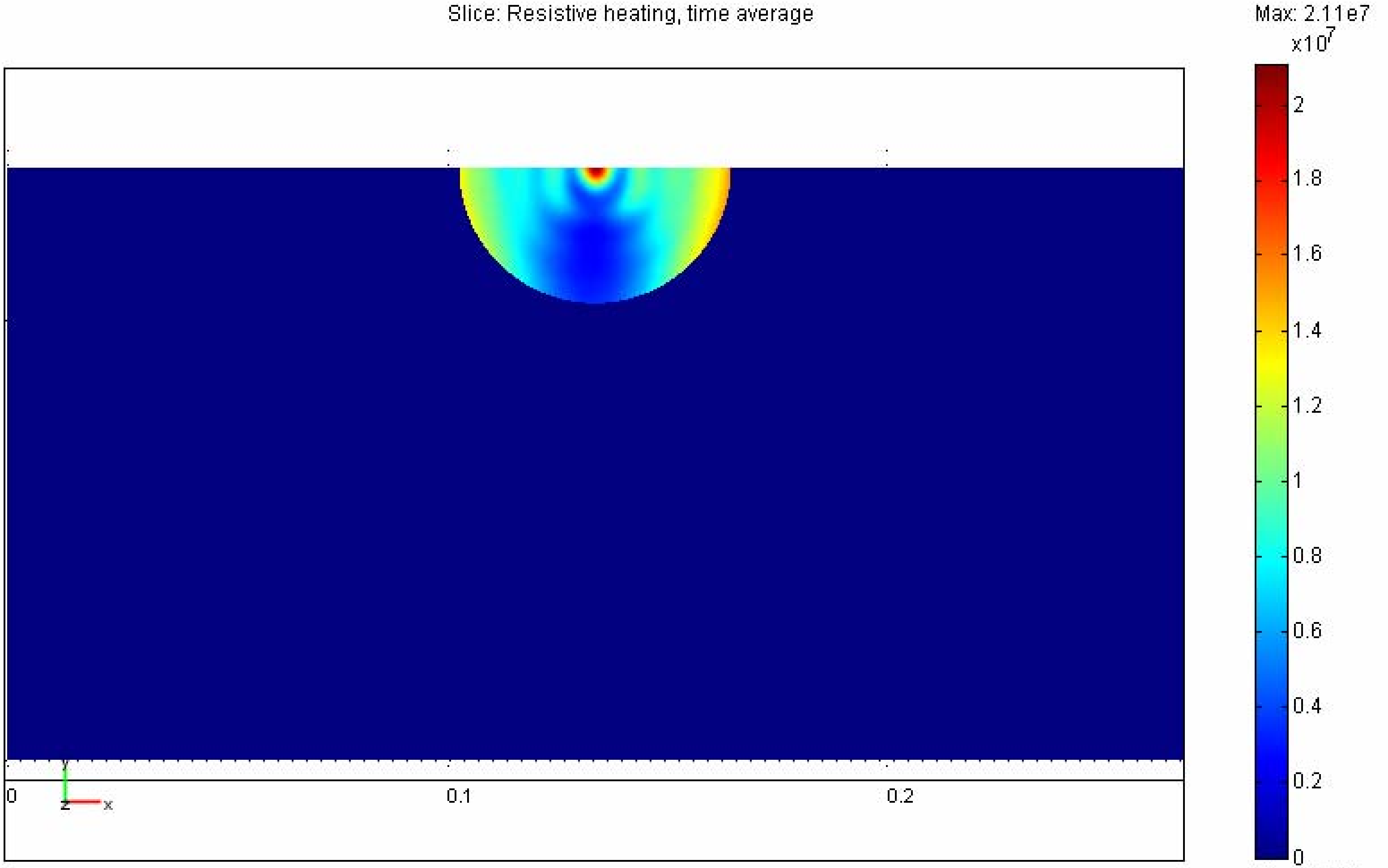
Dissipated power: xz-plane



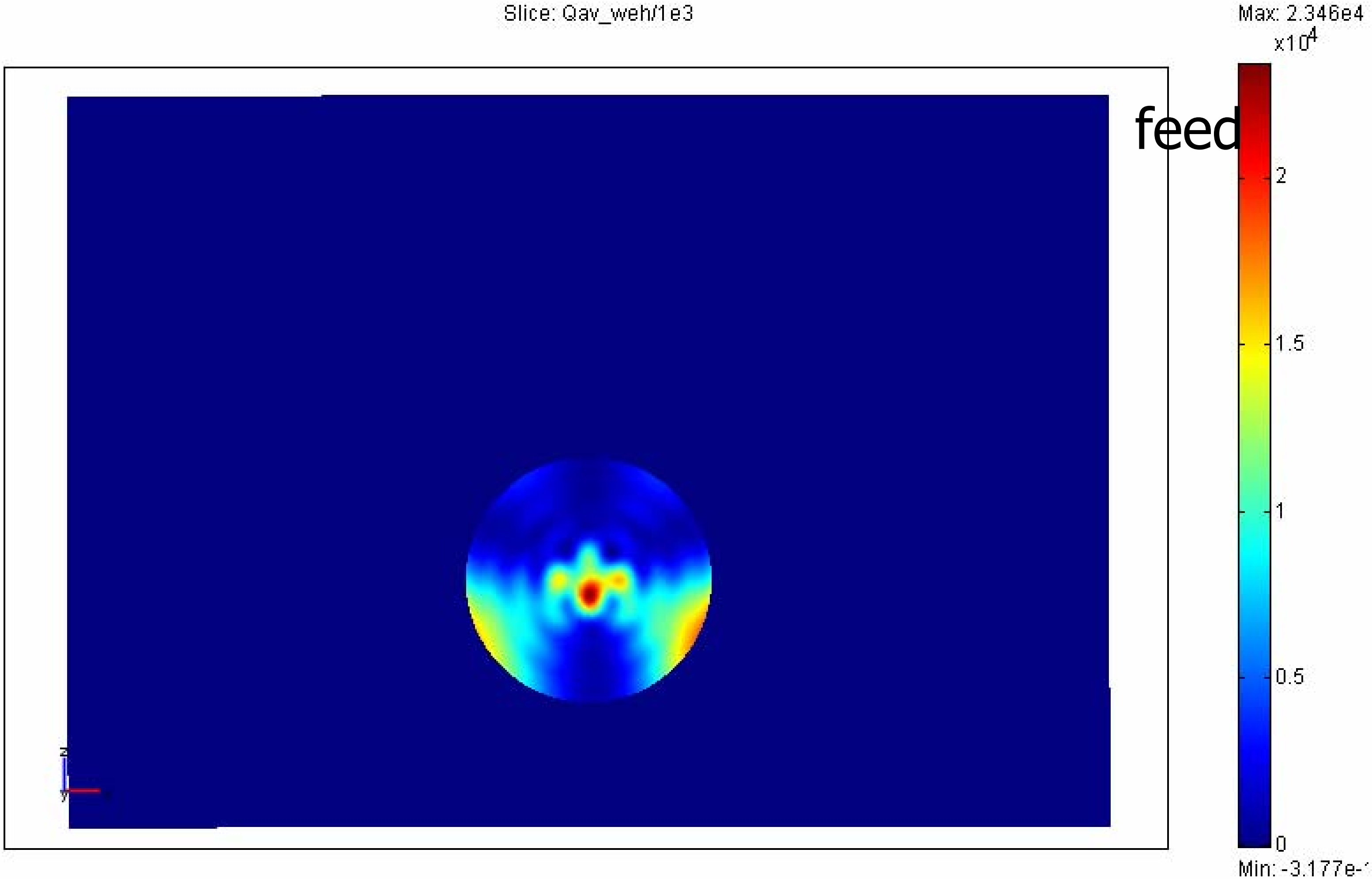
Dissipated power: yz-plane



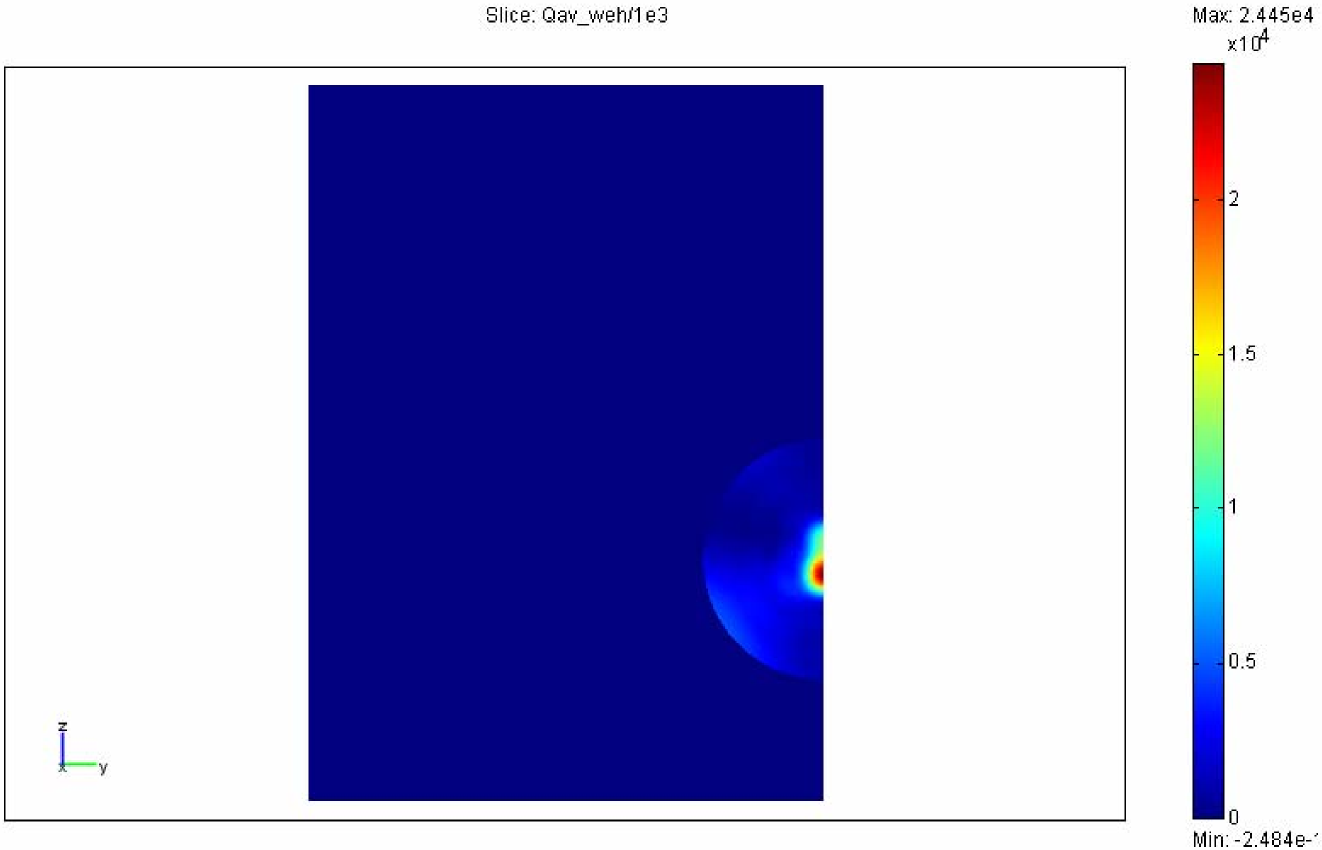
Dissipated power: xy-plane (z=57.5mm)



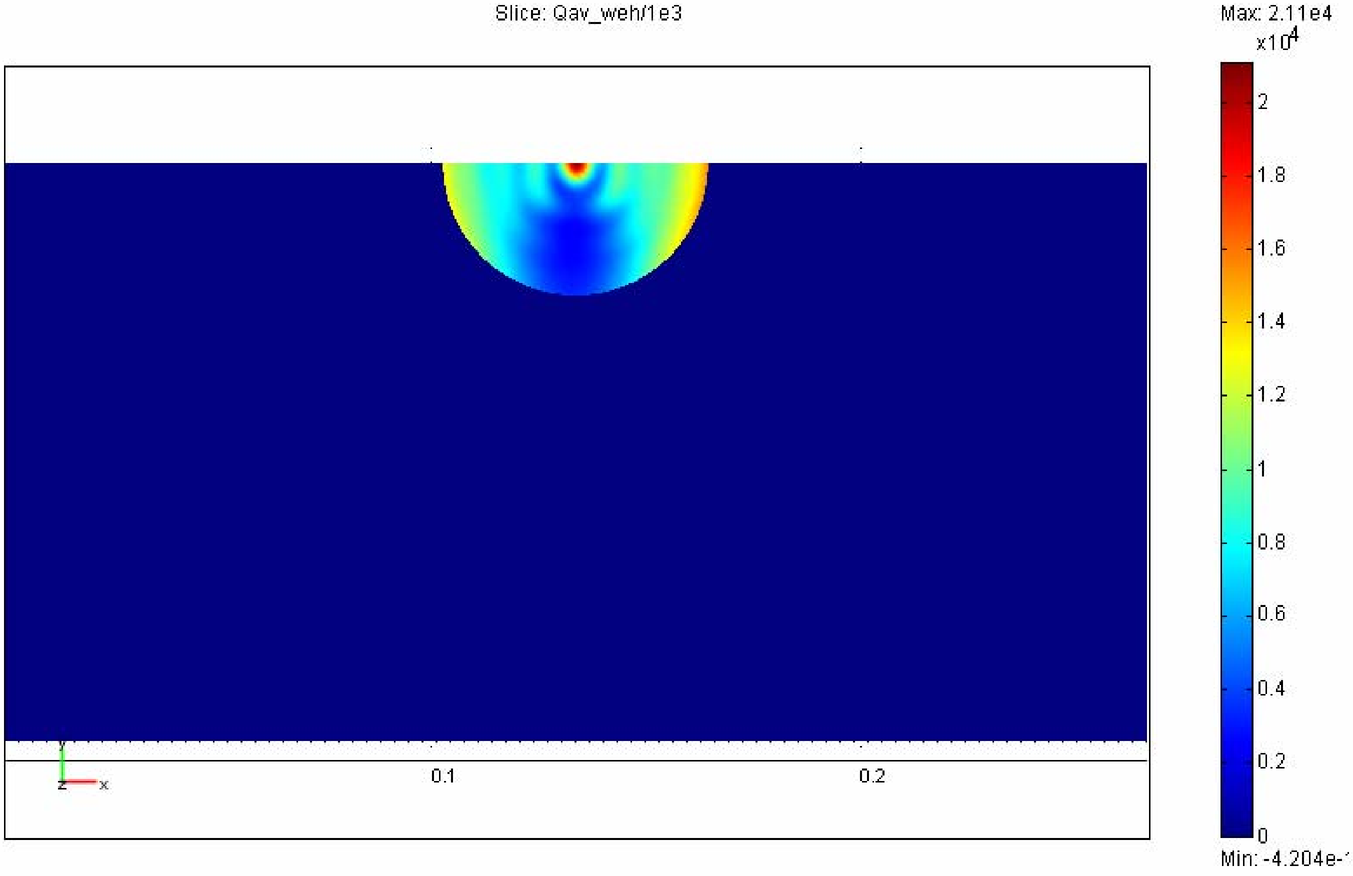
SAR: xz-plane



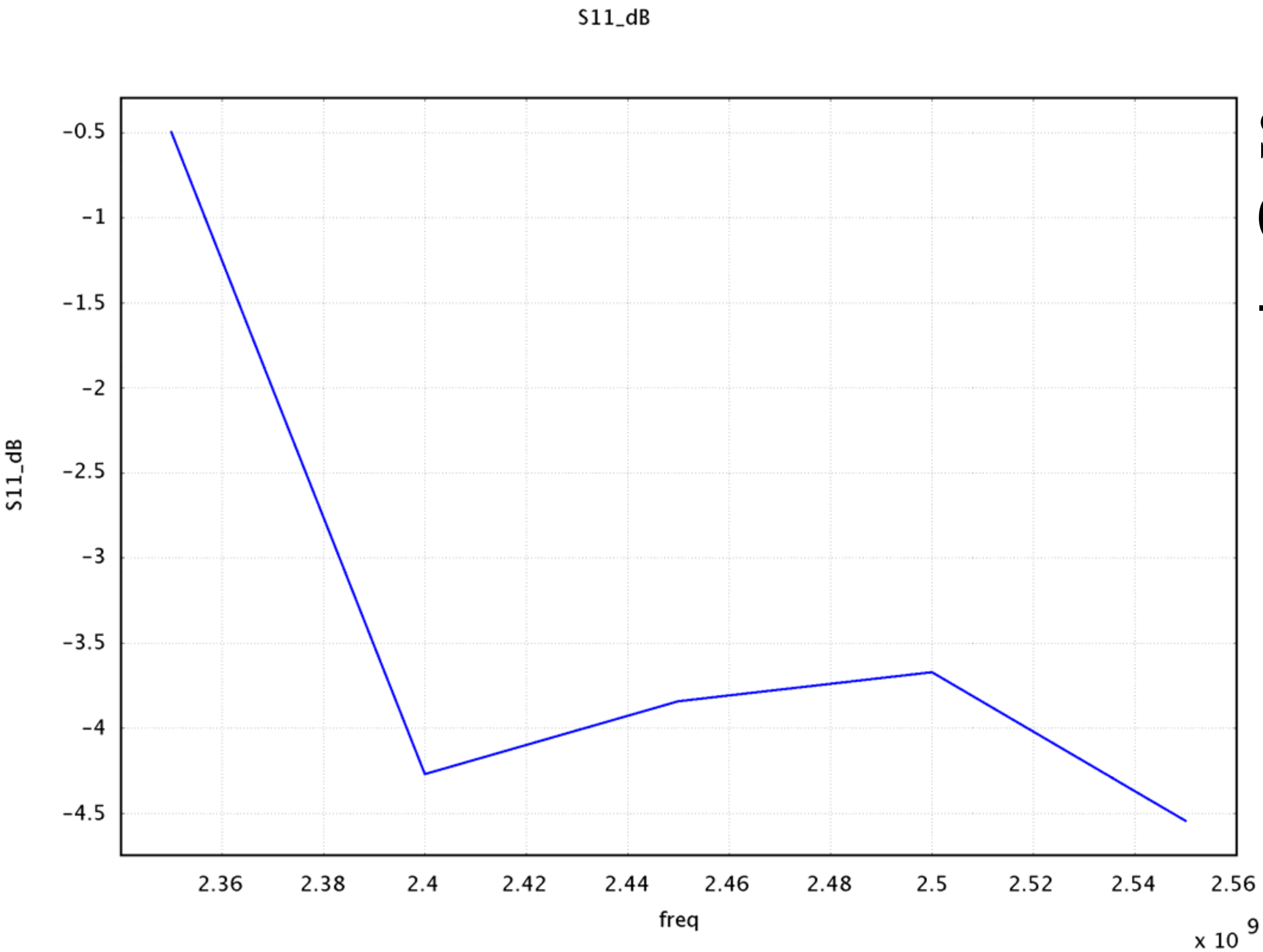
SAR: yz-plane



SAR: xy-plane (z=57.5mm)



S11: 2.35-2.55 GHz (5 points)



S11(2.45 GHz):
0.611- 0.200i
-3.8 dB