Industrial applications-oriented, microwave modeling in Elmer

Roman Szewczyk [1,2], Anna Ostaszewska-Liżewska [1,2], Dominika Kopala [1], Jakub Szałatkiewicz [2,3]

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[2)] Łukasiewicz Research Network - Industrial Research Institute for Automation and Measurements, Warsaw, Poland

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20.05.2021
Warsaw-Espoo, Elmer FEM free webinar series

Plan of the presentation:

Roman Szewczyk (PhD., DSc., ProfTitul.) - few words about the history and the most important ideas behind our work.

Anna Ostaszewska-Liżewska (PhD.) – meshing for Elmer microwave modelling, problems with presentation of 3D vector fields.

Dominika Kopala (engineer, M.Sc.-student) – microwave models and .sif file

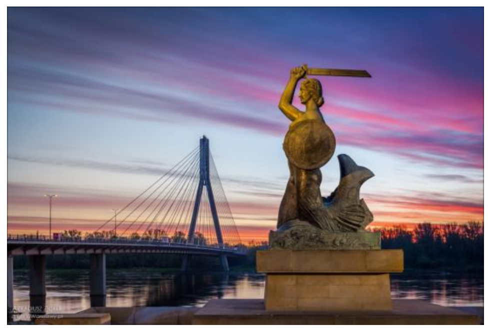
Jakub Szałatkiewicz (PhD., DSc.) – practical applications of microwave technology and Elmer models

Warsaw University of Technology
Faculty of Mechatronics

Leading Polish technical university since 1915
19 faculties, 30 000 students

ŁUKASIEWICZ Research Network –
Industrial Research Institute
for Automation and Measurements

Technology transfer oriented, public research institute, since 1965.



Both in Warsaw, Poland

Our adventure with ELMER FEM started in 2012.

In cooperation with **RADWAG**, Polish private company we undertaken the development of laboratory microwave moisture analyzers – tool for assessment of humidity level in biological materials, such as wood, yoghurt, etc.

Laboratory microwave moisture analyzers:

- 2 producers around the world,
- very expensive,
- highly profitable.

Barrier:

Microwave chamber of laboratory microwave moisture analyzer **has to be kept in resonance**.

To determine the geometry of the microwave chamber suitable for the resonance,
you need to model it using finite elements method.

Cost of commercial software – half of our project’s budget.

Solution: ELMER FEM

PIAP Łukasiewicz

ELMER TEAM: developed microwave module for ELMER FEM

PIAP, WUT: developed the project of microwave chamber

RADWAG: developed the laboratory microwave moisture analyzer
and introduced it to the global market

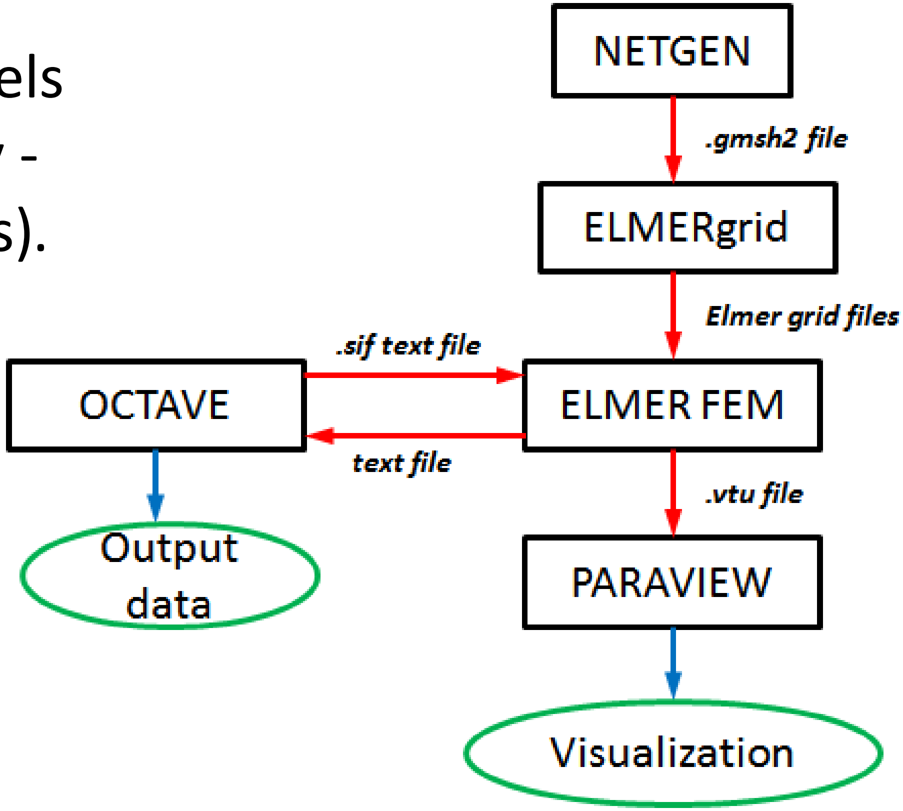
Third company in the global market!

RADWAG BALANCES AND SCALES
ADVANCED WEIGHING TECHNOLOGIES

https://radwag.com/en/pmv-50-microwave-moisture-analyzer,4,401-153

Now, we use **ELMER FEM** as a standard for our education and research.

- No problem with commercialization.
- **Easy integration in large software structures for optimization.**
- Possible to integrate our own models (tensor description of permeability - - mechanical stresses dependences).



R. Szewczyk, M. Nowicki, A. Ostaszewska-Liżewska, A. Bieńkowski , P. Nowak, M. Malinen
„Accuracy of frame-shaped samples based measurements of magnetoelastic characteristics of soft magnetic materials”
Measurement **162 (2020) 107899**

Let us guide you through all microwave system modelling process.

First: tetrahedral meshes for modelling

First: tetrahedral meshes for modelling - why Netgen?

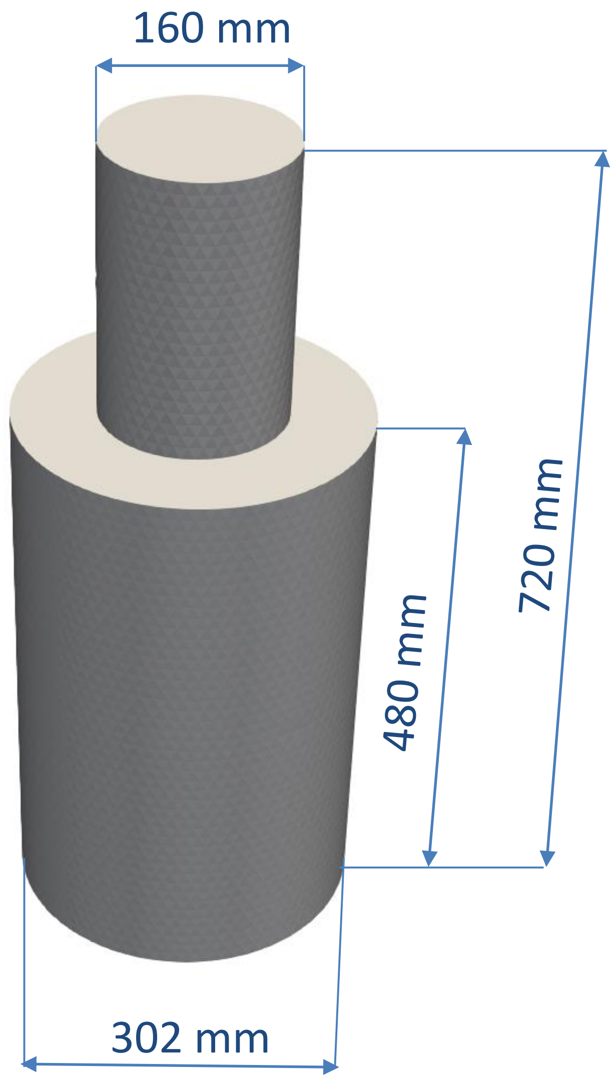
More control -> external mesh generators -> open source:

- **GMSH** - the most popular, fast, light and user friendly, with GUI
- **Salome** - a great cross platform for pre- and postprocessing
- **FreeCAD** - parametric modelling
- **Netgen** - modules for mesh optimization and mesh refinement, writes meshes in Elmer format (linear only)

Remote control of cumputing

text mode

Computing series automation with sripts




```
algebraic3d

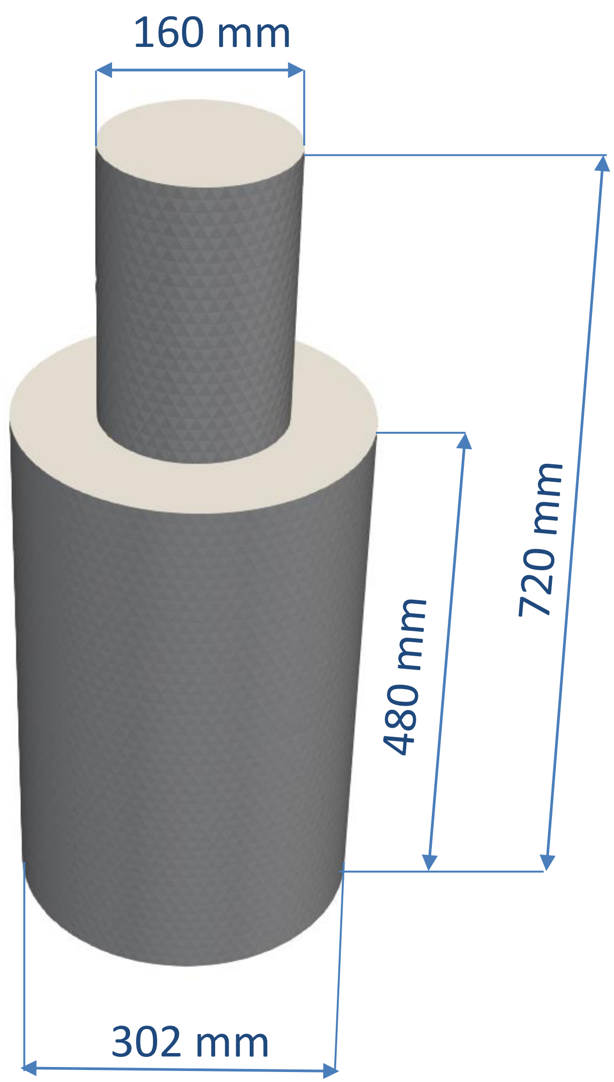
# ------------- Waveguide -------------
solid UP_PIPE = plane(0,0,0;0,0,-1);
solid DOWN_PIPE = plane(0,0,300;0,0,1);
solid PIPE = cylinder(0,0,-100;0,0,400;80);
solid WAVEGUIDE = PIPE and DOWN_PIPE and UP_PIPE;

# ------------- Chamber -------------
solid UP_BOX = plane(0,0,240;0,0,-1);
solid DOWN_BOX = plane(0,0,720;0,0,1);
solid BOX = cylinder(0,0,200;0,0,800;151);
solid CAVITY = BOX and DOWN_BOX and UP_BOX;

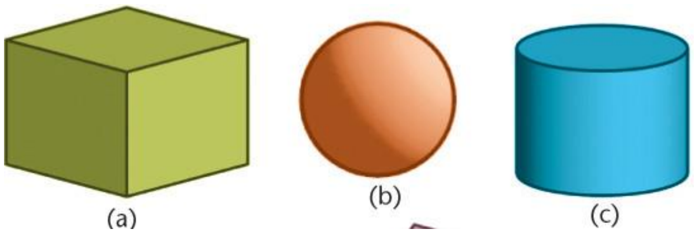
# --------- Join waveguide + chamber ---------
solid MIC = WAVEGUIDE or CAVITY;

# generate object
tlo MIC;
```

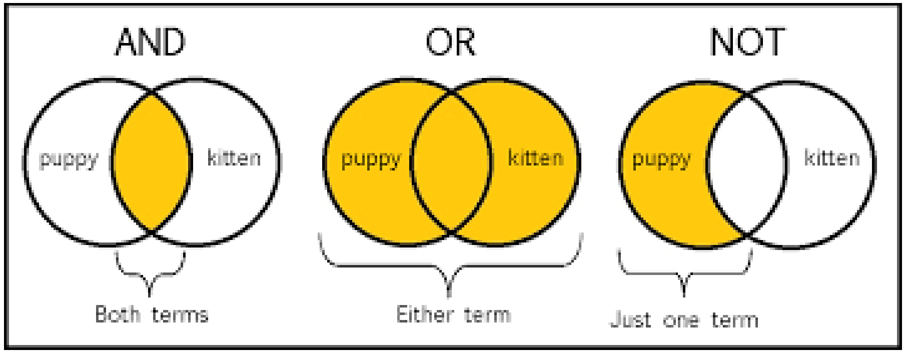
Step one: define gometry



1. Define solid primitives



2. Conduct a logical operation



3. Generate solid

```
algebraic3d
```

comment

```
#------------- Waveguide -------------
solid PIPE = cylinder(0,0,-100;0,0,400;80);
```

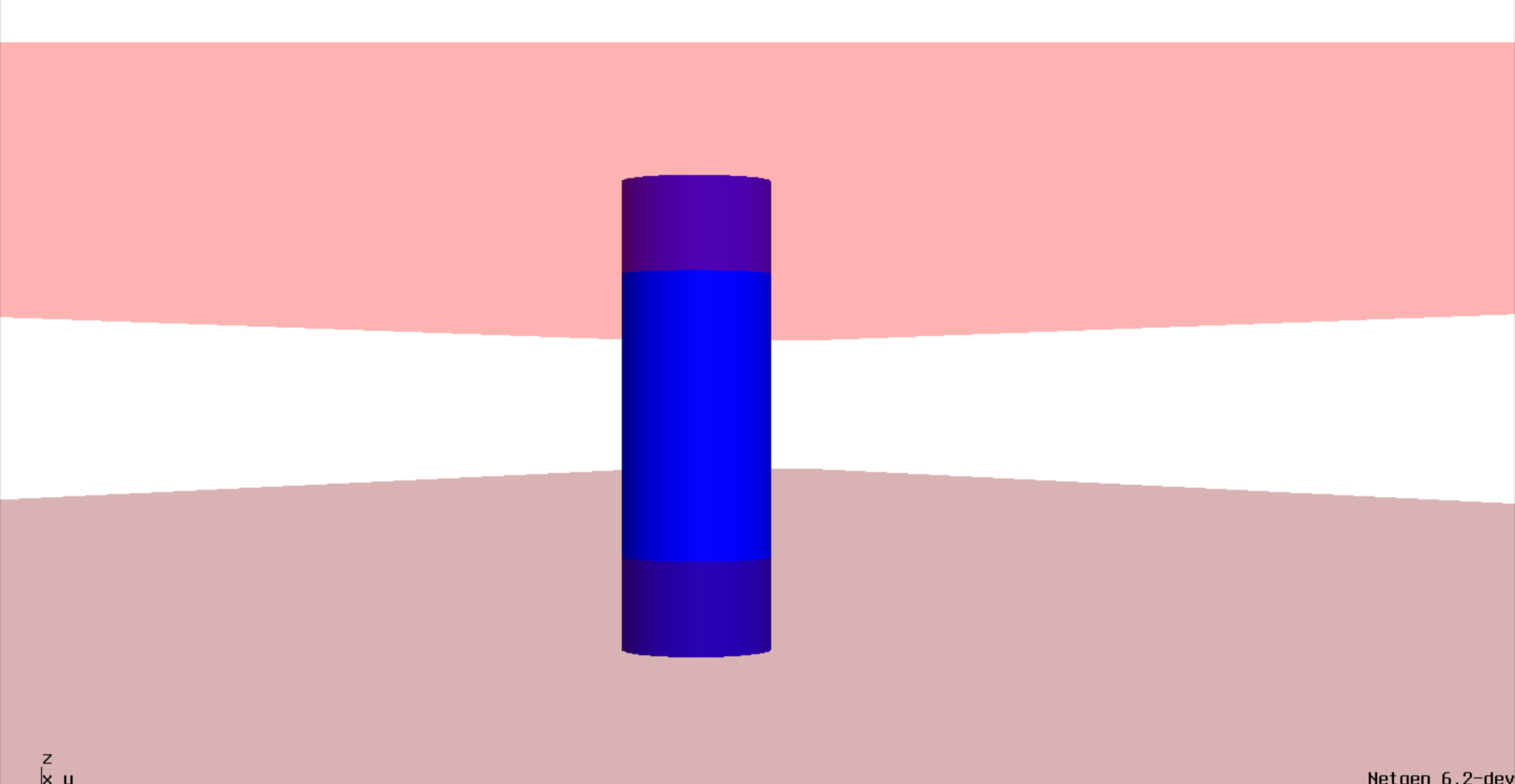
primitive name type X_a, Y_a, Z_a; X_b, Y_b, Z_b radius

AB points of the axis

```
# generate object
tlo PIPE;
```


y
z x
Netgen 6.2-dev

Lifehack alert!



```
algebraic3d#

-------------- Waveguide --------------
solid PIPE = cylinder(0,0,-100;0,0,400;80);
solid UP_PIPE = plane(0,0,0;0,0,-1);
```

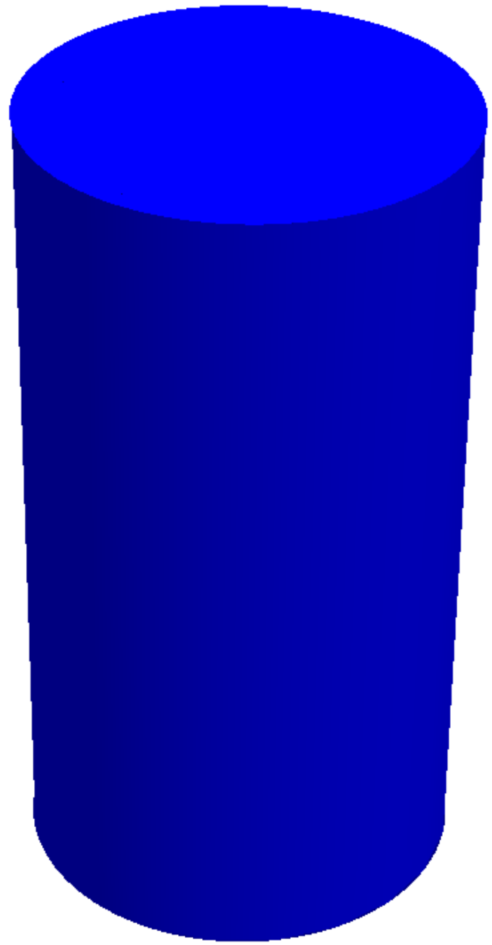
primitive name type $P_x, P_y, P_z; n_x, n_y, n_z$

point of the plane; coordinates of normal vector

```
solid DOWN_PIPE = plane(0,0,300;0,0,1);
solid WAVEGUIDE = PIPE and DOWN_PIPE and UP_PIPE;
```

logical operation on solids

```
# generate object
tlo WAVEGUIDE;
```



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algebraic3d#

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solid CAVITY = BOX and DOWN_BOX and UP_BOX;

# --------- Join waveguide + chamber ---------
solid MIC = WAVEGUIDE or CAVITY;

# generate object
tlo MIC;
```

Generate the final solid only

Lifehack alert: changing units in Netgen

```
algebraic3d#

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solid DOWN_PIPE = plane(0,0,300;0,0,1);
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solid CAVITY = BOX and DOWN_BOX and UP_BOX;

# --------- Join waveguide + chamber ---------
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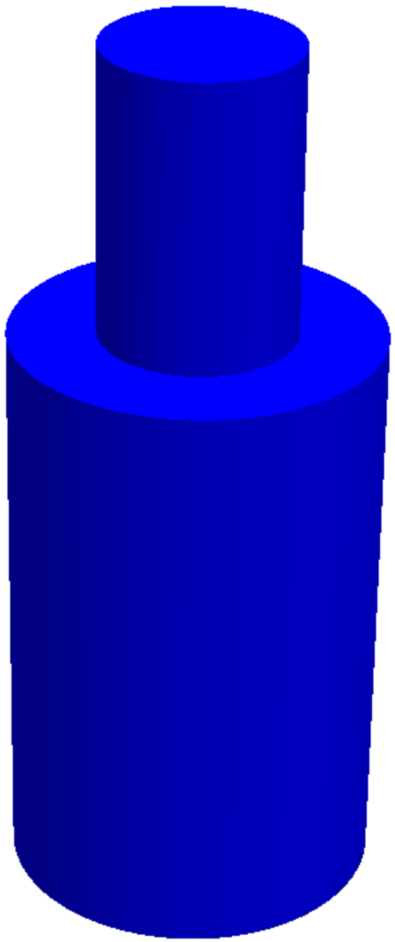
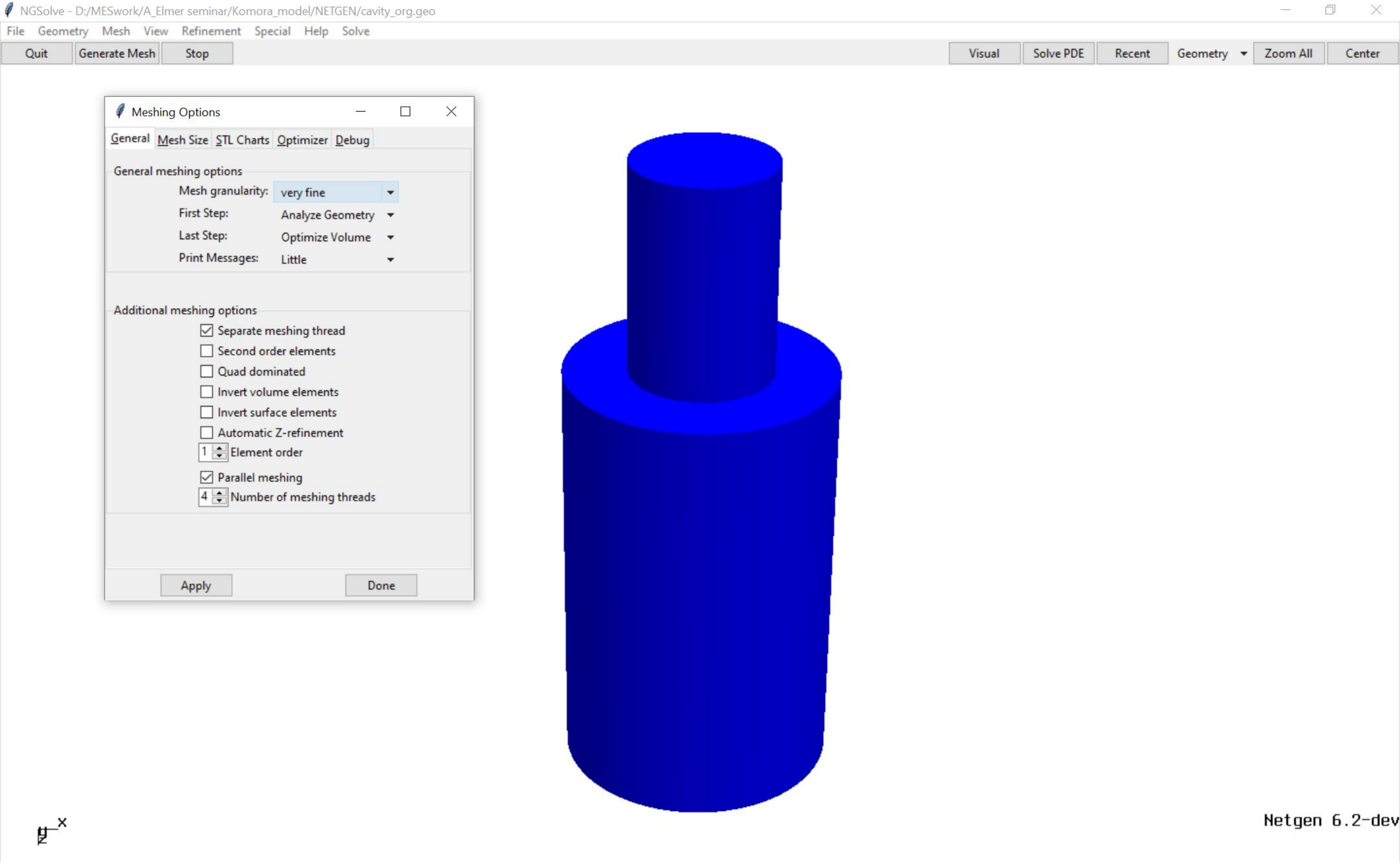
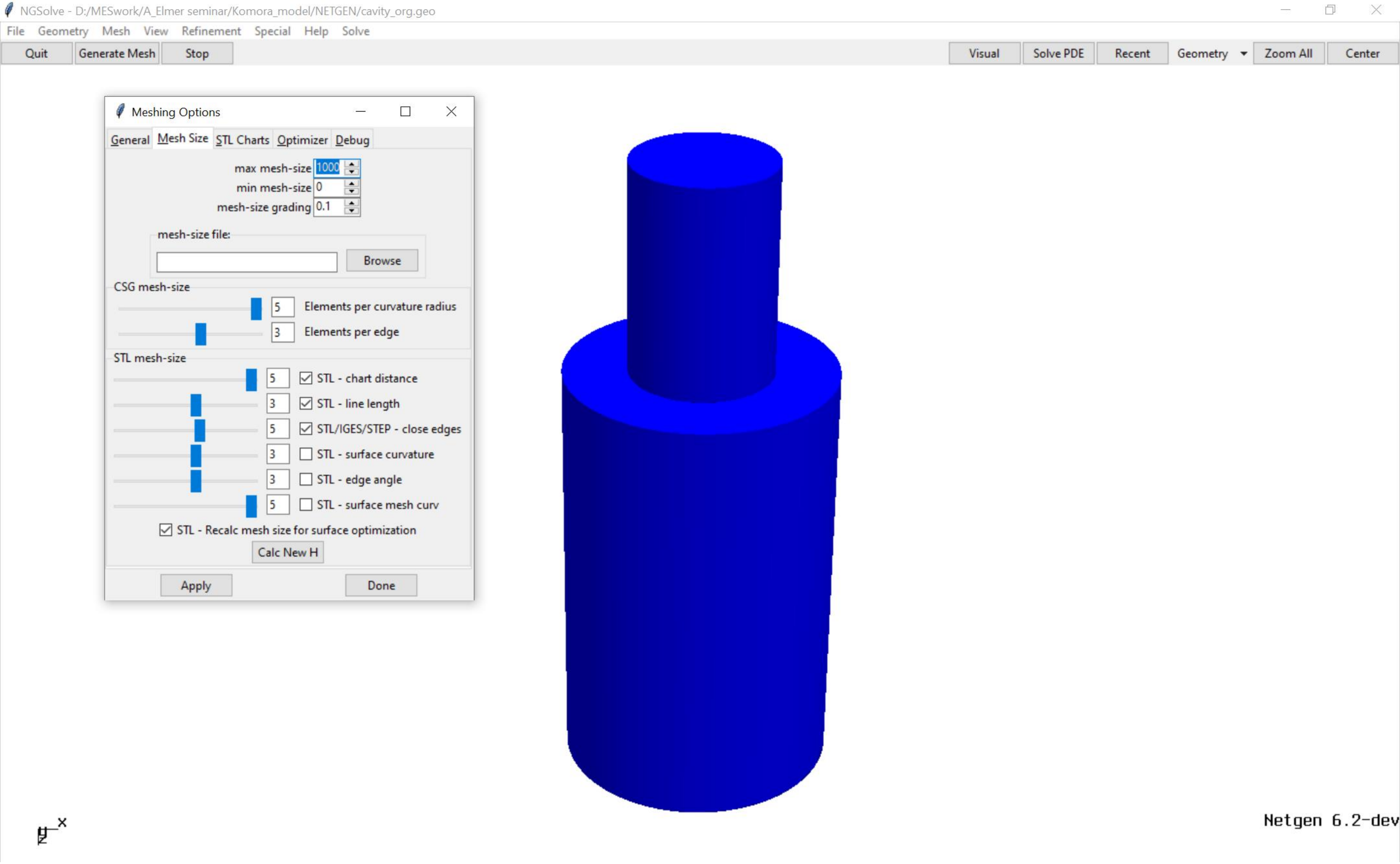
# generate object
tlo MIC;
```

Geometry defined in meters

Step two: generate the mesh




NGSolve - D:/MESwork/A_Elmer seminar/Komora_model/NETGEN/cavity_org.geo
File Geometry Mesh View Refinement Special Help Solve
Quit
Generate Mesh
Stop
Visual
Solve PDE
Recent
Geometry
Zoom All
Center
Meshing Options
General Mesh Size STL Charts Optimizer Debug
General meshing options
Mesh granularity: very fine
First Step: Analyze Geometry
Last Step: Optimize Volume
Print Messages: Little
Additional meshing options
Separate meshing thread
Second order elements
Quad dominated
Invert volume elements
Invert surface elements
Automatic Z-refinement
1 Element order
Parallel meshing
4 Number of meshing threads
Apply
Done
Netgen 6.2-dev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Solve PDE
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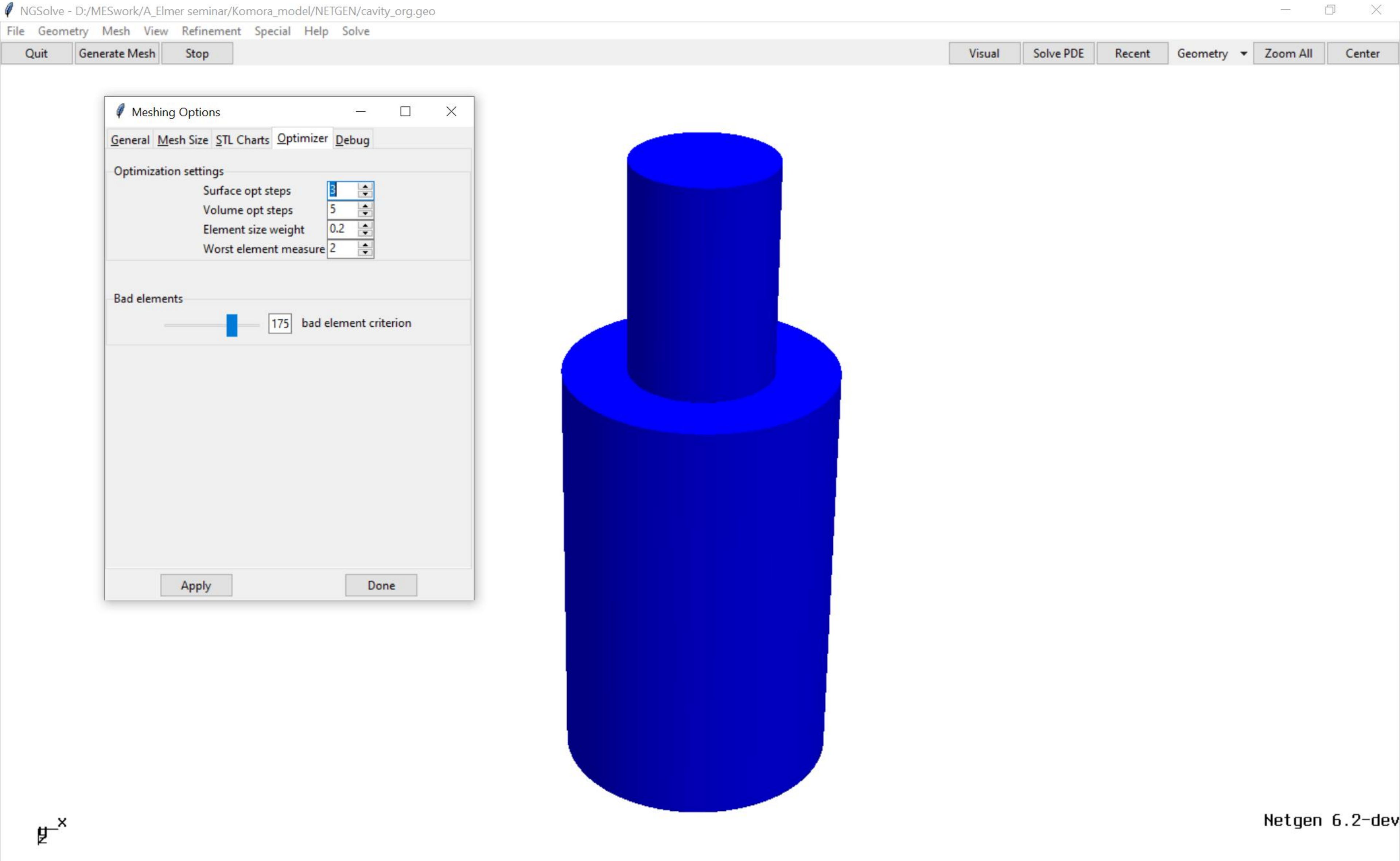
Center
Meshing Options
General
Mesh Size
STL Charts
Optimizer
Debug
max mesh-size
1000
min mesh-size
0
mesh-size grading
0.1
mesh-size file:
Browse
CSG mesh-size
5
Elements per curvature radius
3
Elements per edge
STL mesh-size
5
STL - chart distance
3
STL - line length
5
STL/IGES/STEP - close edges
3
STL - surface curvature
3
STL - edge angle
5
STL - surface mesh curv
STL - Recalc mesh size for surface optimization
Calc New H
Apply
Done
Netgen 6.2-dev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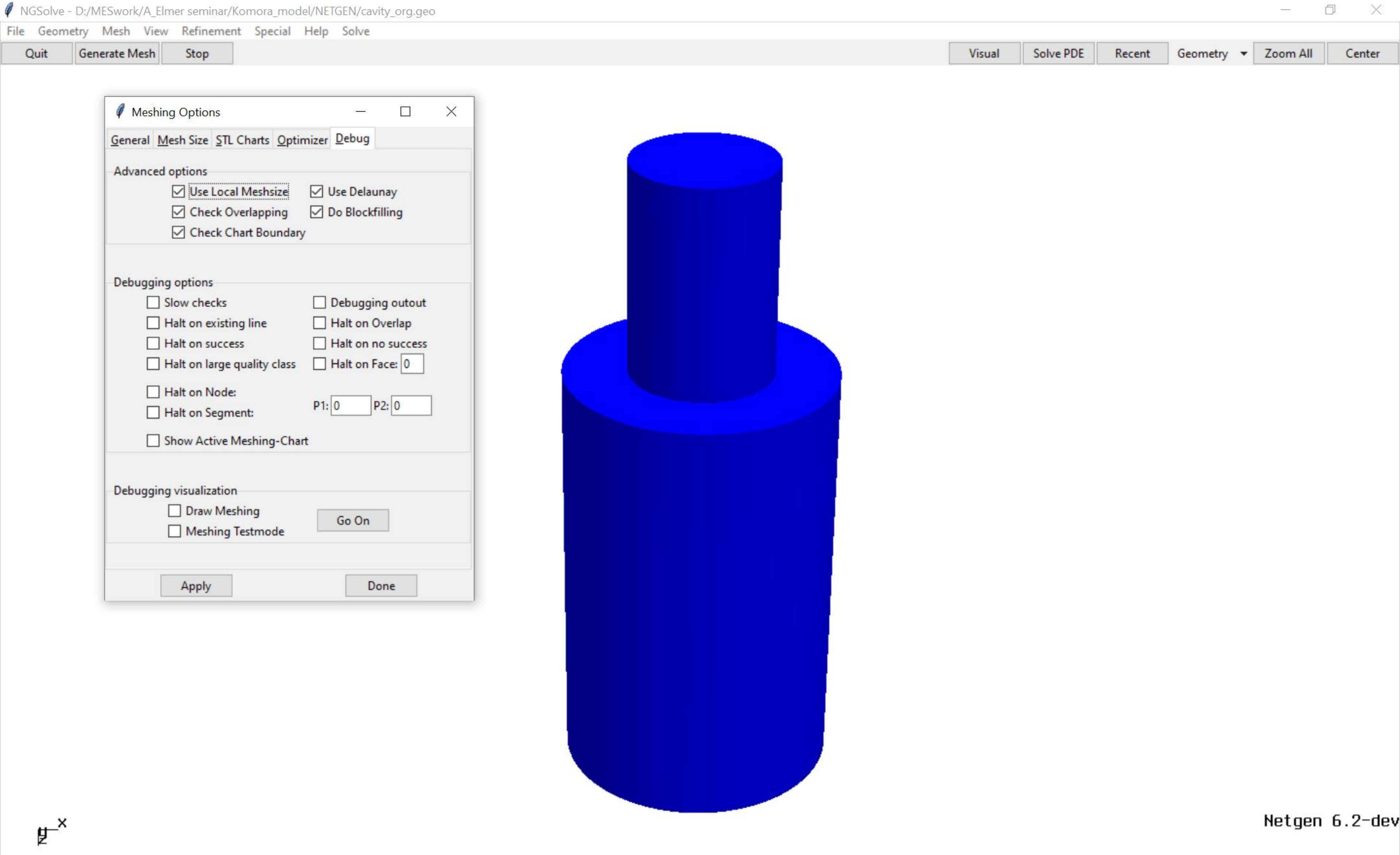
File Geometry Mesh View Refinement Special Help Solve
Quit Generate Mesh Stop
Visual Solve PDE Recent Geometry Zoom All Center
Meshing Options
General Mesh Size STL Charts Optimizer Debug
Optimization settings
Surface opt steps 3
Volume opt steps 5
Element size weight 0.2
Worst element measure 2
Bad elements
175 bad element criterion
Apply
Done
Netgen 6.2-dev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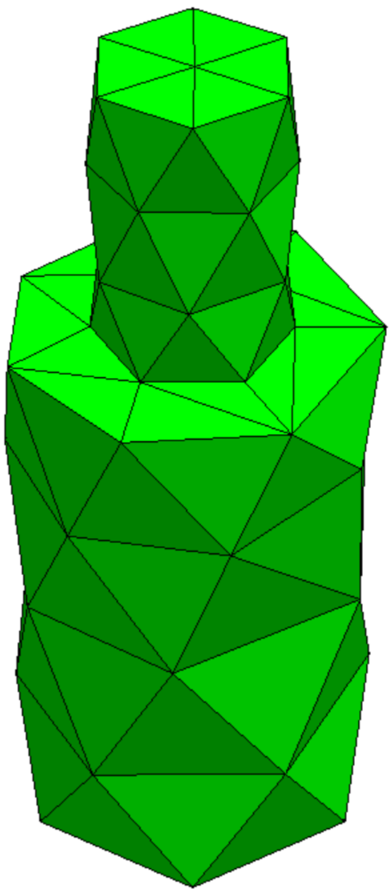
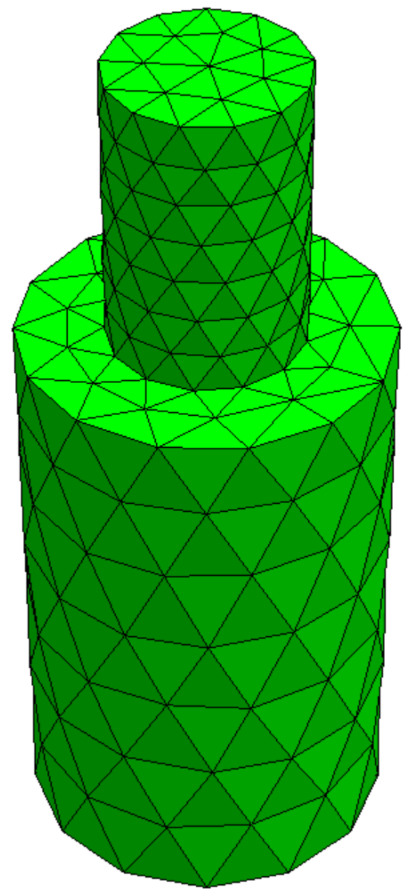
Meshing Options
General
Mesh Size
STL Charts
Optimizer
Debug
Advanced options
Use Local Meshsize
Use Delaunay
Check Overlapping
Do Blockfilling
Check Chart Boundary
Debugging options
Slow checks
Debugging outout
Halt on existing line
Halt on Overlap
Halt on success
Halt on no success
Halt on large quality class
Halt on Face: 0
Halt on Node:
Halt on Segment:
P1: 0
P2: 0
Show Active Meshing-Chart
Debugging visualization
Draw Meshing
Meshing Testmode
Go On
Apply
Done
Netgen 6.2-dev

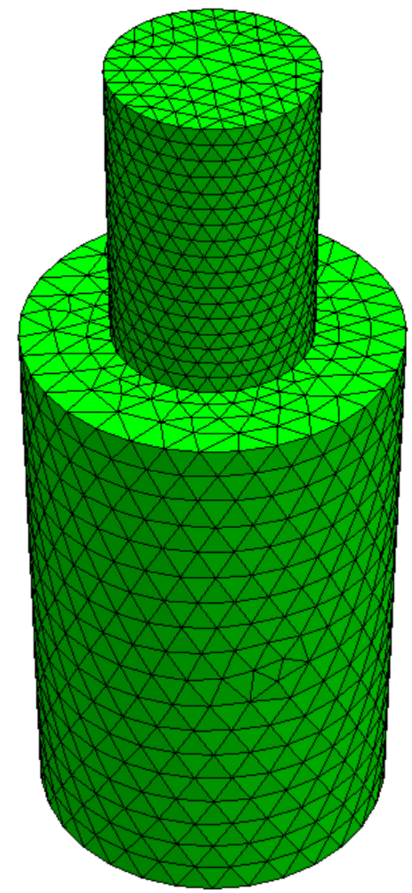
Mesh -> meshing options -> mesh granularity:



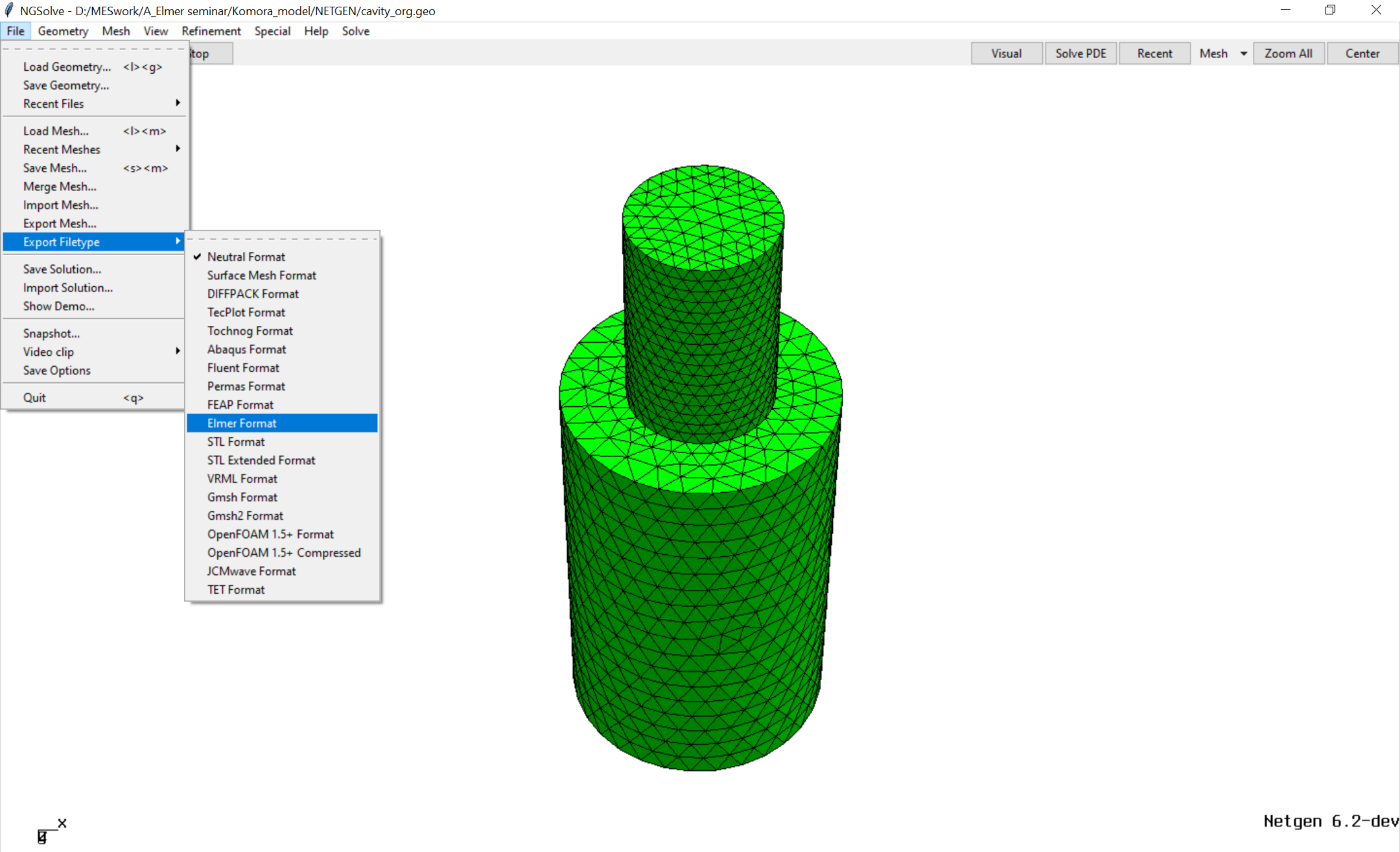
very coarse



moderate



very fine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Visual
Solve PDE
Recent
Mesh
Zoom All
Center
Load Geometry... <l><g>
Save Geometry...
Recent Files
Load Mesh... <l><m>
Recent Meshes
Save Mesh... <s><m>
Merge Mesh...
Import Mesh...
Export Mesh...
Export Filetype
Save Solution...
Import Solution...
Show Demo...
Snapshot...
Video clip
Save Options
Quit <q>
Neutral Format
Surface Mesh Format
DIFFPACK Format
TecPlot Format
Tochnog Format
Abaqus Format
Fluent Format
Permas Format
FEAP Format
Elmer Format
STL Format
STL Extended Format
VRML Format
Gmsh Format
Gmsh2 Format
OpenFOAM 1.5+ Format
OpenFOAM 1.5+ Compressed
JCMwave Format
TET Format
Netgen 6.2-dev

No elmer file type -> convert with ElmerGrid:

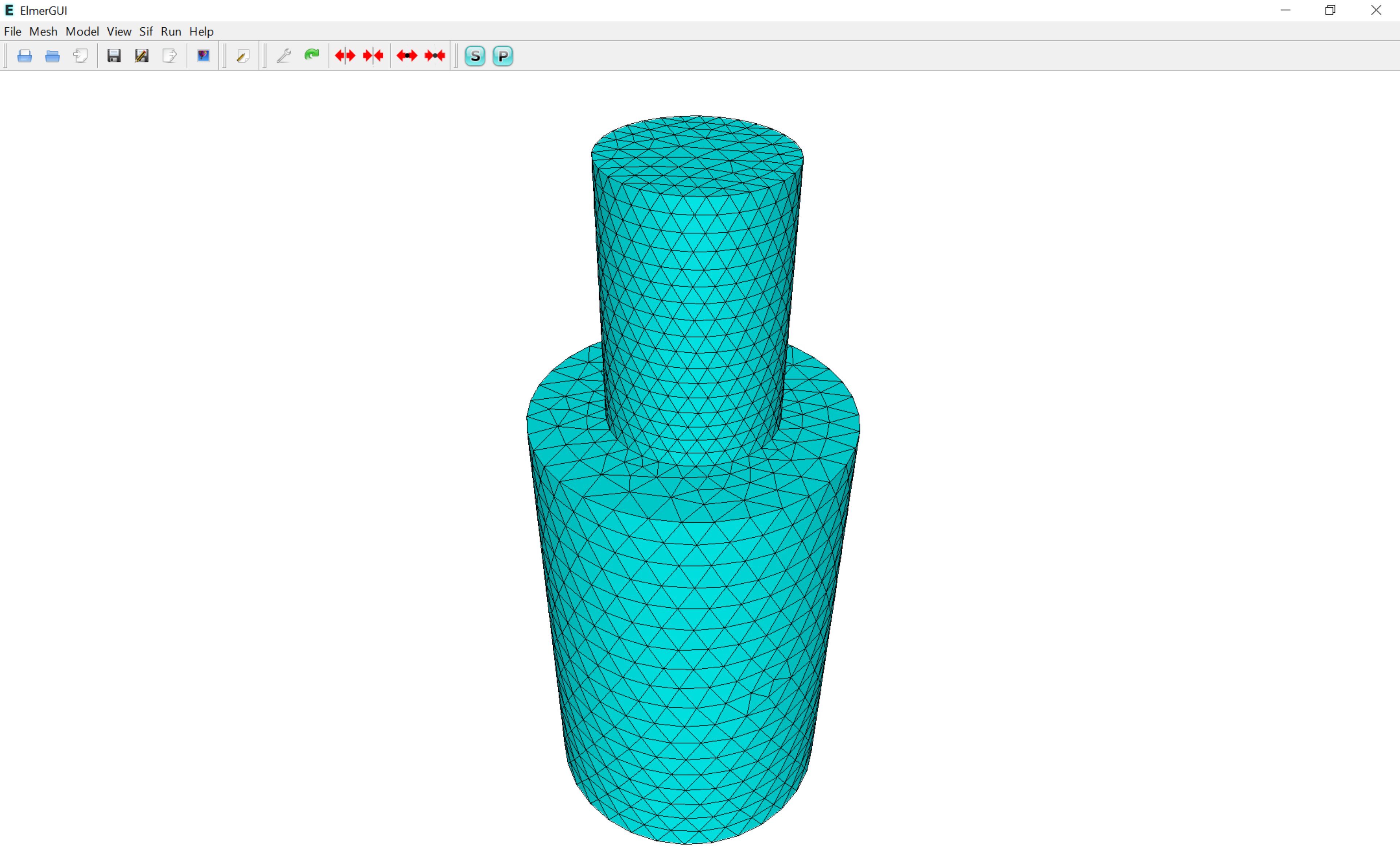
ElmerGrid #in #out meshname – parameters

ElmerGrid 14 2 tensductor.gmsh2 $\underbrace{\text{-scale 0.001 0.001 0.001}}$ -autoclean

from m to mm

For bodyID and Boundary Index numbering from 1

Lifehack alert!



Ready to set the .sif file

Electromagnetic field – described by **Maxwell equations**

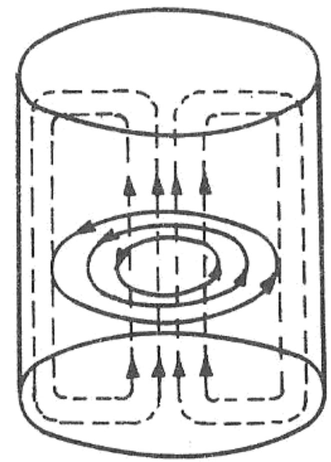
- Faraday's law $$\frac{1}{\mu}\nabla \times \vec{\boldsymbol{E}} = i\omega\vec{\boldsymbol{H}}$$
- Ampère's law $$\nabla \times \vec{\boldsymbol{H}} = -i\omega\varepsilon\vec{\boldsymbol{E}} + \vec{\boldsymbol{J}}$$

$\vec{\boldsymbol{E}}$	electrical field
$\vec{\boldsymbol{H}}$	magnetic field strength
$\vec{\boldsymbol{J}}$	impressed current distribution

- Time-harmonic form enables introducing wave frequency given in $\omega = 2\pi f$
- In terms of EM waves Maxwell equations are transformed into **Helmholtz equations**

Model parameters

- Resonance frequency – ***f* = 2,5 GHz**
- Material:
  - walls – **copper**
  - interior of the chamber – **air**
- Chamber's shape: cylindrical
- Waveguide's shape: cylindrical
- Construction: axisymmetric
- Wave type: **TE011**
  - **TE –** EM field vector configuration
  - **m** = 0, **n** = 1, **p** = 1 - modes
  - *determines the form of Helmholtz equations and the shape of EM field distribution*



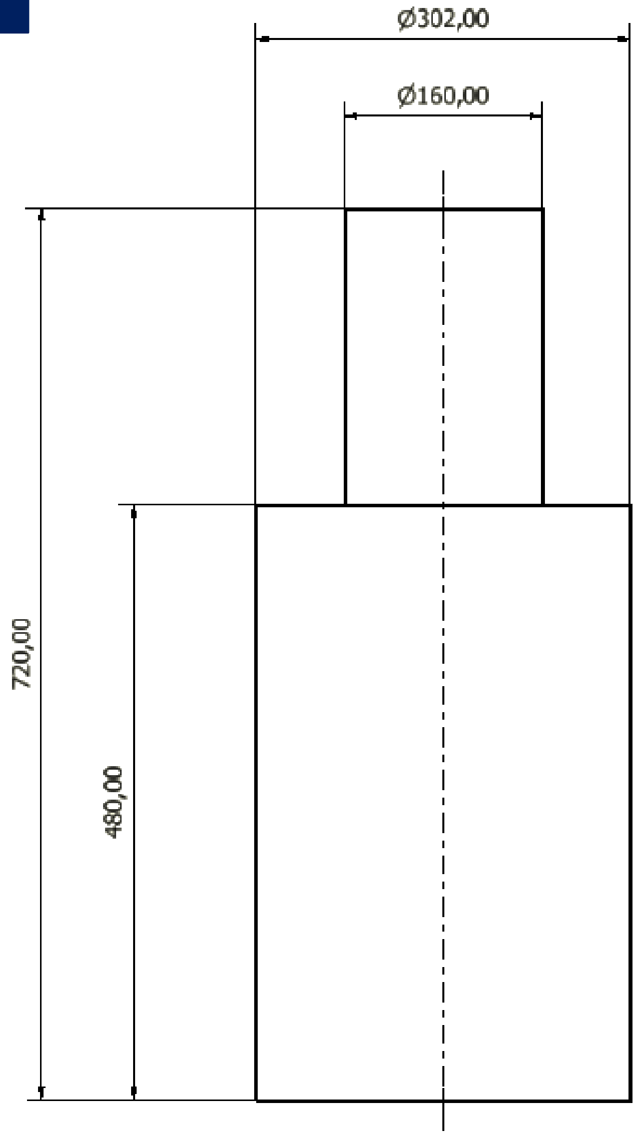
TE_{011}

Source: DOBROWOLSKI J.A. *Mikrofale.(Microwaves)* Warszawa, Wydawnictwa PW, 1991

Size of the model

- Chamber's size:
  - Diameter: **302 mm**
  - Length: **480 mm**
- Waveguide's size:
  - Diameter: **160 mm**
  - Length: **240 mm**

- *Length is an integer multiple of the wavelength*
- *Chamber's diameter is calculated from equation for resonance frequency dependent on chamber's dimension*
- *Waveguide's diameter chosen based on phase constant value (needs to be real value)*



Specific Helmholtz equation

wave identifying vector

n-th root of the derivative of m-th order Bessel function

amplitude of Hz in point (0,0,0) for t = 0

cylindrical coordinates

$$H_z = H_z(0)J_{\boldsymbol{m}}\left(\frac{u'_{\boldsymbol{mn}}}{\boldsymbol{r}} \cdot \varrho\right) \cdot \cos(\boldsymbol{m}\varphi) \cdot e^{-j\beta_z \cdot z}$$

m-th order Bessel function

waveguide’s radius

phase constant

Basic parts of .sif file

Simulation

```
Simulation
   Max Output Level = 9
   Coordinate System = "Cartesian"
   Simulation Type = Steady
   Timestepping Method = BDF
   Timestep Sizes = 1
   Timestep Intervals = 10
   Steady State Max Iterations = 1
   Post File = case.vtu
   Output Intervals(1) = 1
End
```

- Steady type - solution for a steady state
- No time stepping solutions required
- Result file in .vtu format

Equation

```
Equation 1
   Name = "VectorHelmholtz_equation"
   Active Solvers(3) = 1 2 3
   Angular Frequency = Real $w
End
```

Angular frequency given by

$$\omega = 2\pi f$$

Solvers

VectorHelmholtz Solver

Implement Maxwell equations

VectorHelmholtz CalcFields

Calculate values of EM wave parameters

SaveGridData

Save values of EM wave parameters in an external file

Specific for the problem

Universal

VectorHelmholtzSolver

```
Solver 1
   Equation = "VectorHelmholtz"
   Variable = E[E re:1 E im:1]
   Procedure = "VectorHelmholtz„ "VectorHelmholtzSolver"
   …
End
```

- Parameters are calculated relative to the vector *E*

Constants

```
! Constants for wave equation
$ beta=21.243
$ beta_lim=47.896
$ const=0.013292
$ w=2*pi*(2.5e9)
! Constant for Leontovich
boundary condition
$ l=767340
```

- Phase constant **β**
- Limit phase constant **βlim**
- $const = \frac{d_{wave}}{\pi u'_{01}}$
- Angular frequency $\omega = 2\pi f$
- $l = \mu_0 \sqrt{\frac{\omega_{res} \cdot \sigma_{Cu}}{2\mu_{Cu}}}$

VectorHelmholtzCalcFields

```
 Solver 2
   Equation = "calcfields"
   Procedure = "VectorHelmholtz" "VectorHelmholtzCalcFields"

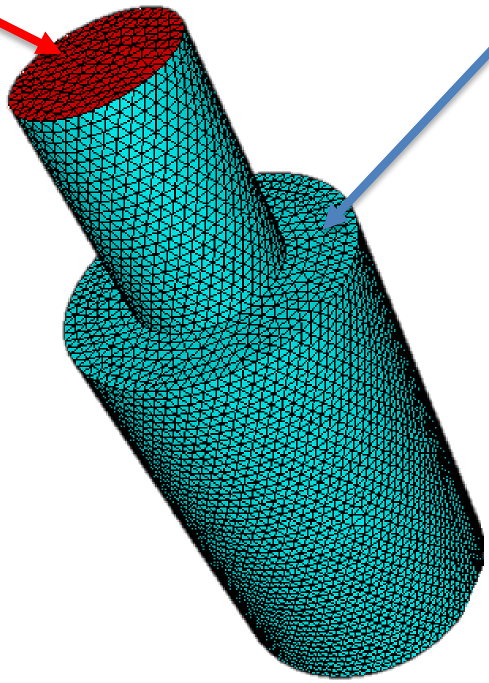
   Field Variable =  String "E"
   Calculate Elemental Fields = Logical True
   Calculate Magnetic Field Strength = Logical True
   Calculate Magnetic Flux Density = Logical True
   Calculate Poynting vector = Logical True
   Calculate Div of Poynting Vector = Logical True
   Calculate Electric field = Logical True
   Calculate Energy Functional = Logical True
   …
End
```

- For „SaveGridData” solver only **Electric field *E*** and **Magnetic Field Strength *H*** vectors are saved in an external file

Boundary conditions

Inport

- Source of EM wave
- Described by the wave equation specific for the wave type



Walls

- Energy absorbing material - copper
- Described by Leontovich impedance boundary condition

Inport

```
Boundary Condition 1
  Target Boundaries(1) = 2
  Name = "Inport"
  Electric Robin Coefficient im = Real $ beta
  Magnetic Boundary Load im 2 = Variable Coordinate 1, Coordinate 2
  Real MATC "2*beta*sqrt(const/sqrt(tx(0)*tx(0)+tx(1)*tx(1)))
*cos(beta_gr*sqrt(tx(0)*tx(0)+tx(1)*tx(1))-0.785398)"
End
```

- EM wave source for TE011 type described by Robin boundary condition:
- Electric Robin Coefficient: $\alpha = i\beta$
- Magnetic Boundary Load:

$$g = i \cdot 2\beta \cdot \sqrt{\frac{2}{\pi\left(\frac{2 \cdot u'_{01}}{d_{wave}} \cdot \sqrt{x^2+y^2}\right)}}\, cos\left[\left(\frac{2 \cdot u'_{01}}{d_{wave}} \cdot \sqrt{x^2+y^2}\right) - \frac{\pi}{4}\right]$$

Simplified Bessel function

Walls

```
Boundary Condition 2
  Target Boundaries(4) = 1 3 4 5
  Name = "Walls"
  ! Leontovich impedance boundary
  Electric Robin Coefficient = Real $ -1
  Electric Robin Coefficient im = Real $ 1
End
```

- Energy absorption described by Leontovich impedance boundary condition in form of Robin condition:
- Electric Robin Coefficient:

$$\alpha = (1 - i) \cdot \mu_0 \sqrt{\frac{\omega_{res} \cdot \sigma_{Cu}}{2\mu_{Cu}}}$$

Walls material's parameters

Interior material's parameter

Code files

Code for the project available on **GitHub**:

- GEO file for geometry
- SIF file for ELMER FEM solver

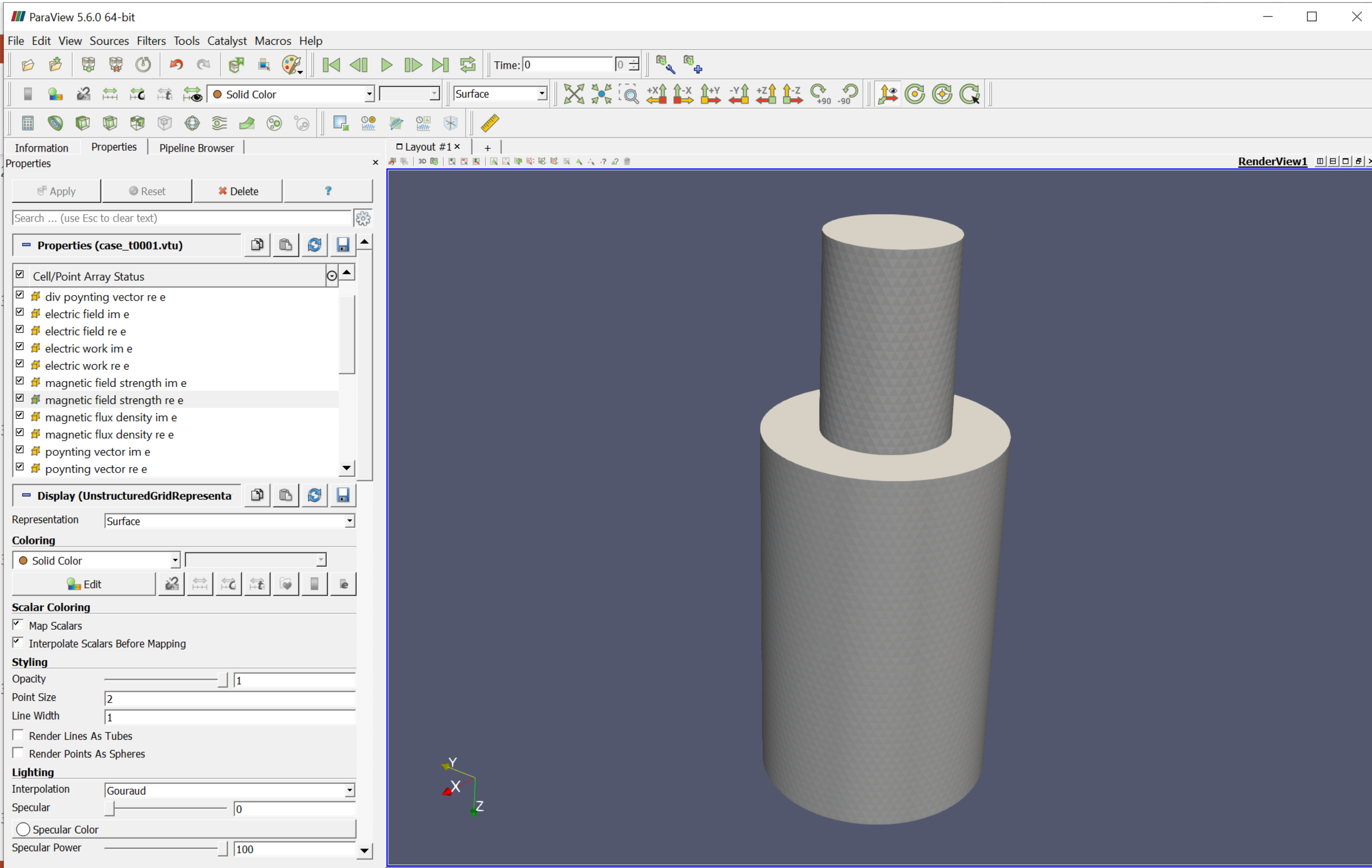
https://github.com/DKopala/MicrowaveChamber

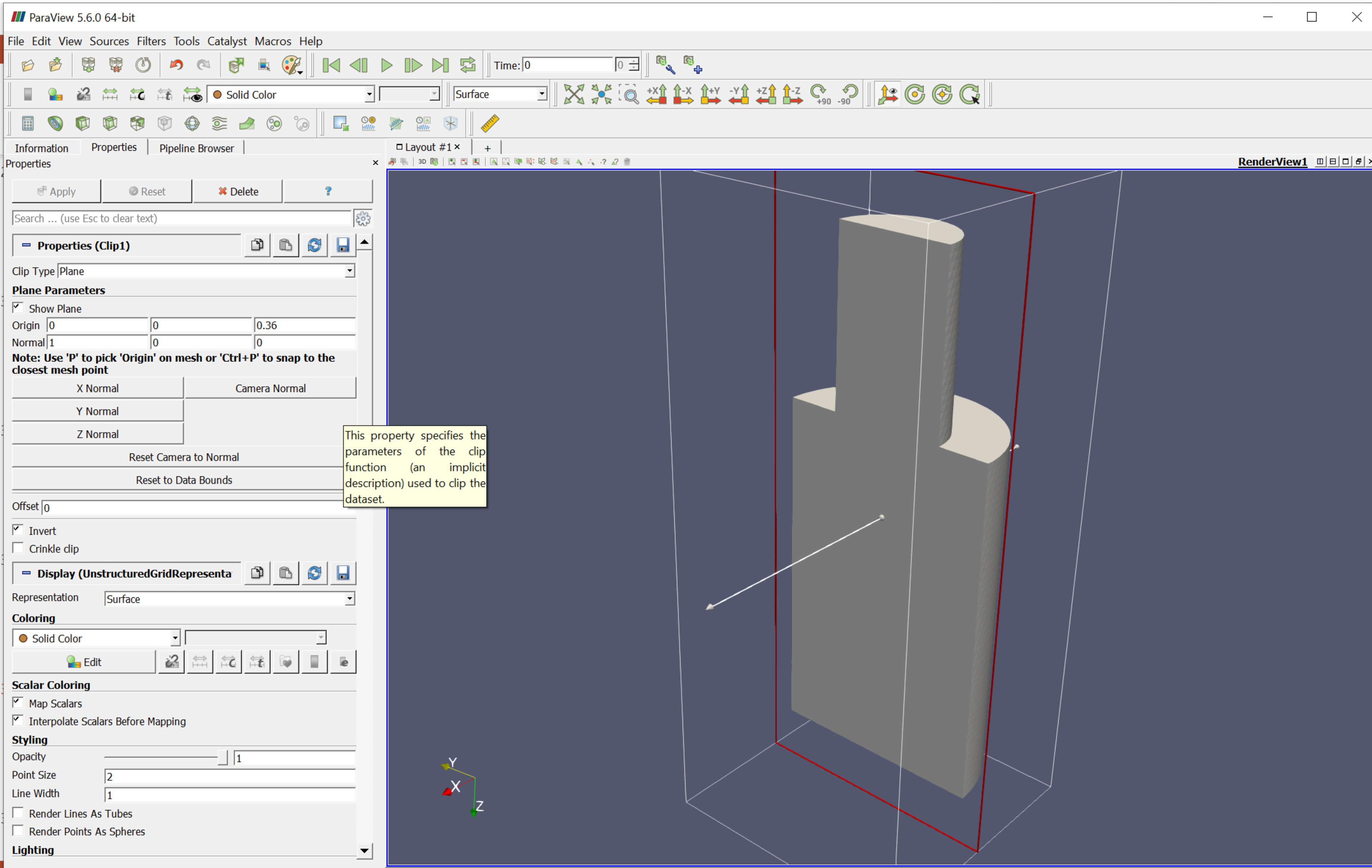
Data analysis and visualization

ParaView:

- open-source, multi-platform application
- qualitative and quantitative visualisation
- interactive data exploration in 3D
- batch processing
- high performance computation

The goal: find the areas of resonance of the standing waves in the chamber




ParaView 5.6.0 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
Solid Color
Surface
Information
Properties
Pipeline Browser
Layout #1
RenderView1
Properties
Apply
Reset
Delete
?
Search ... (use Esc to clear text)
Properties (Clip1)
Clip Type Plane
Plane Parameters
Show Plane
Origin 0 0 0.36
Normal 1 0 0
Note: Use 'P' to pick 'Origin' on mesh or 'Ctrl+P' to snap to the closest mesh point
X Normal
Camera Normal
Y Normal
Z Normal
Reset Camera to Normal
Reset to Data Bounds
This property specifies the parameters of the clip function (an implicit description) used to clip the dataset.
Offset 0
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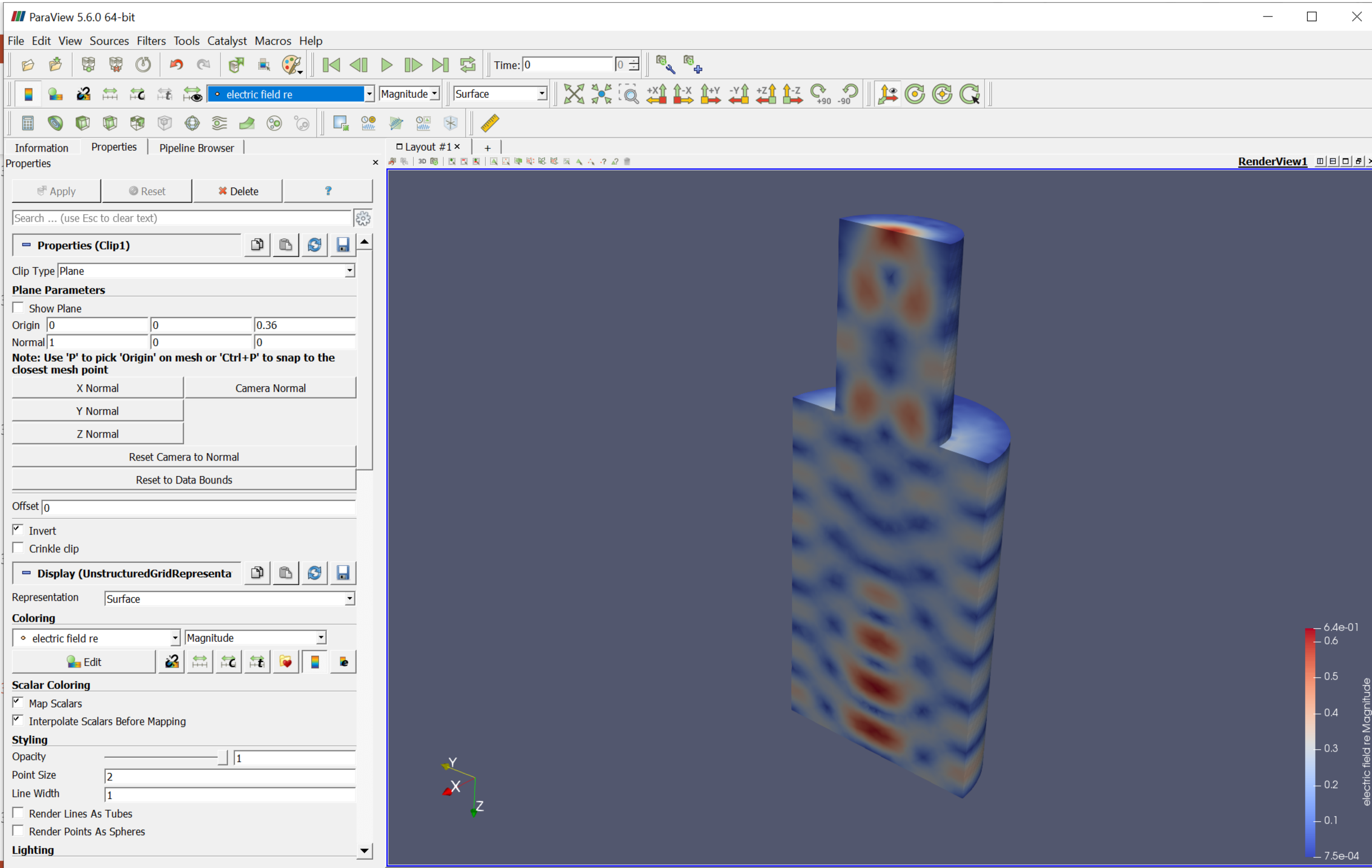
Coloring
Solid Color
Edit
Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
Styling
Opacity 1
Point Size 2
Line Width 1
Render Lines As Tubes
Render Points As Spheres
Lighting
Y
X
Z


ParaView 5.6.0 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
Time: 0
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Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (Clip1)
Clip Type Plane
Plane Parameters
Show Plane
Origin 0 0 0.36
Normal 1 0 0
Note: Use 'P' to pick 'Origin' on mesh or 'Ctrl+P' to snap to the closest mesh point
X Normal
Camera Normal
Y Normal
Z Normal
Reset Camera to Normal
Reset to Data Bounds
Offset 0
Invert
Crinkle clip
Display (UnstructuredGridRepresenta
Representation Surface
Coloring
electric field re
Magnitude
Edit
Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
Styling
Opacity 1
Point Size 2
Line Width 1
Render Lines As Tubes
Render Points As Spheres
Lighting
6.4e-01
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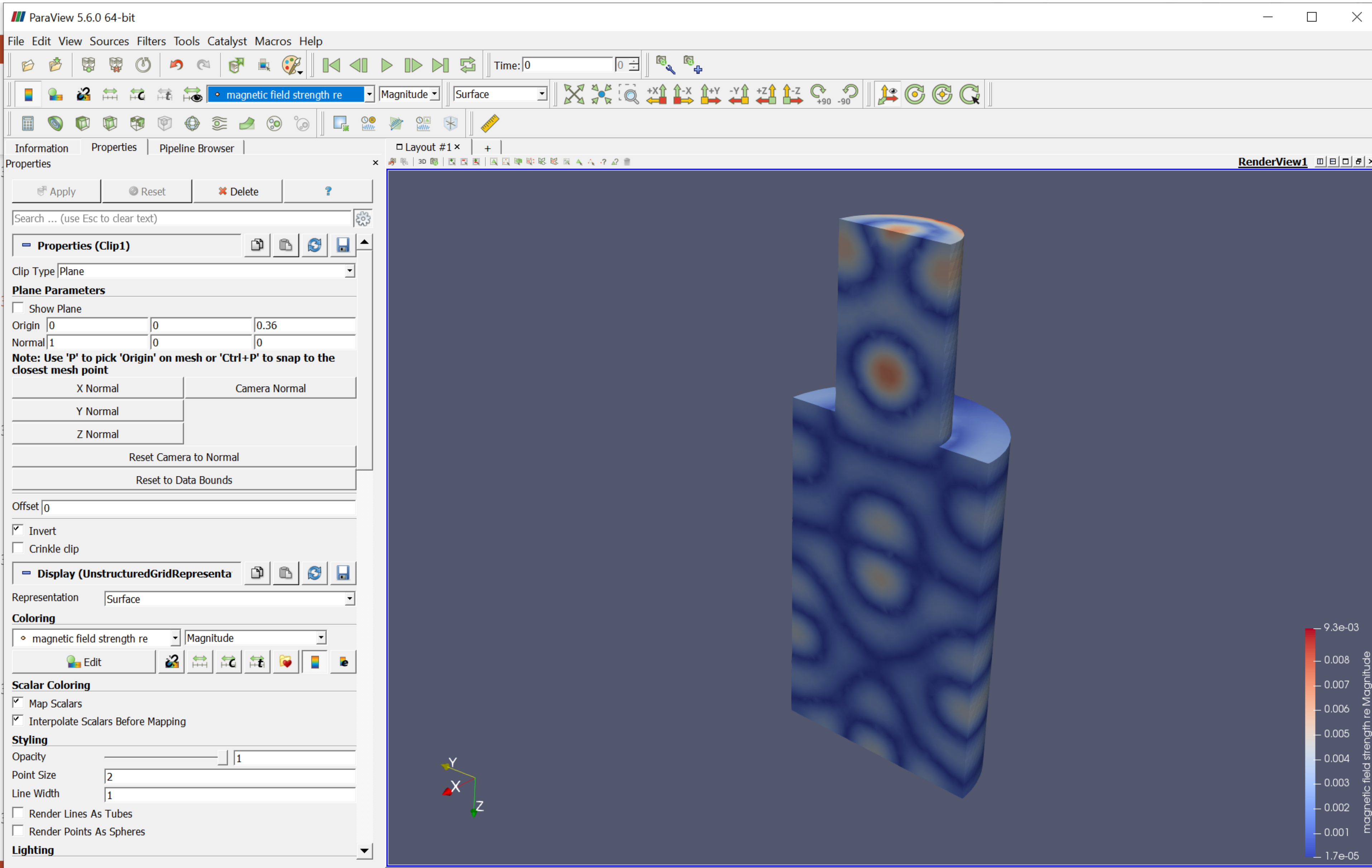
0.5
0.4
0.3
0.2
0.1
7.5e-04
electric field re Magnitude
Y
X
Z


ParaView 5.6.0 64-bit
File Edit View Sources Filters Tools Catalyst Macros Help
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Magnitude
Surface
Information
Properties
Pipeline Browser
Layout #1
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (Clip1)
Clip Type Plane
Plane Parameters
Show Plane
Origin 0 0 0.36
Normal 1 0 0
Note: Use 'P' to pick 'Origin' on mesh or 'Ctrl+P' to snap to the closest mesh point
X Normal
Camera Normal
Y Normal
Z Normal
Reset Camera to Normal
Reset to Data Bounds
Offset 0
Invert
Crinkle clip
Display (UnstructuredGridRepresenta
Representation Surface
Coloring
magnetic field strength re
Magnitude
Edit
Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
Styling
Opacity 1
Point Size 2
Line Width 1
Render Lines As Tubes
Render Points As Spheres
Lighting
RenderView1
9.3e-03
0.008
0.007
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0.004
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0.002
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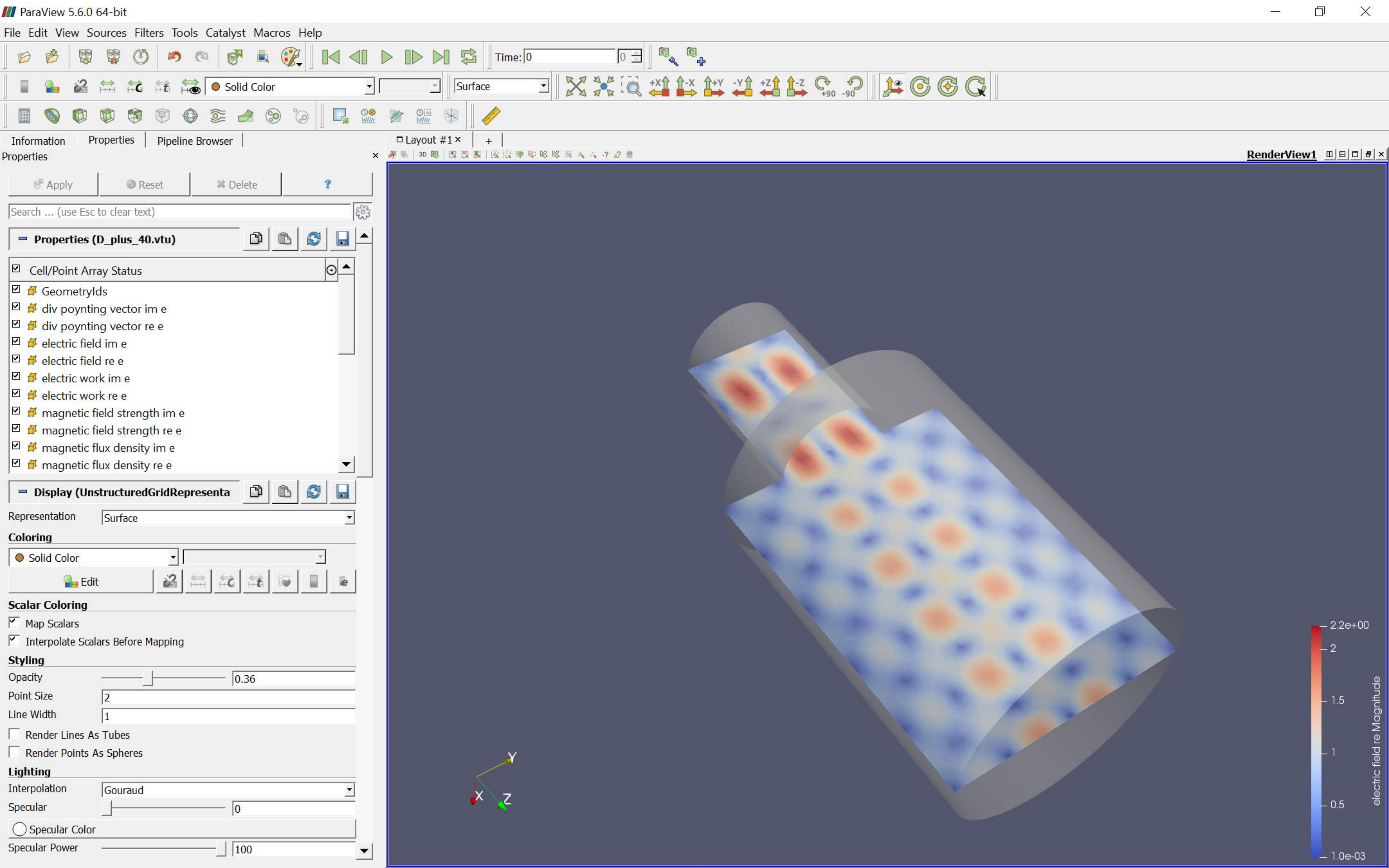
magnetic field strength re Magnitude
Y
X
Z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File Edit View Sources Filters Tools Catalyst Macros Help
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Solid Color
Surface
Information
Properties
Pipeline Browser
Layout #1
RenderView1
Properties
Apply
Reset
Delete
Search ... (use Esc to clear text)
Properties (D_plus_40.vtu)
Cell/Point Array Status
GeometryIds
div poynting vector im e
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electric field im e
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electric work im e
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magnetic field strength im e
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magnetic flux density im e
magnetic flux density re e
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Representation
Surface
Coloring
Solid Color
Edit
Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
Styling
Opacity
0.36
Point Size
2
Line Width
1
Render Lines As Tubes
Render Points As Spheres
Lighting
Interpolation
Gouraud
Specular
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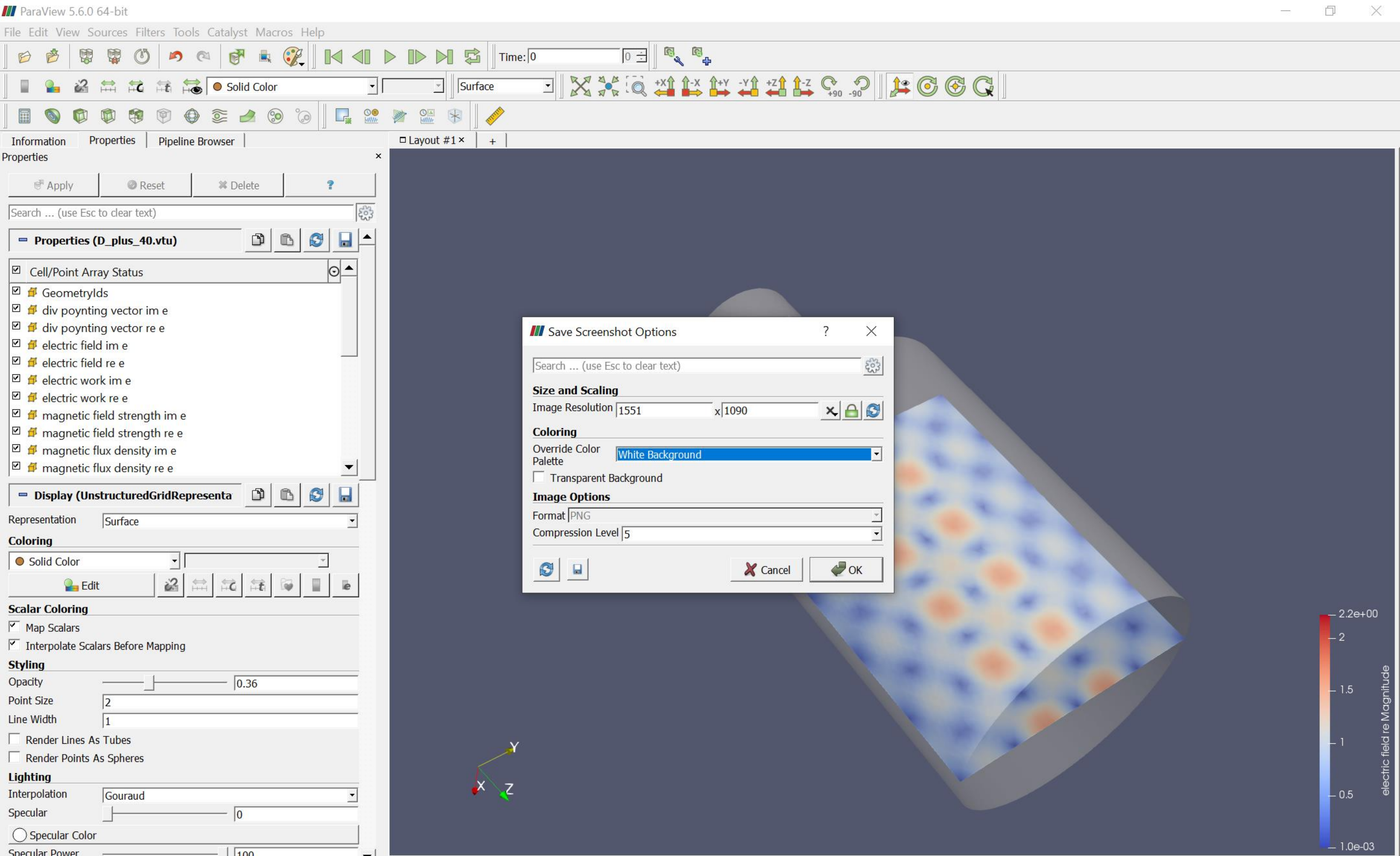
0.5
1.0e-03
electric field re Magnitude
Y
X
Z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Surface
Information
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Properties (D_plus_40.vtu)
Cell/Point Array Status
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electric work im e
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Scalar Coloring
Map Scalars
Interpolate Scalars Before Mapping
Styling
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Point Size
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Line Width
1
Render Lines As Tubes
Render Points As Spheres
Lighting
Interpolation
Gouraud
Specular
0
Specular Color
Specular Power
100
Save Screenshot Options
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Size and Scaling
Image Resolution
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x
1090
Coloring
Override Color Palette
White Background
Transparent Background
Image Options
Format
PNG
Compression Level
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electric field re Magnitude
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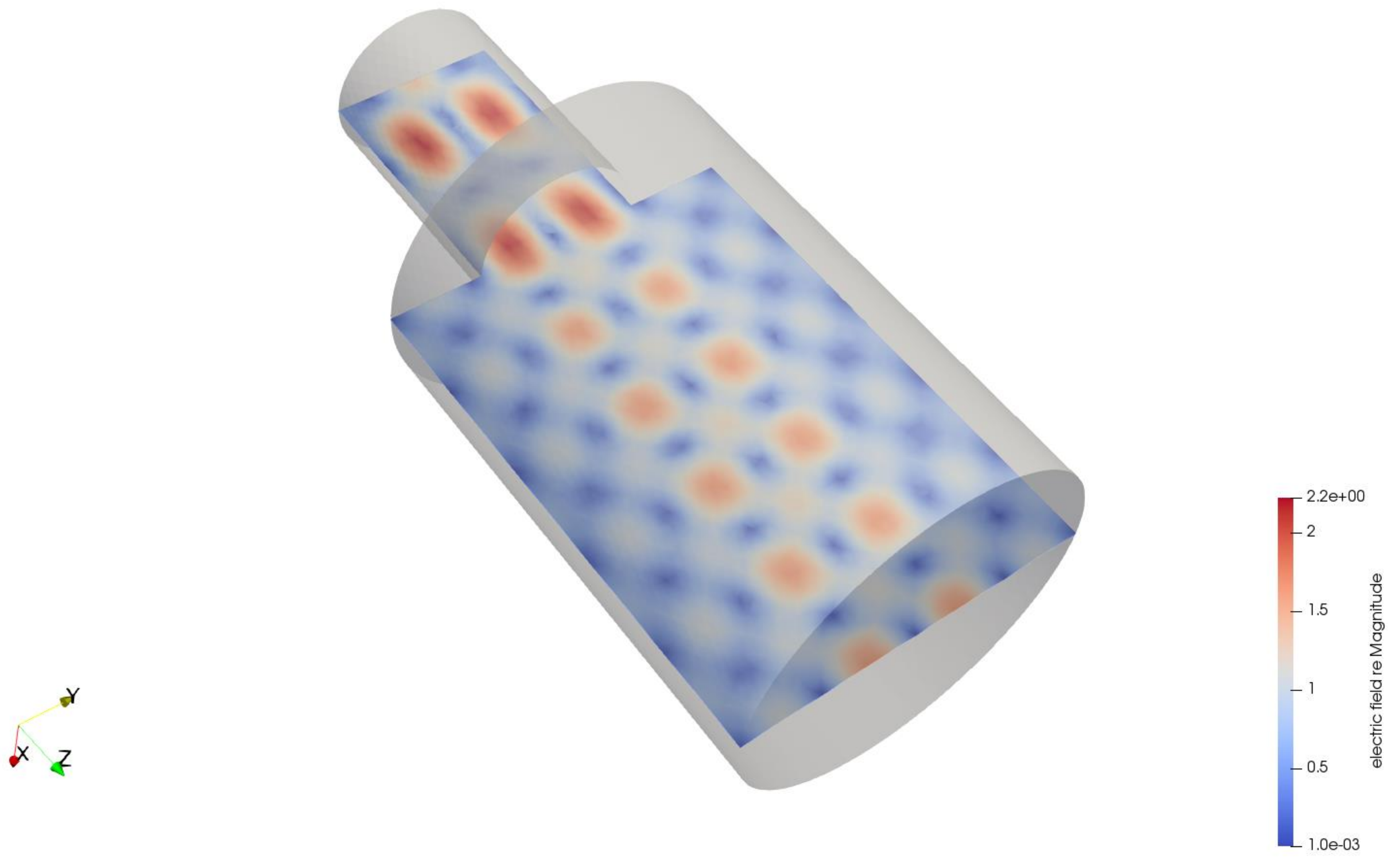

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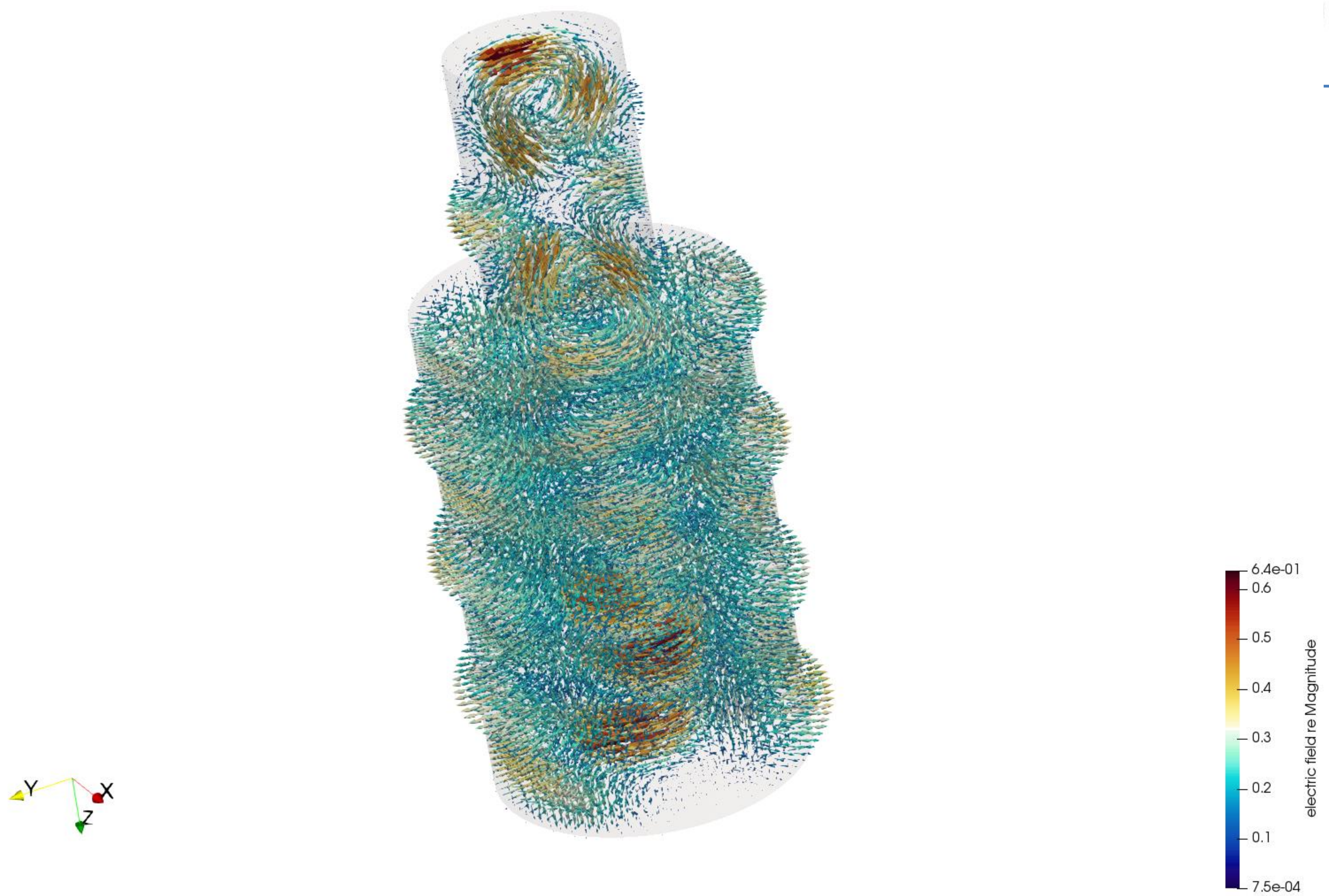

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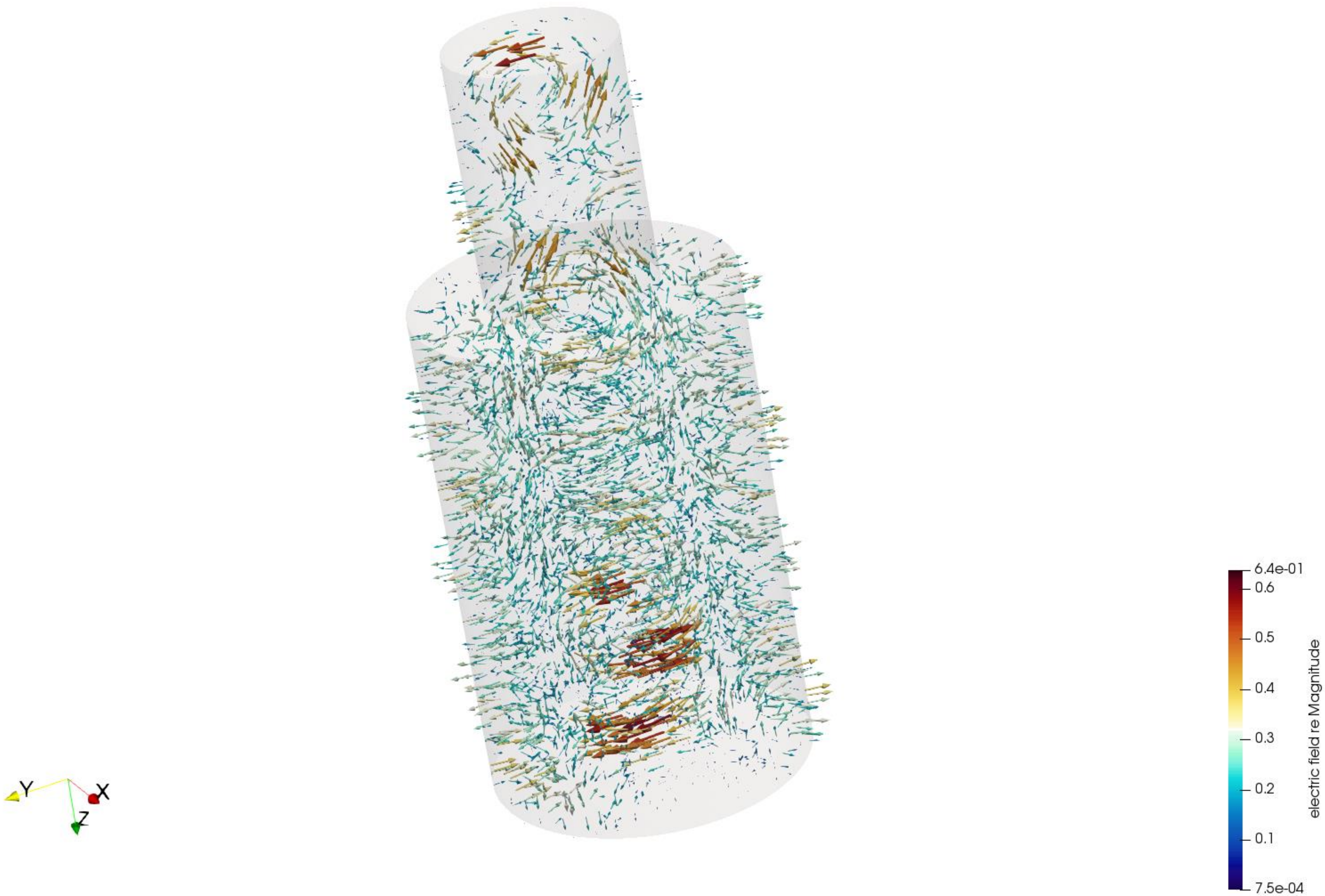
electric field re Magnitude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electric field re Magnitude
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electric field re Magnitude

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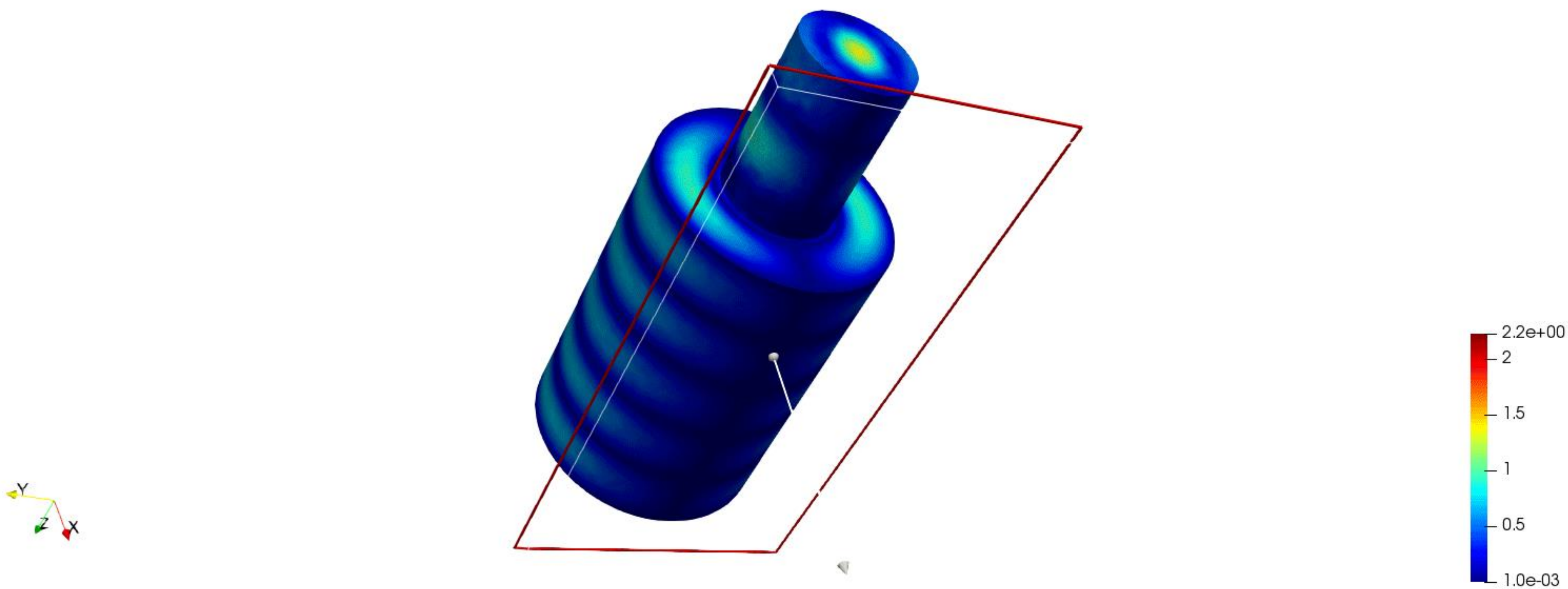
electric field re Magnitude



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electric field re Magnitude
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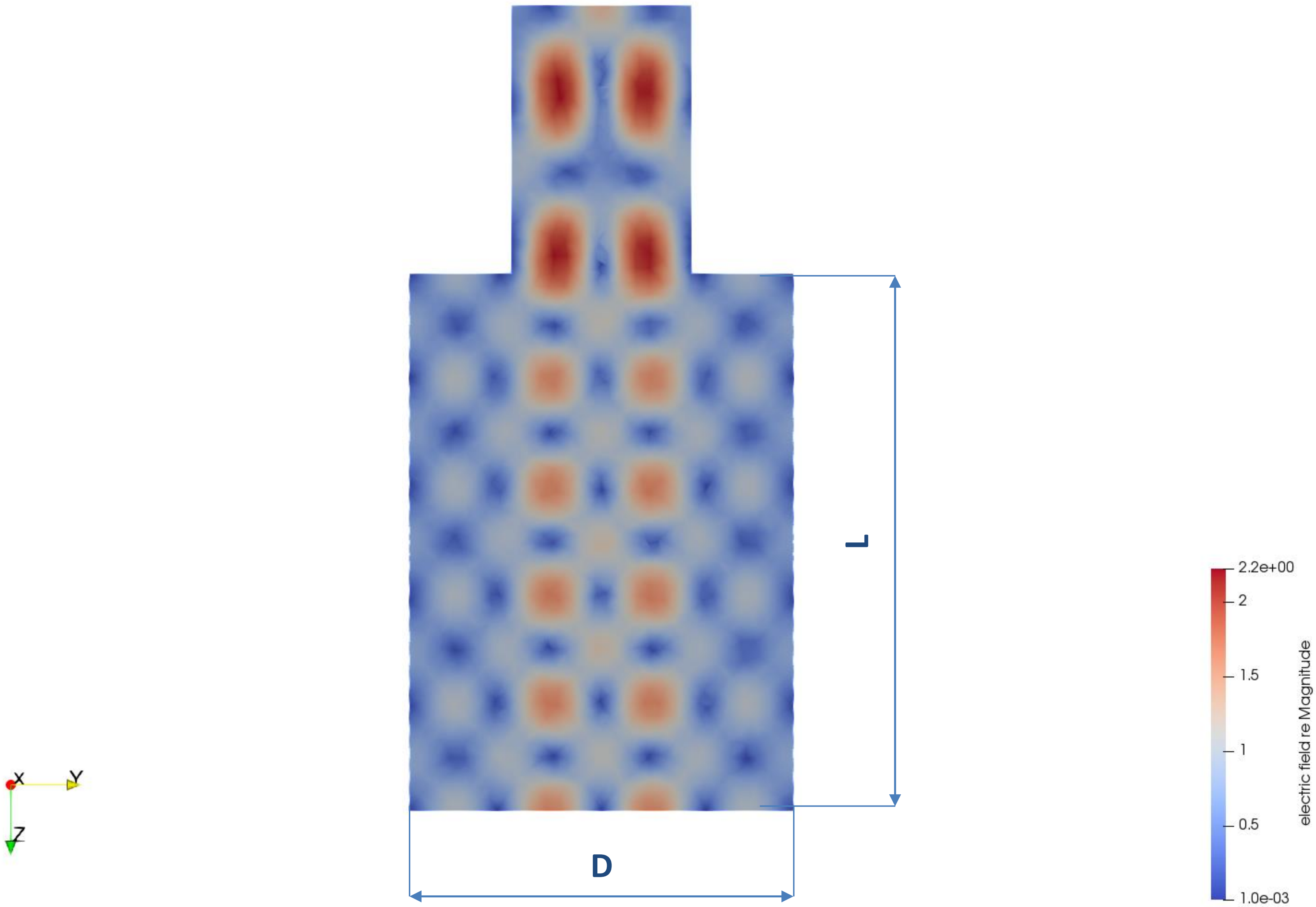
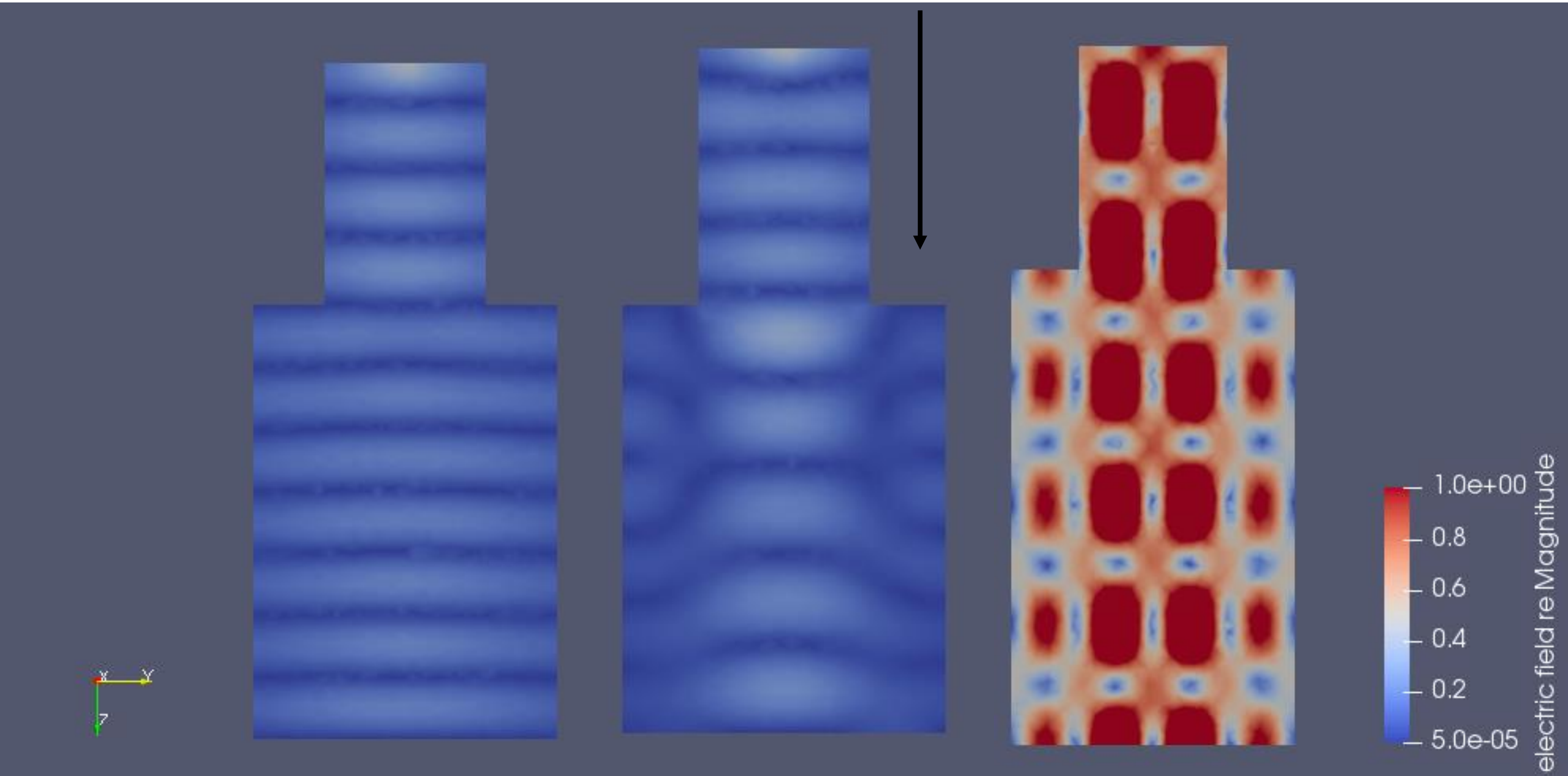
Z
X

The final goal: analyse the influence of chamber dimensions on standing waves resonance



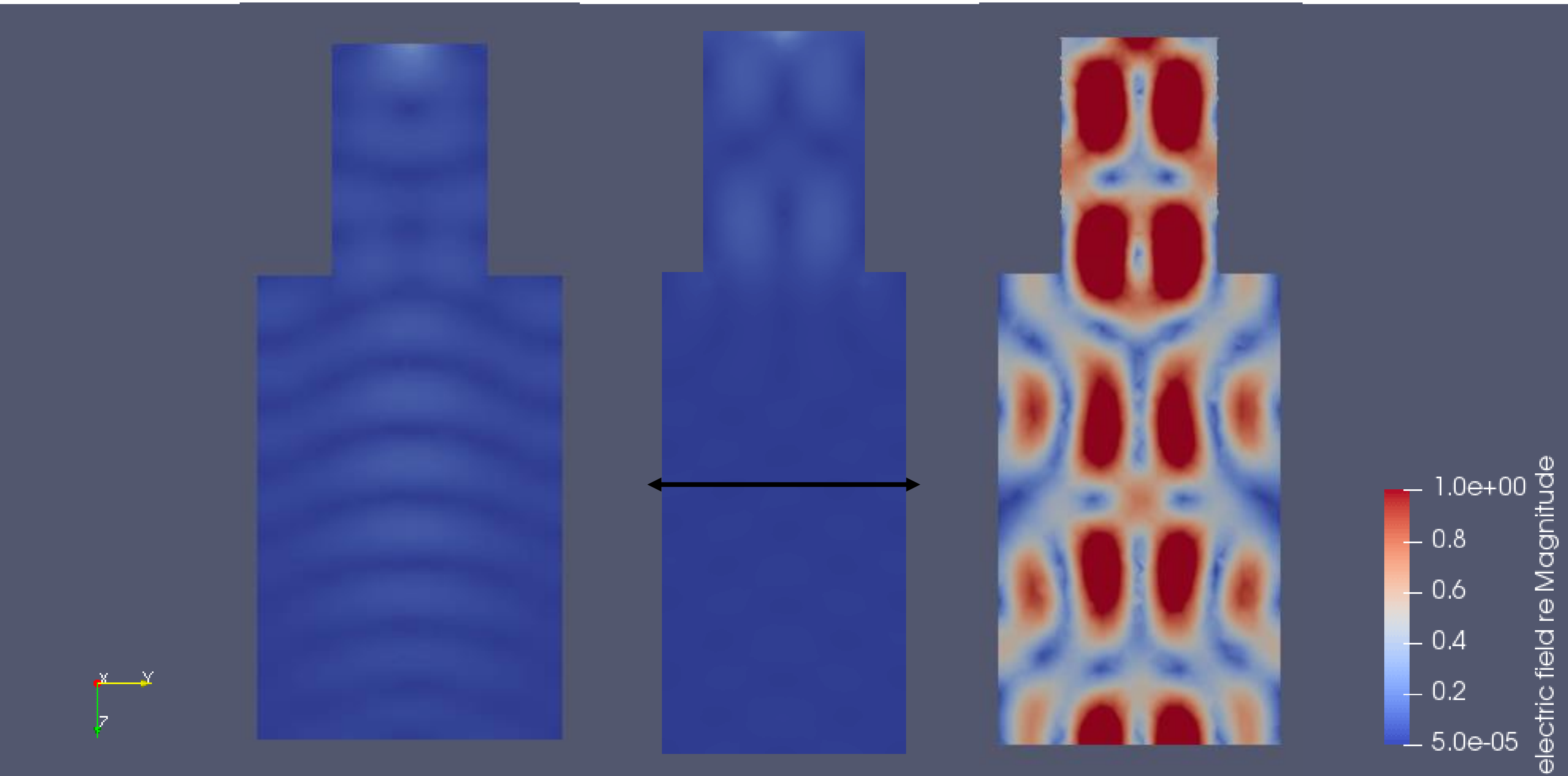
weak resonance	influence of the length change	strong resonance - standinng wave



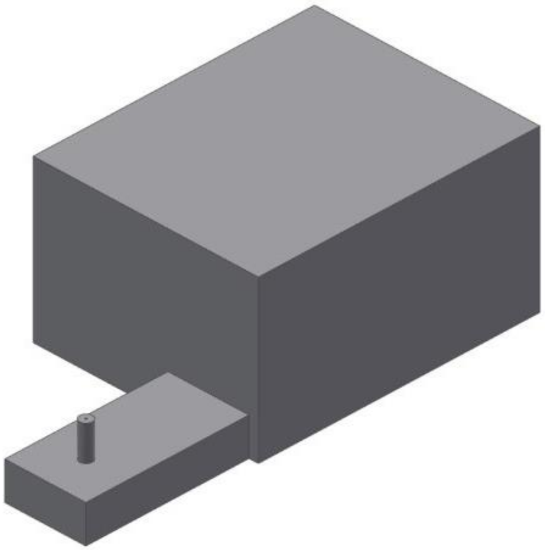
weak resonance

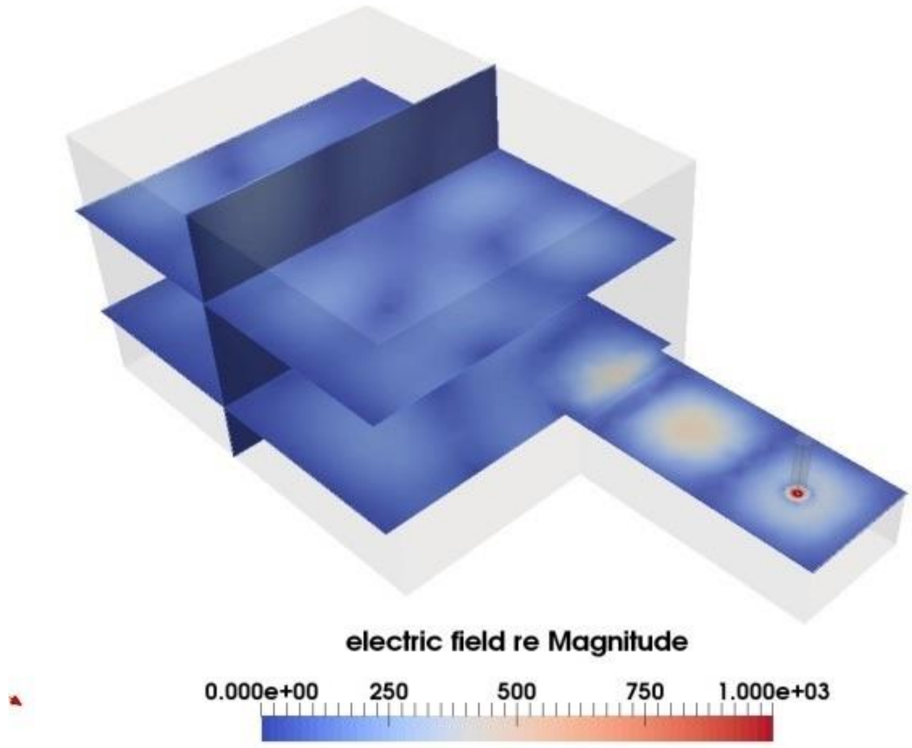
influence of the length change

strong resonance - standinng wave



Rectangular cavity
„Microwave oven type”

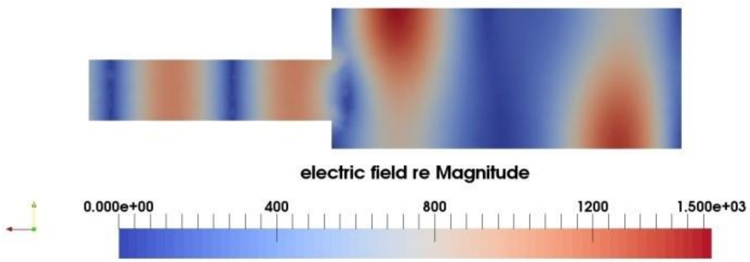




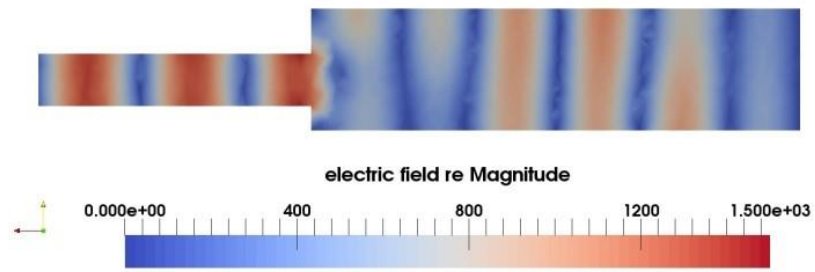
3D view of rectangular cavity model

Electric field distribution, slices, rectangular cavity with waveguide of lenght 130.5mm

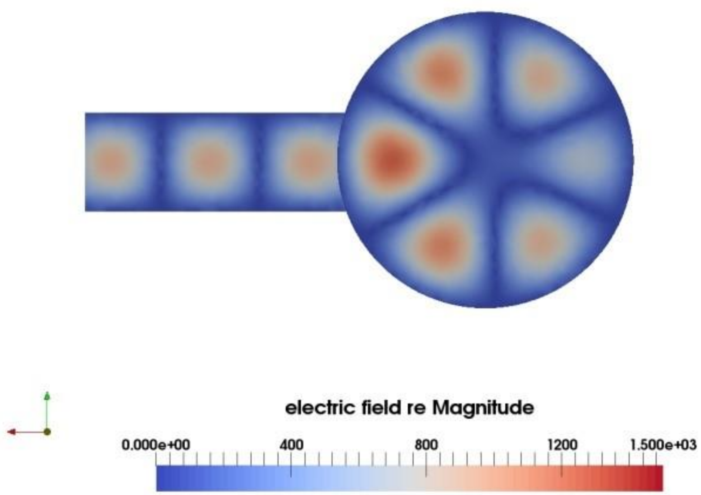
Cilindrical cavities



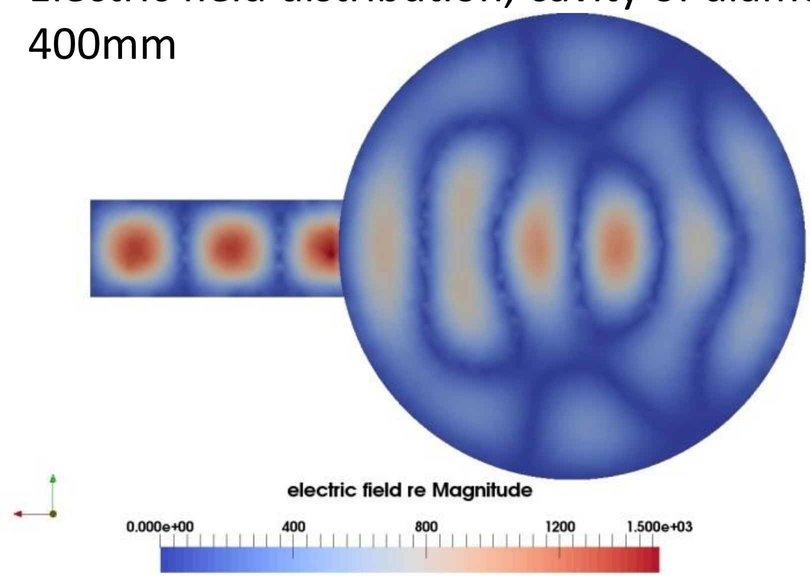
Electric field distribution, cavity of diameter 250mm



Electric field distribution, cavity of diameter 400mm

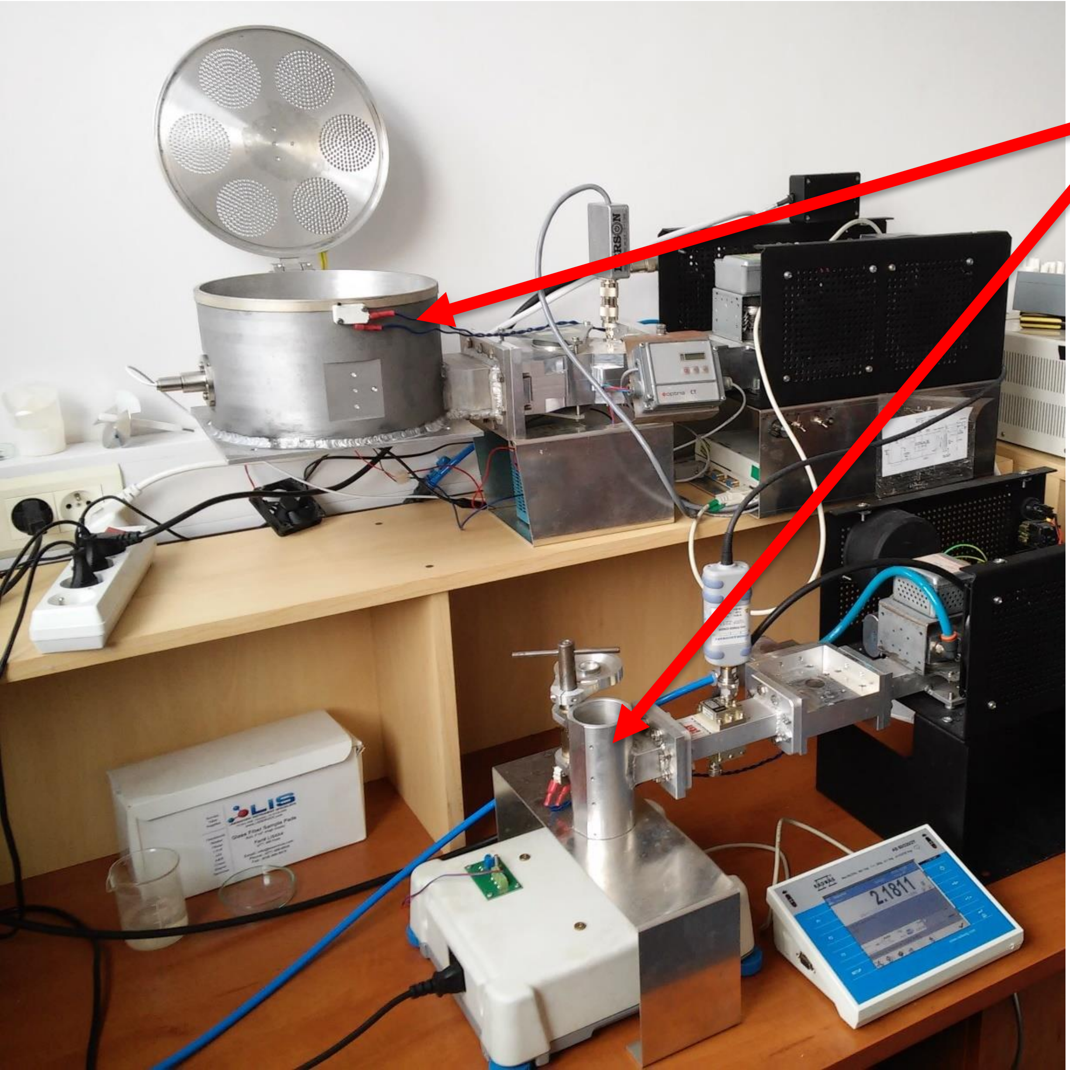


Electric field distribution, cavity of diameter 250mm



Electric field distribution, cavity of diameter 400mm

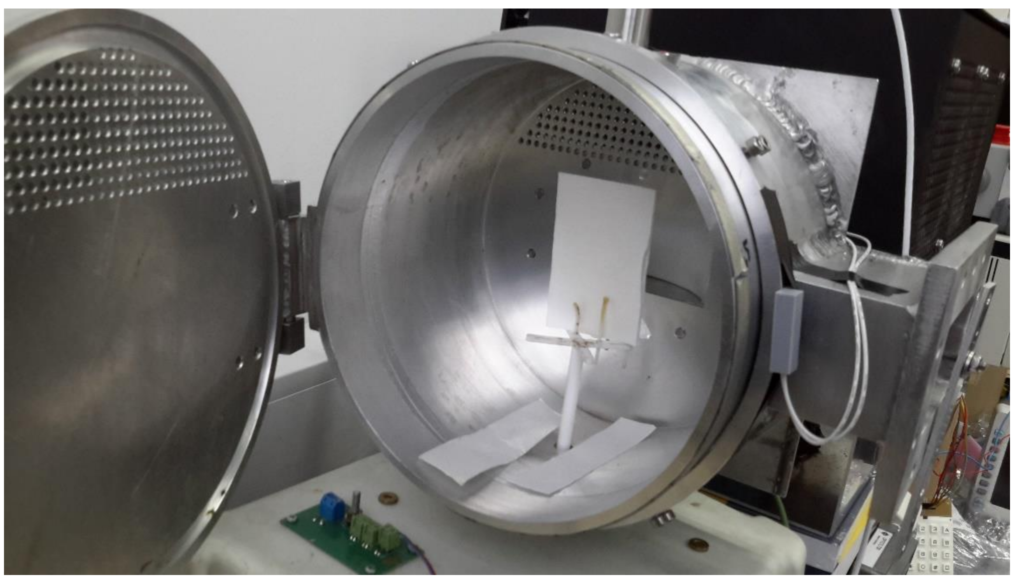
Why do we do this?

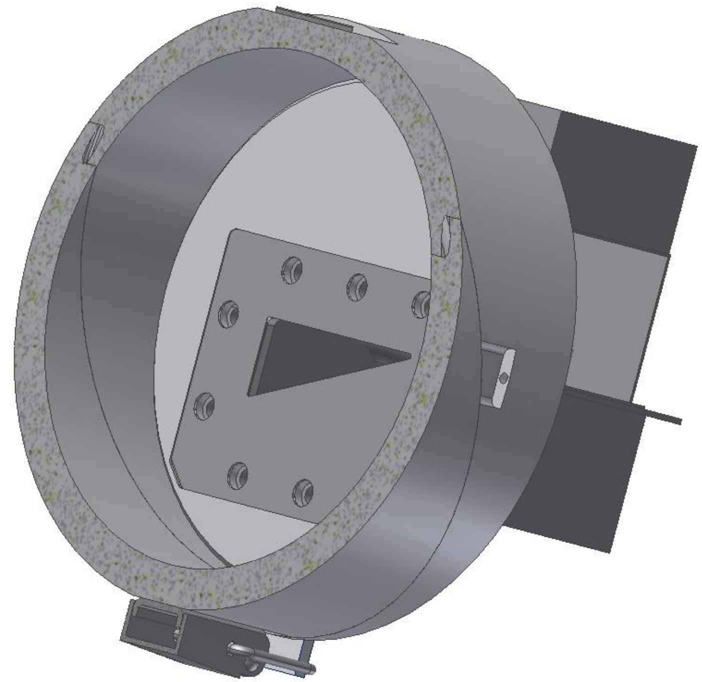


Resonant cavities

Interior of the cavitity
with sample holder

Prototype of microwave dryier





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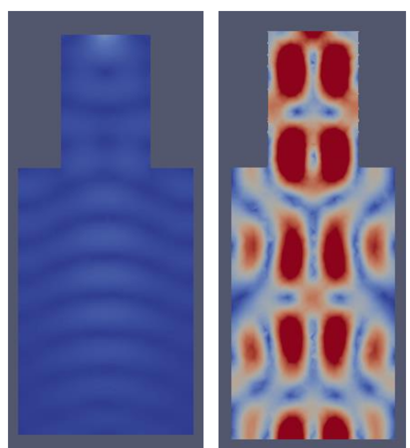
Prototype of microwave dryier

and the final product



RADWAG BALANCES AND SCALES
ADVANCED WEIGHING TECHNOLOGIES

Summary:

Microwave module for ELMER FEM is radical innovation.
It changed the world and the market of microwave modelling.

Microwave module for ELMER FEM **enabled small and medium companies** (like RADWAG) to participate in global market of high-tech products.

ELMER FEM is very flexible and easy to integrate in larger systems.
It is perfect environment for scientific research
– but this is another story.

Thank you very much for your attention.