SIMULATION METHODS FOR RF

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Outline

- **What are numerical simulations for?**
- **Using math algorithms for RF.**
- **Volume discretization and its issues.**
- **Simulations vs measurements.**
- **Setting up a problem in CST-MWS.**
- **Other related problems.**

Disclaimer

- **Great deal of the material for this presentation has been taken from seminars and talks from other people, specially my colleagues:**

  – Graeme Burt.

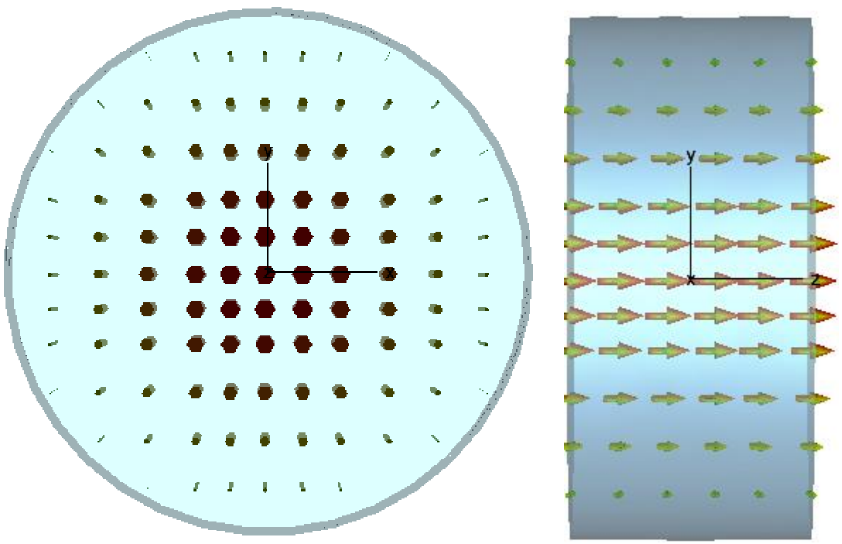
  – Subashini de Silva.

The Pillbox

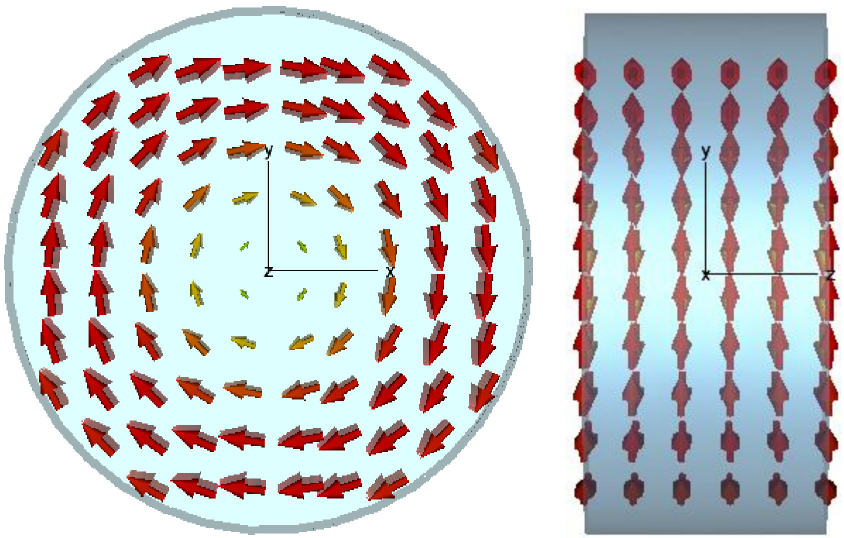
- $\mathbf{TM_{010}}$

$$\omega_0 = \frac{2.405c}{R}$$

Electric



Magnetic



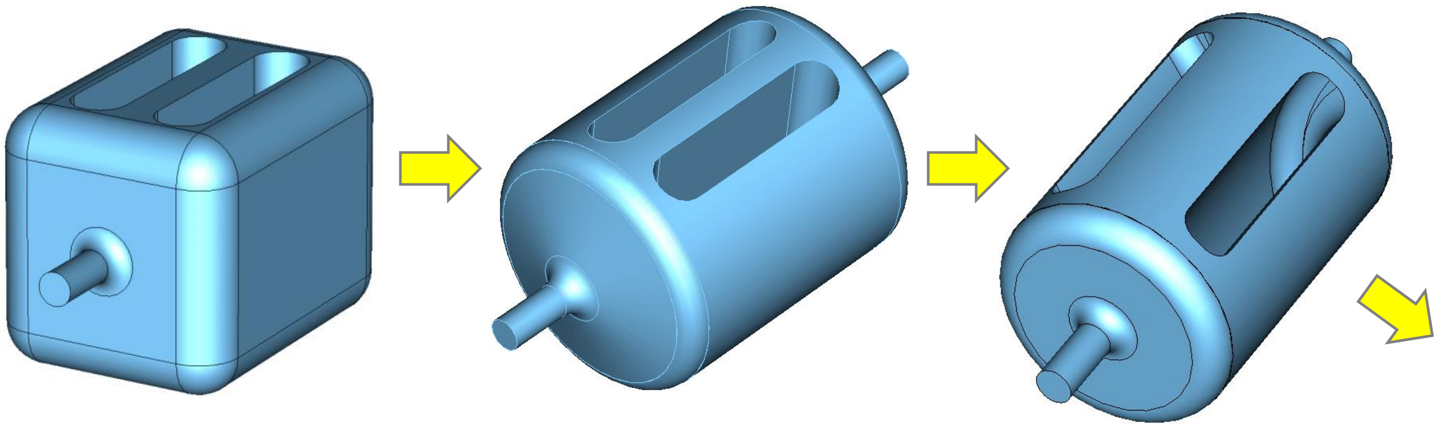
Cavity Design

- Accelerator components design
  - RF (radio frequency) cavity design for a variety of applications.
  - Power couplers, higher order mode couplers.
  - Using electromagnetic and mechanical simulators for performance analysis.

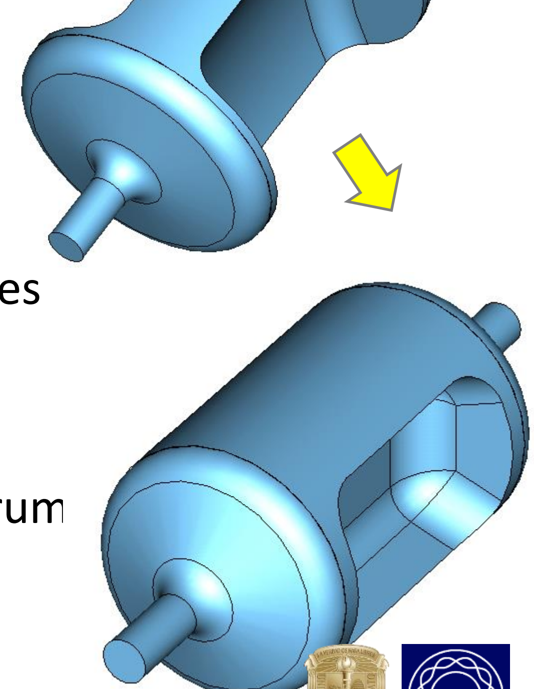
- Limitations:
  - Typically need multiple tools.
  - No good communication available between the tools.

*from S. U. de Silva, ODU.

Design Optimization



*from S. U. de Silva, ODU.



- Aspects of optimization
  - Lower and balanced peak surface fields
  - Stability of the design
    - ➢ Cylindrical shape is preferred to reduce flat surfaces
  - Cavity processing
    - ➢ Curved end plates for cleaning the cavity
  - Wider separation in Higher Order Mode (HOM) spectrum
  - Multipacting

Numerical Solution of Maxwell's Equations

- Analytical solutions to Maxwell's equations bounded in a cavity are practical for only a few simple cases, instead we solve numerically.
- Most numerical EM codes solve the Helmholtz equation but can be split into two types.

$$\left(\nabla^2 + k^2\right)\Phi = 0$$

Approximate operator
Finite Difference Method

Approximate function
Finite Element Method

*from G. Burt, Lancaster University.

Types of EM solvers

- Finite Difference (Approximate operator)
- Finite Element (Approximate function)
- Boundary Element (uncommon, uses Green's functions)
- Finite Volume (no commercial codes, ignored here)

- Frequency Domain (solve at discrete frequencies)
- Time Domain (solve at time steps)
- Eigenmode (solve for resonant orthonormal eigenmodes of the system)

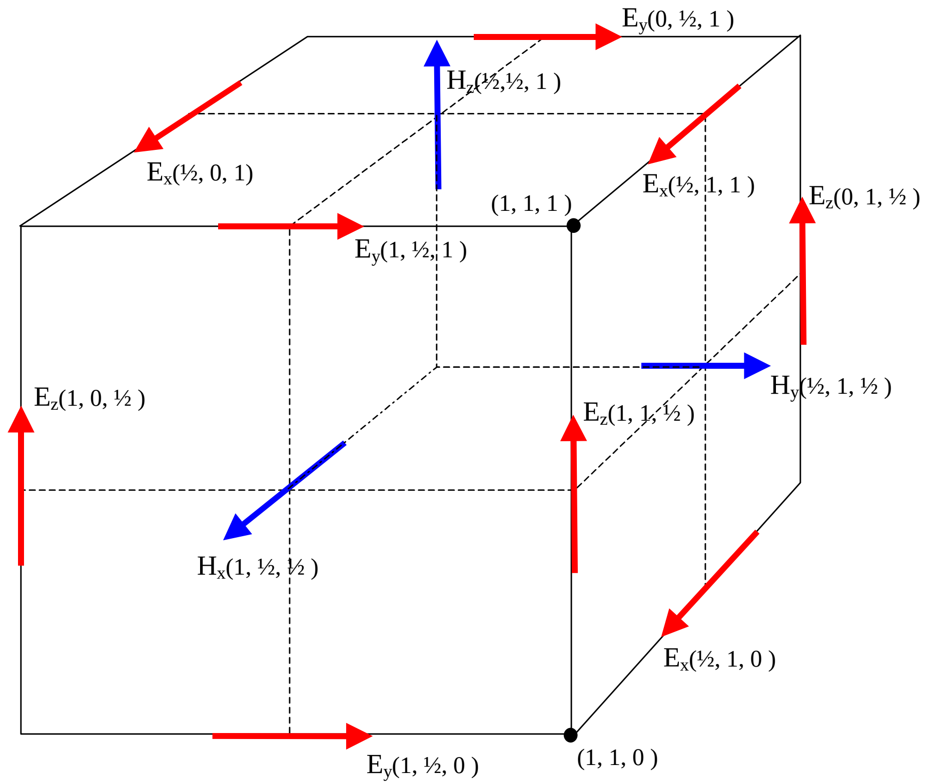
*from G. Burt, Lancaster University.

Yee Cell

Discretise the fields onto a conformal mesh then assume no variation over the unit cell edges.

$$\oint \underline{E} \cdot \underline{dr} = -\frac{\partial}{\partial t} \int \underline{B} \cdot \underline{dS}$$

Becomes (for each face)

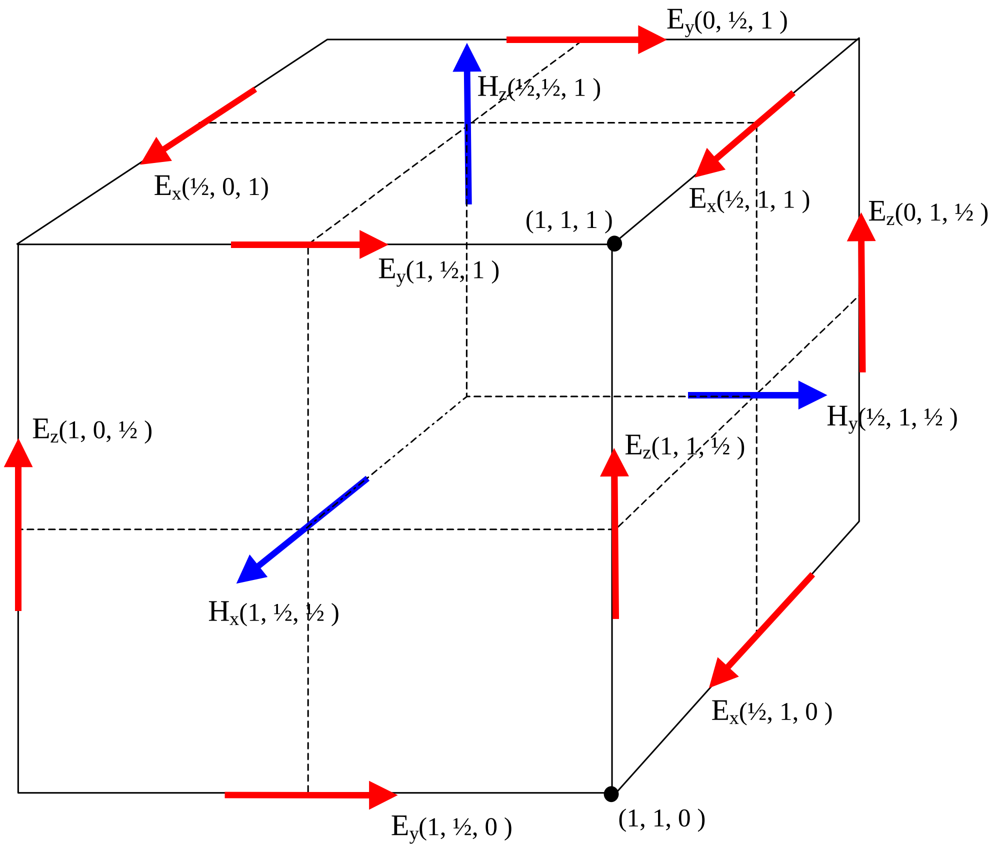


$$B_x\left(t+\tfrac{1}{2}\delta t,\ x+\delta x,\ y+\tfrac{1}{2}\delta y,\ z+\tfrac{1}{2}\delta z\right) = B_x\left(t,\ x+\delta x,\ y+\tfrac{1}{2}\delta y,\ z+\tfrac{1}{2}\delta z\right)$$
$$-\frac{\delta t}{2\delta y}\left\{E_z\left(t,\ x+\delta x,\ y+\delta y,\ z+\tfrac{1}{2}\delta z\right)-E_z\left(t,\ x+\delta x,\ y,\ z+\tfrac{1}{2}\delta z\right)\right\}$$
$$+\frac{\delta t}{2\delta z}\left\{E_y\left(t,\ x+\delta x,\ y+\tfrac{1}{2}\delta y,\ z+\delta z\right)-E_y\left(t,\ x+\delta x,\ y+\tfrac{1}{2}\delta y,\ z\right)\right\}$$

*from G. Burt, Lancaster University.

Surface Fields

- As E and H fields are solved on separate grids each a half mesh step apart you can only solve one field at the boundary
- The other field has to be interpolated which can lead to errors

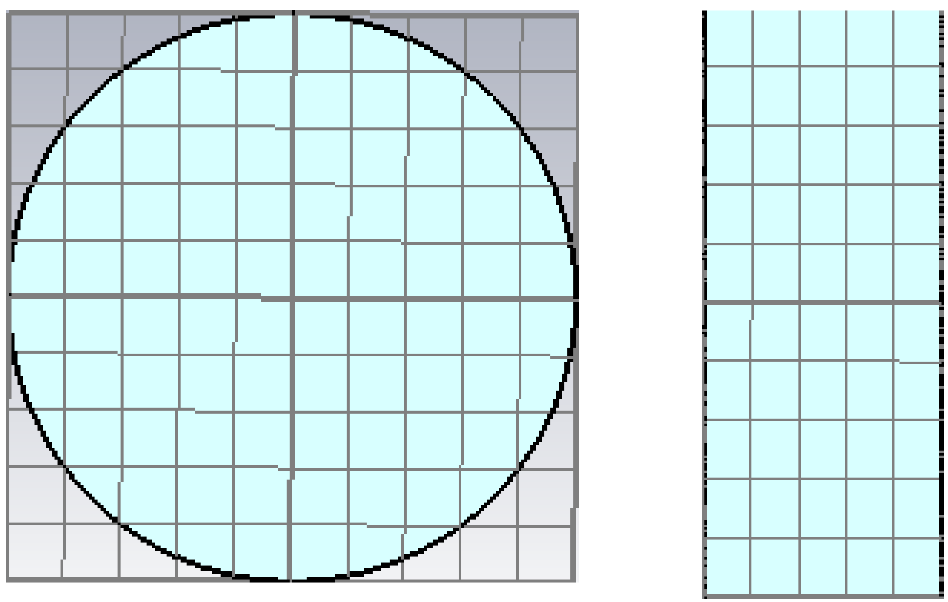


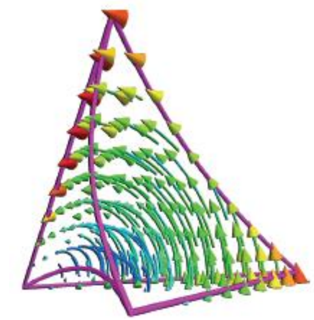
*from G. Burt, Lancaster University.

EM & Volume Discretisation

- The volume is discretized using Hexahedral (simplest) or Tetrahedral cells (better approximation).

Hexahedral



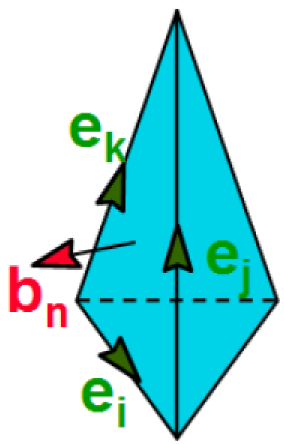


Tetrahedral

EM & Volume Discretisation

- Calculation of resonant modes and rf properties of complex electromagnetic structures.

- Solve Maxwell's Equations:
  - Using finite element method (FIT).



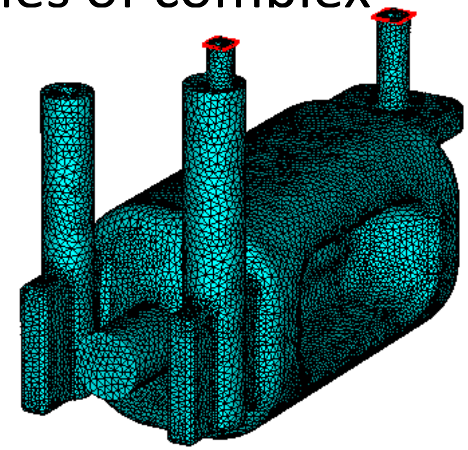
$$\oint_{\partial A_j} \vec{E}\cdot d\vec{s} = -\frac{\partial}{\partial t}\iint_{A_j} \vec{B}\cdot d\vec{A}$$

$$e_i + e_j - e_k = -\frac{\partial}{\partial t} b_n$$

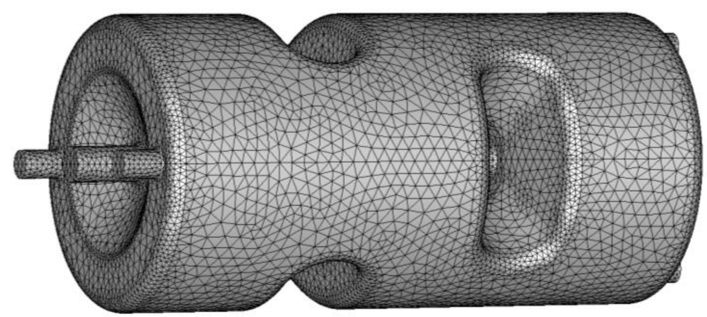
e_i : electrical voltage

b_j : magnetic flux

*from S. U. de Silva, ODU.

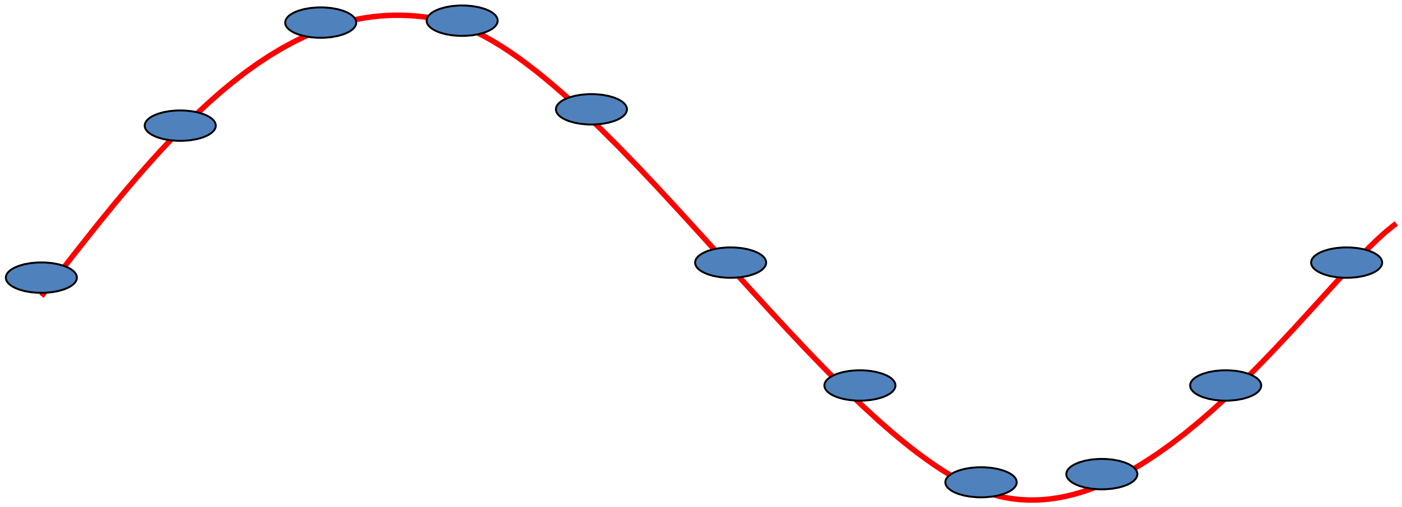


400 MHz, rf-dipole crabbing cavity (531,000 total tetrahedrons)



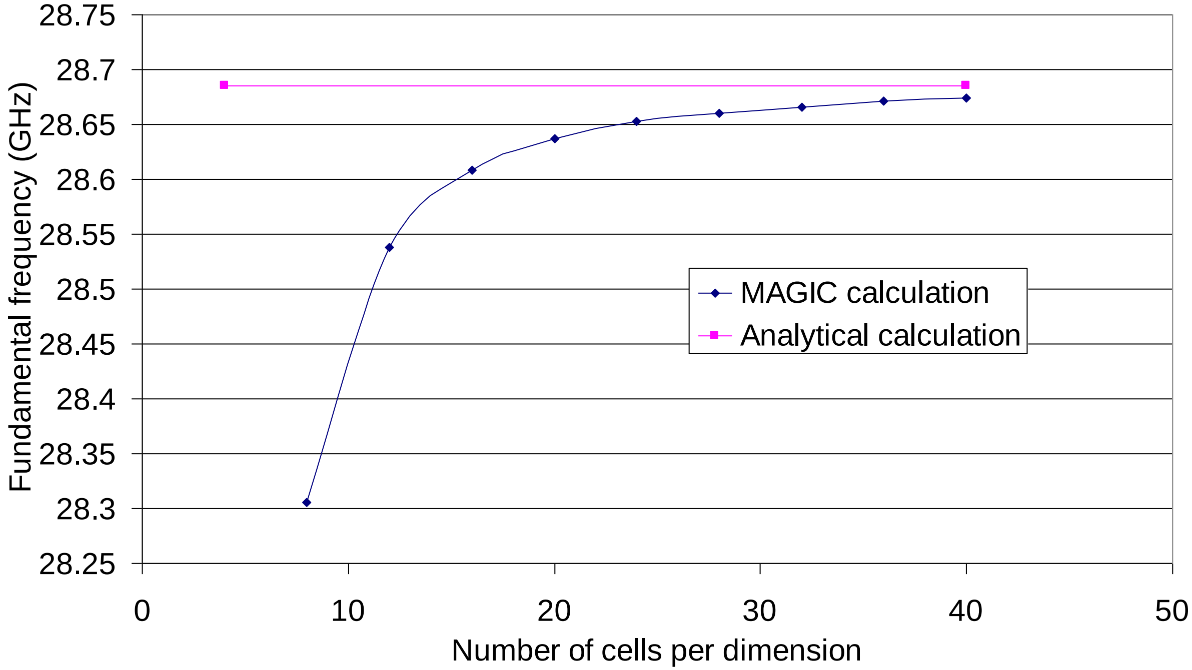
500 MHz, $\beta_0 = 1$ double-spoke cavity (168,000 total tetrahedrons)

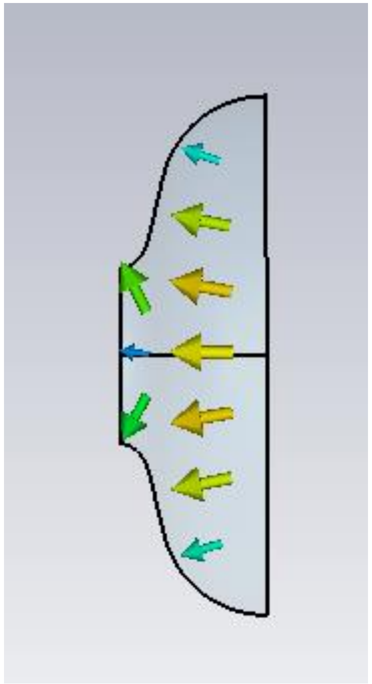
How many points are required to define a wavelength?



*from G. Burt, Lancaster University.

How mesh size effects simulation

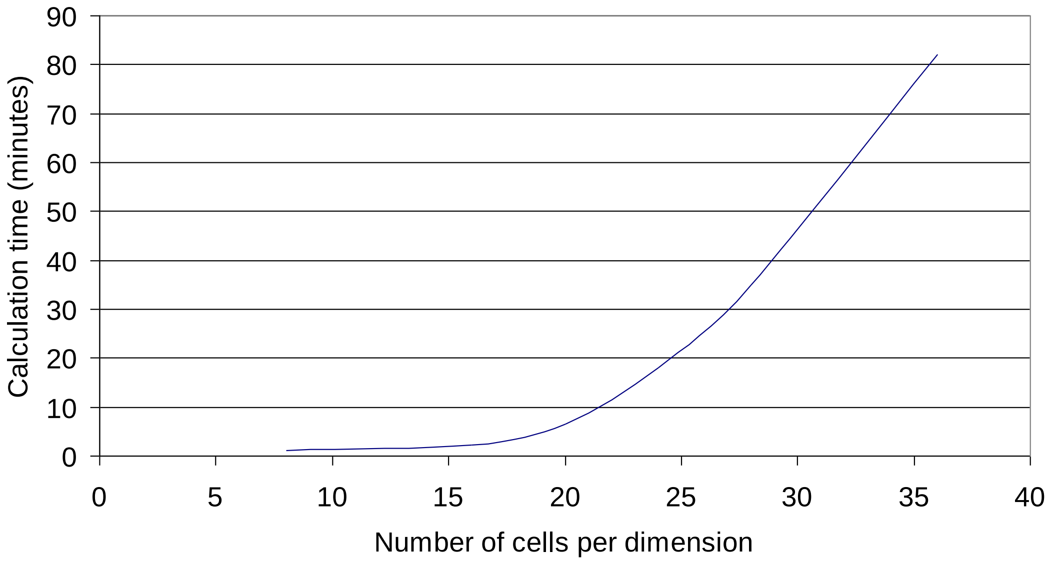


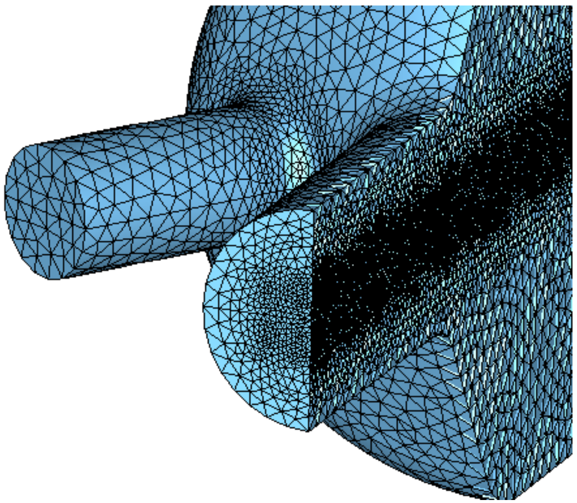


The accuracy of your results is dependant on the mesh density. In order to test your code you should increase the mesh with various runs until the results do not vary with mesh size.

*from G. Burt, Lancaster University.

How mesh size effects simulation



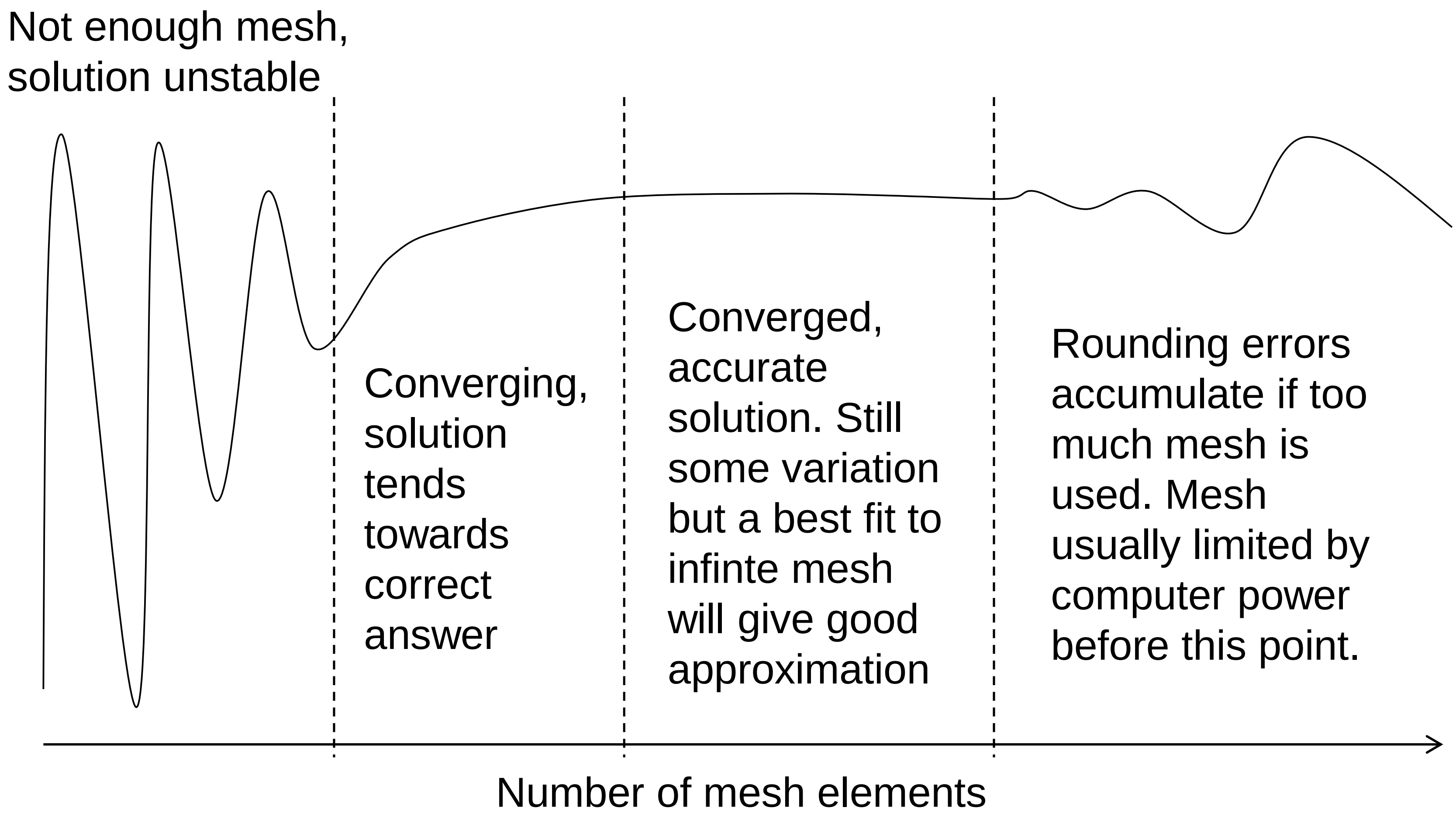


Beware! The run time of your simulation also increases.

Runtime is roughly proportional to the number of mesh cells in the simulation, or the number of cells per dimension cubed, N^3

*from G. Burt, Lancaster University.

Mesh Stability

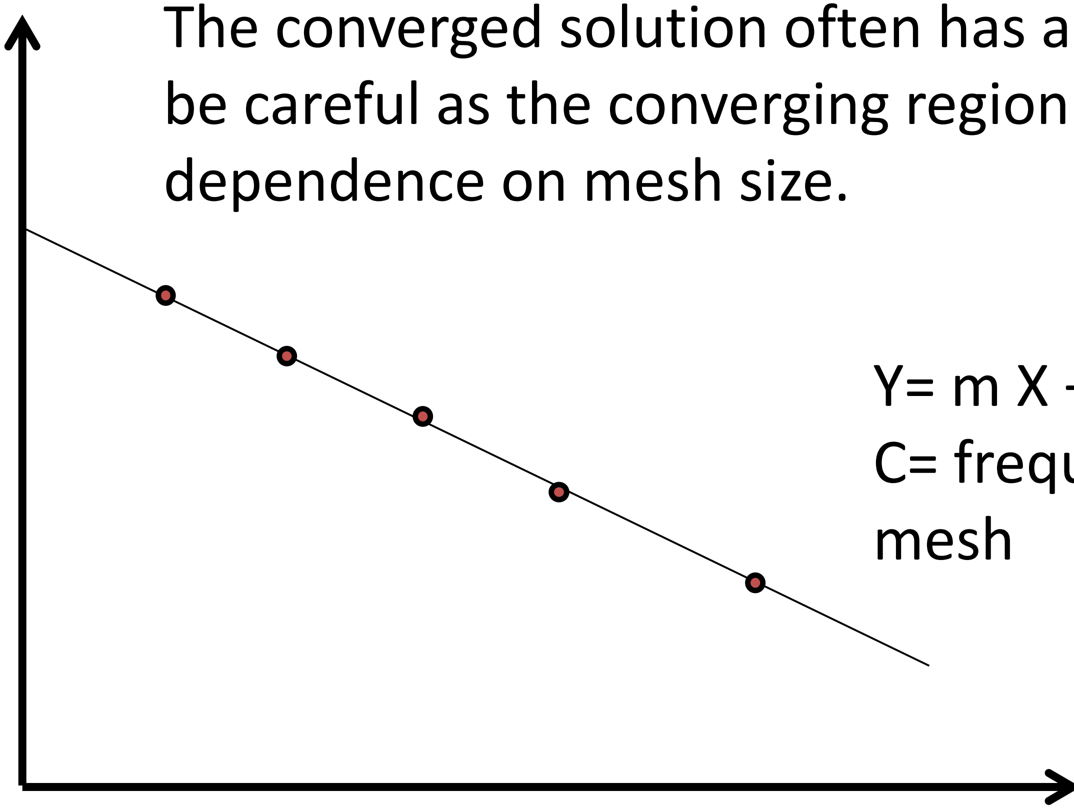


*from G. Burt, Lancaster University.

A cunning trick

The converged solution often has a linear trend, but be careful as the converging region has a quadratic dependence on mesh size.

frequency



Y= m X + C

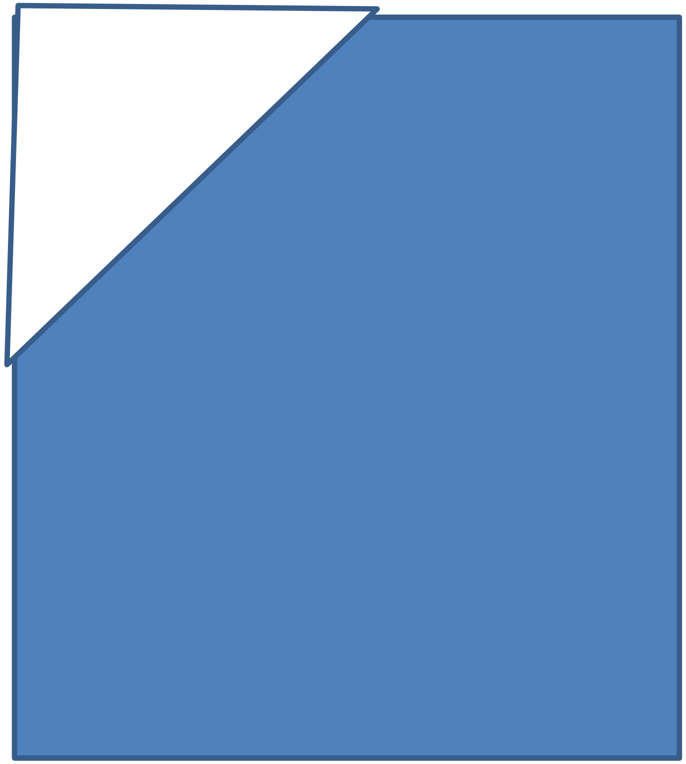
C= frequency at infinite mesh

1 / No of Mesh elements or average cell size

*from G. Burt, Lancaster University.

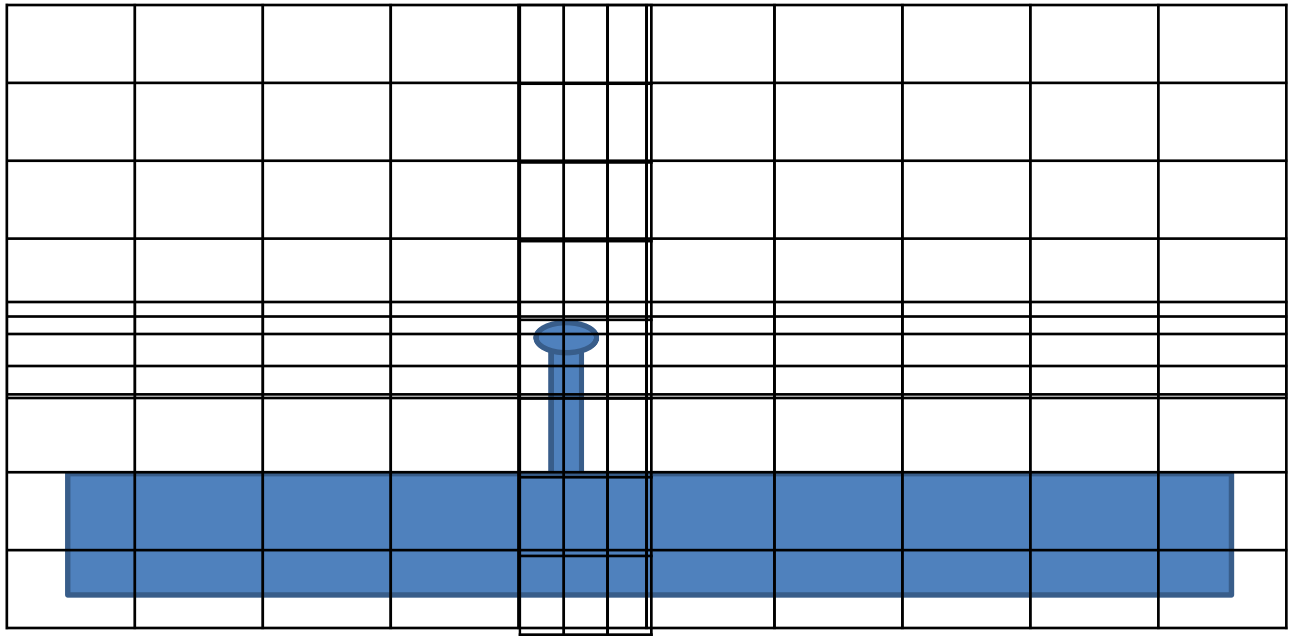
Perfect Boundary Approximations

- Corrections can be applied to the Yee Algorithm to account for a single cut across a cell.
- This is known as the Perfect Boundary Approximation (CST) or Dey-Mitra Algorithm (VORPAL).
- Not an exact solution so has some issues.
- The cut reduces the cell size so Courant conditions require smaller time steps.



*from G. Burt, Lancaster University.

Mesh refinement

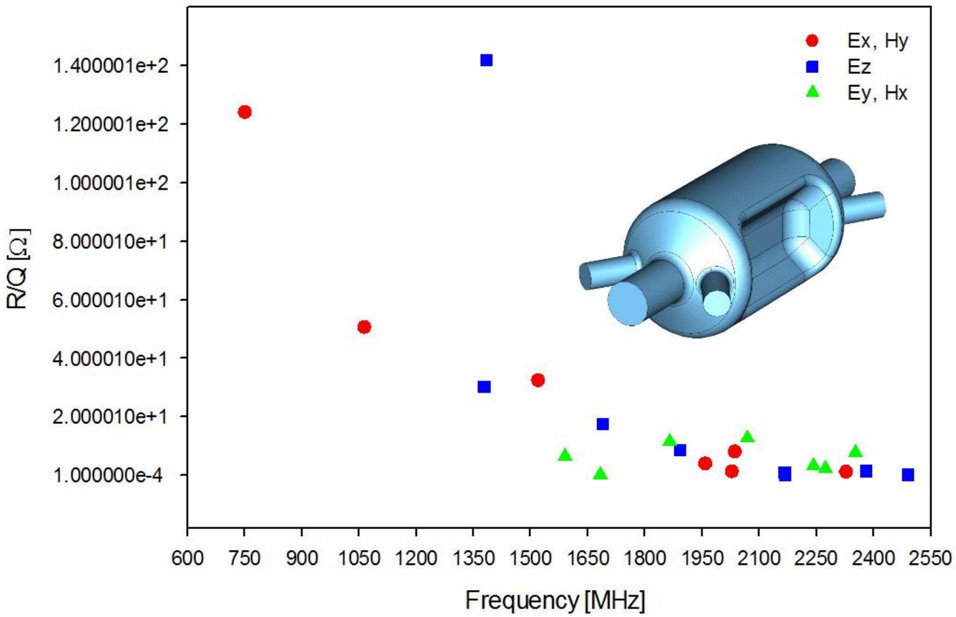


One drawback of a conformal mesh is you cannot refine the mesh at critical points without refining the mesh along a cross pattern in all directions.

*from G. Burt, Lancaster University.

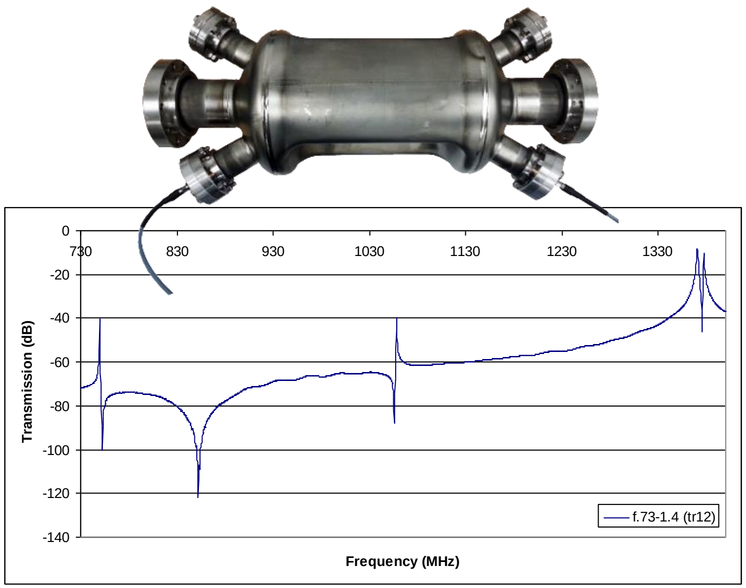
750 MHz CC Trimming Results

Calculated



- **df/dz per total length**
  – calculated: -0.46769 MHz/mm
  – measured: -0.46299 MHz/mm

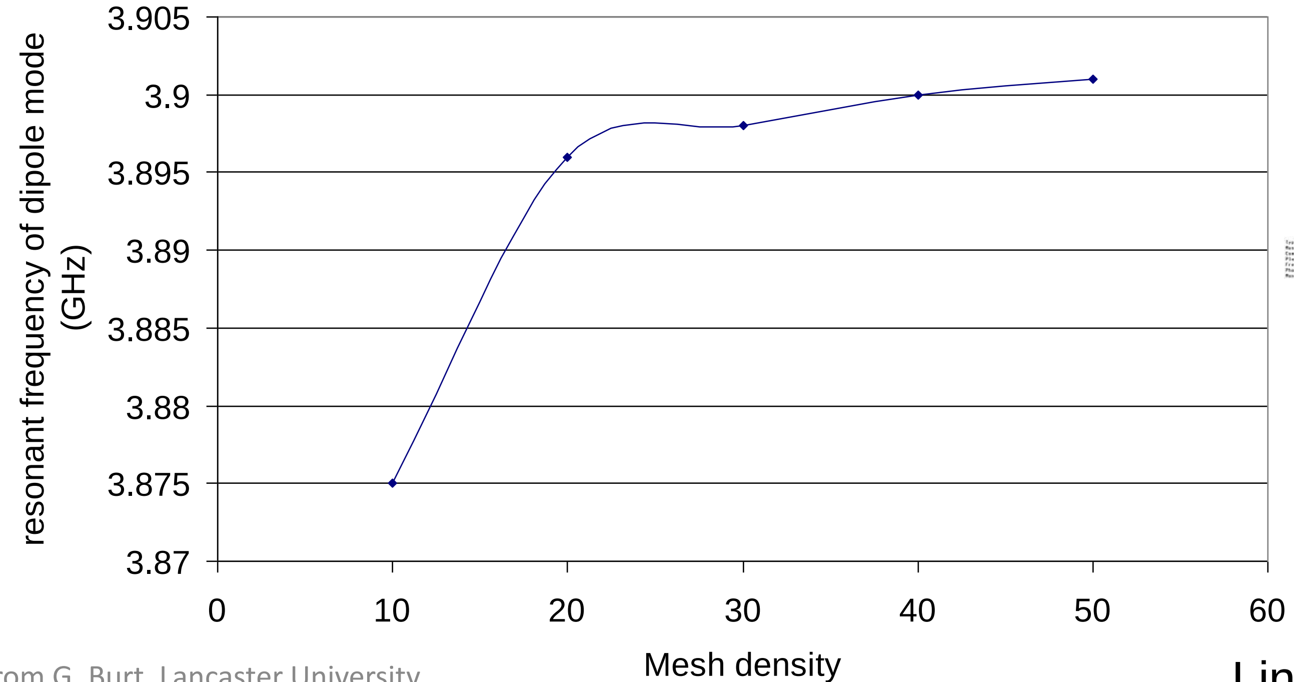
Measured

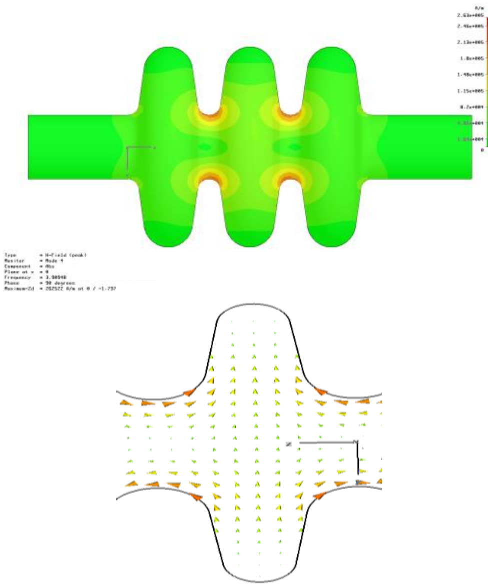


Mode	f (MHz)	Q	Loss (dB)
1	749.492	5600	-53
2	1058.027	6900	-37
3	1370.410	1200	-16
4	1377.506	2000	-19

Real results-Resonant frequency

The particle have a set separation and should all arrive at the same phase hence the cavity frequency must be known. The results start to converge at about 40 lines per wavelength.





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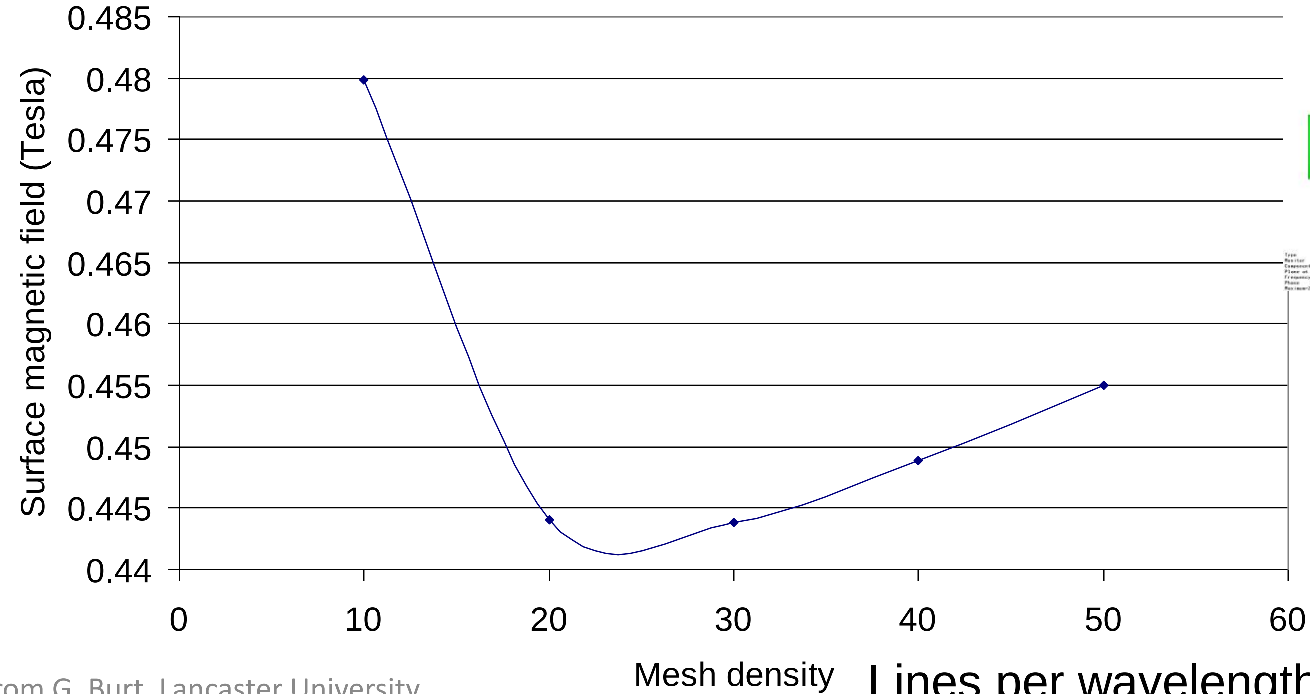
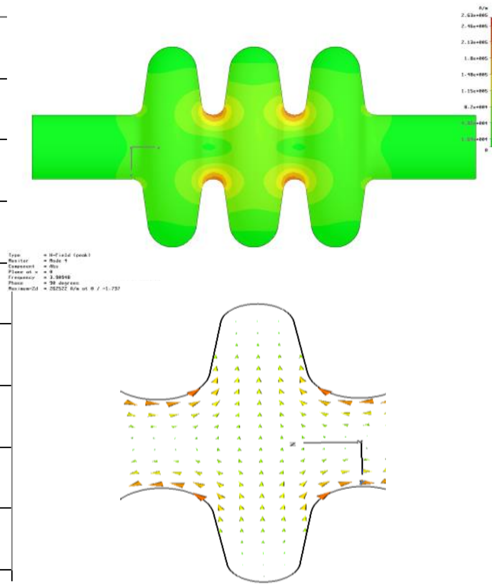
Lines per wavelength

Real results-Magnetic field

The surface magnetic field can cause a superconducting cavity to become normal conducting. The mesh density doesn't just effect the resonant frequency it can also effect fields.



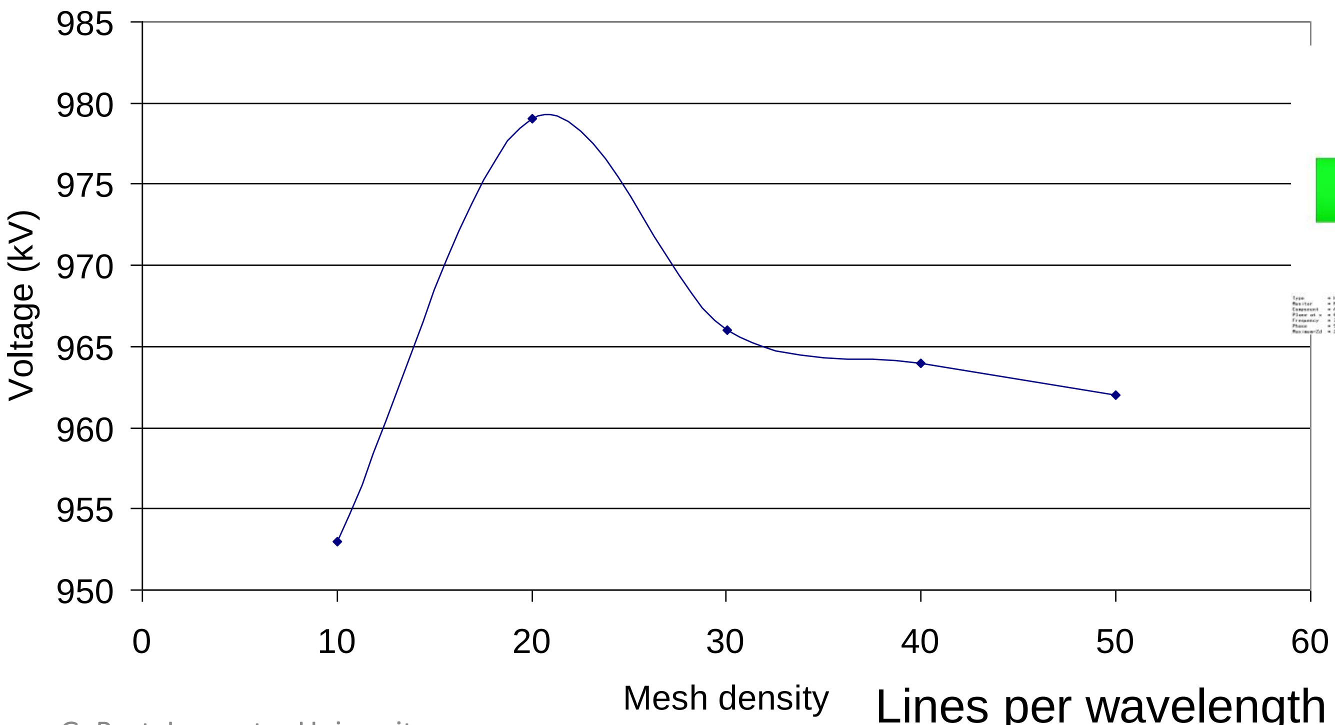


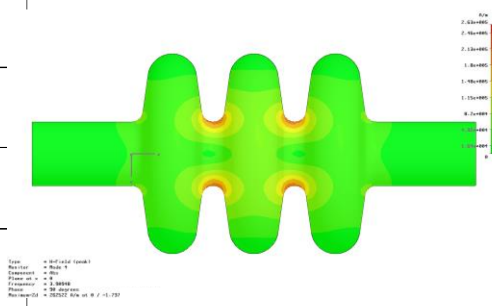
Lines per wavelength

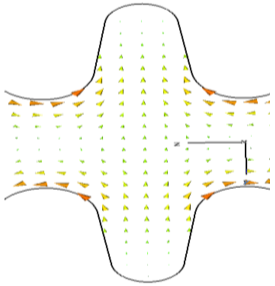
*from G. Burt, Lancaster University.

Real results- Voltage

In particle physics the cavity voltage is the Electric field seen by a particle travelling at the speed of light integrated over the cavity length.



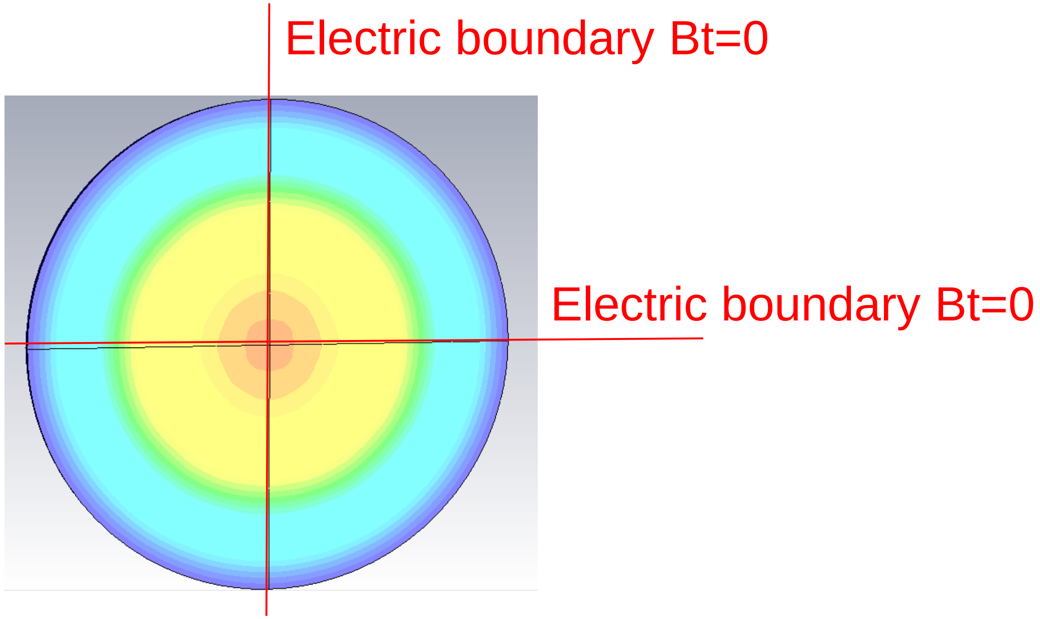




*from G. Burt, Lancaster University.

Symmetry Planes

- Most RF structures have axis of symmetry (both in field and geometry)
- We can make use of image charges and currents in walls to make our simulations smaller by applying boundary conditions to these symmetry planes.



*from G. Burt, Lancaster University.

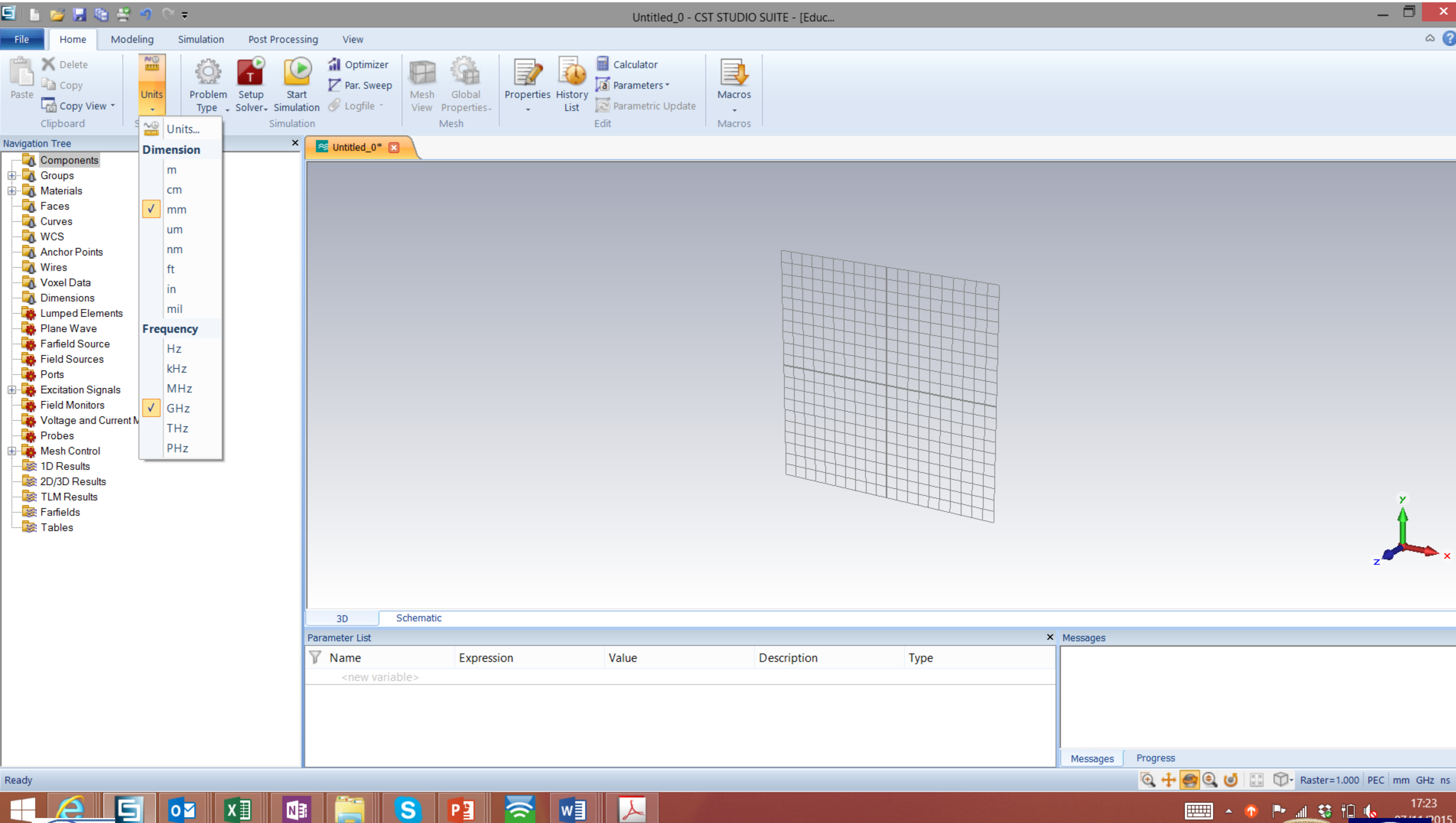
Setting up a Pillbox in CST Microwave Studio

Required Steps

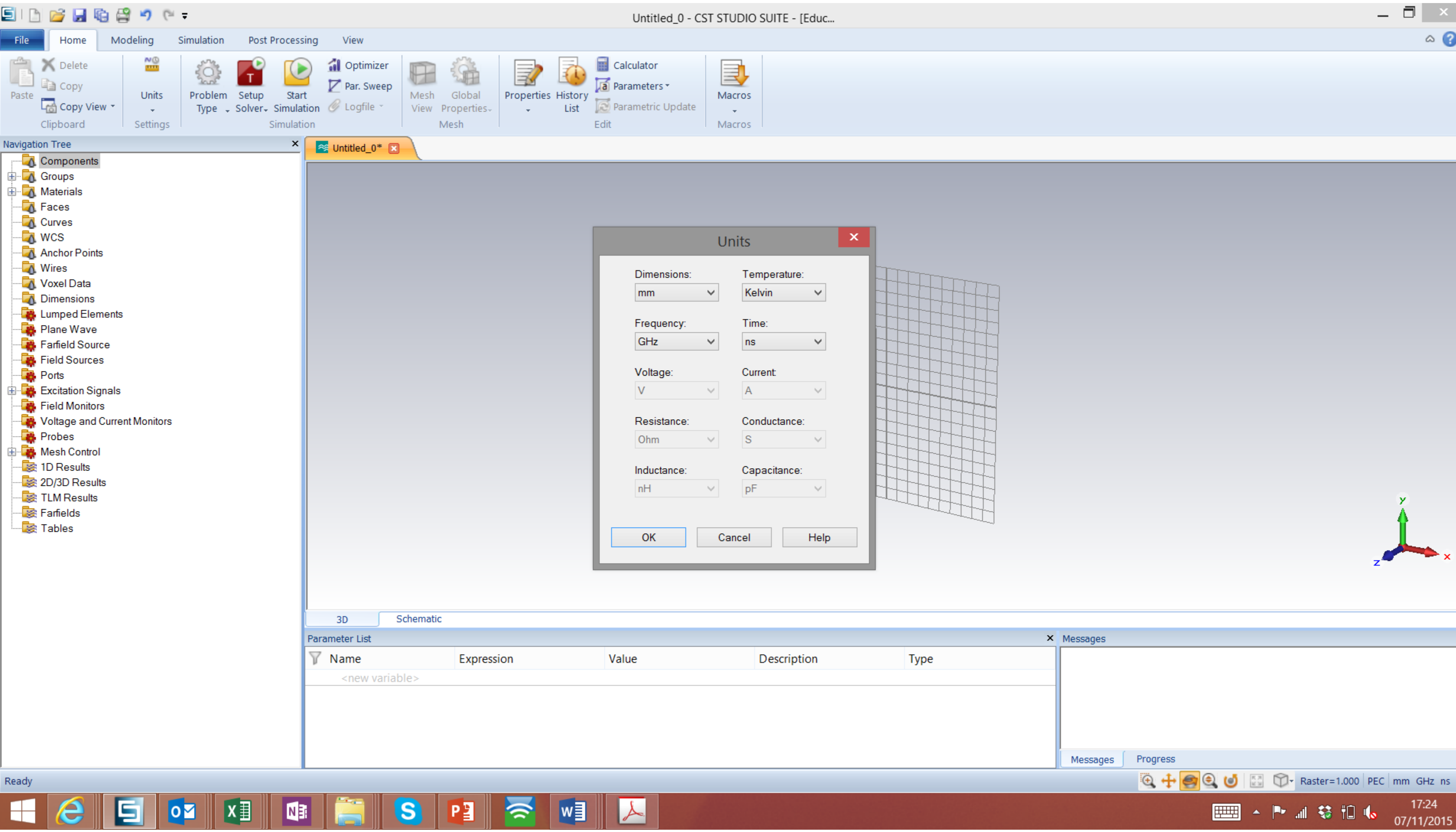
- Choose Units and background material
- Draw Geometry
- Set Boundary conditions and symmetry planes
- Set frequency Range
- Set mesh
- Set up Ports if required
- Add any monitors
- Run the simulation
- Post-processing

*from G. Burt, Lancaster University.

Getting Started



A. Castilla, MEPAS2.0 Gto. Mex. 11^{th} – 21^{st} Nov. 2015 *from G. Burt, Lancaster University.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Global Properties
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History List
Calculator
Parameters
Parametric Update
Edit
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Navigation Tree
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WCS
Anchor Points
Wires
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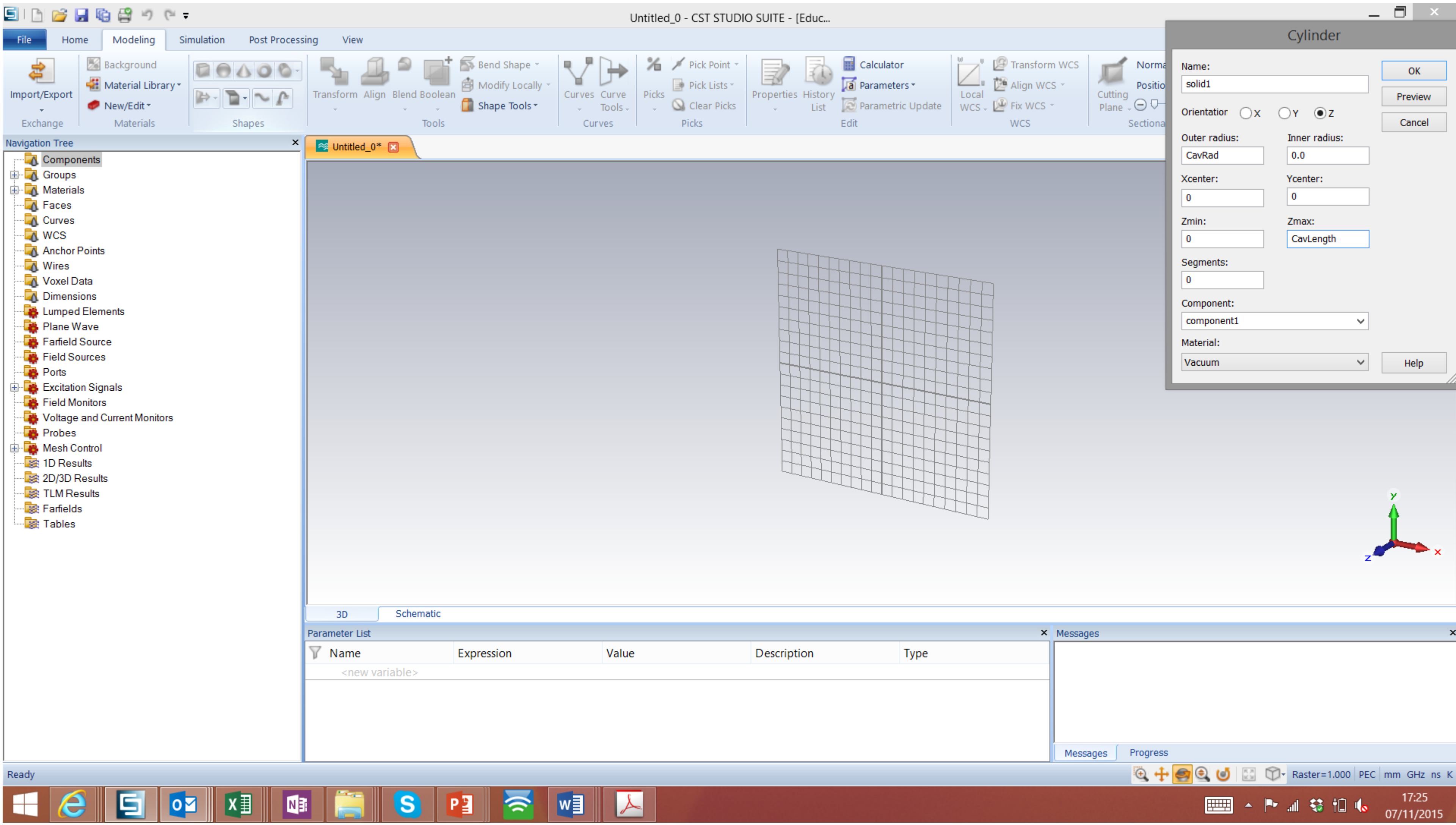
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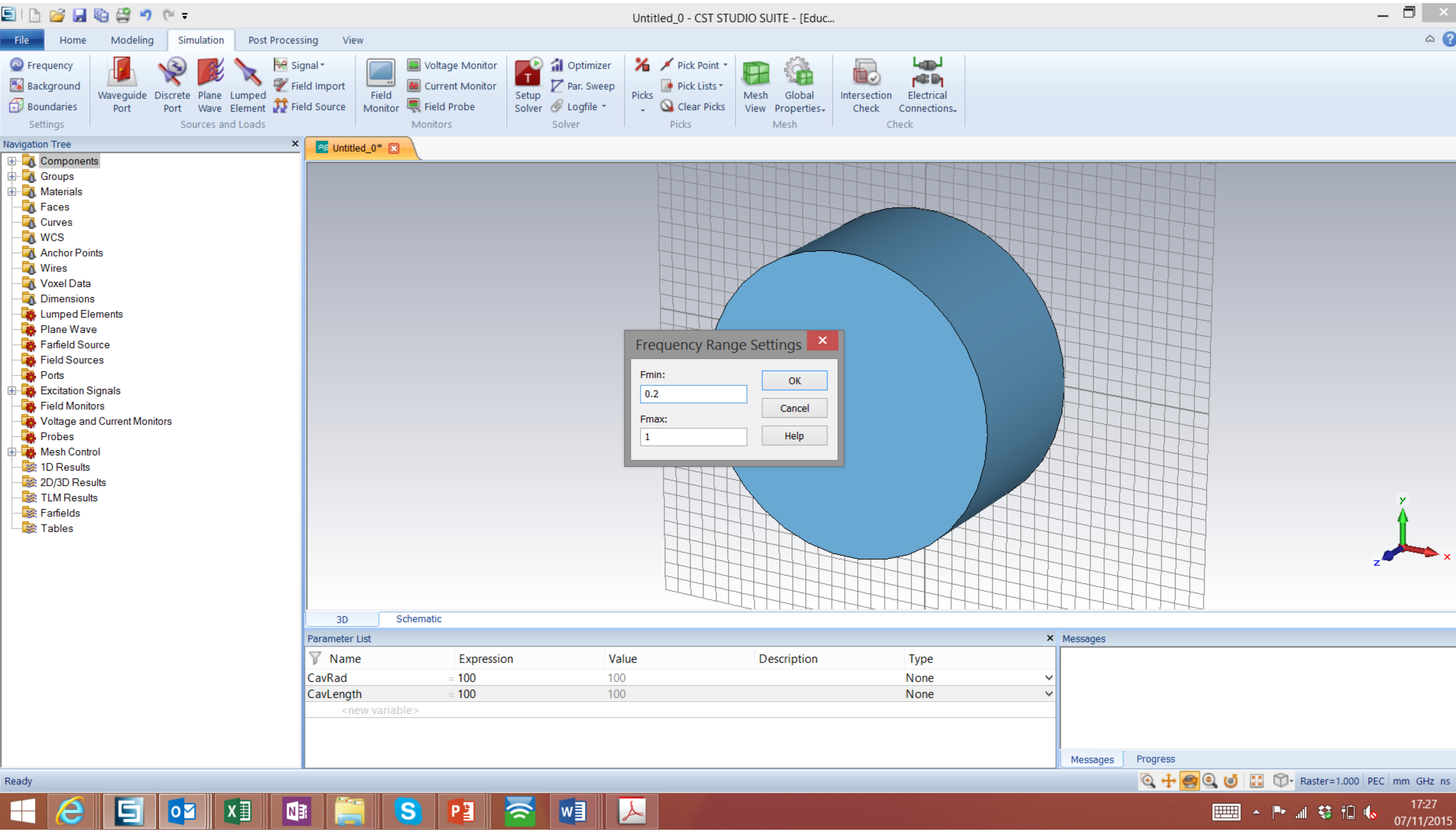
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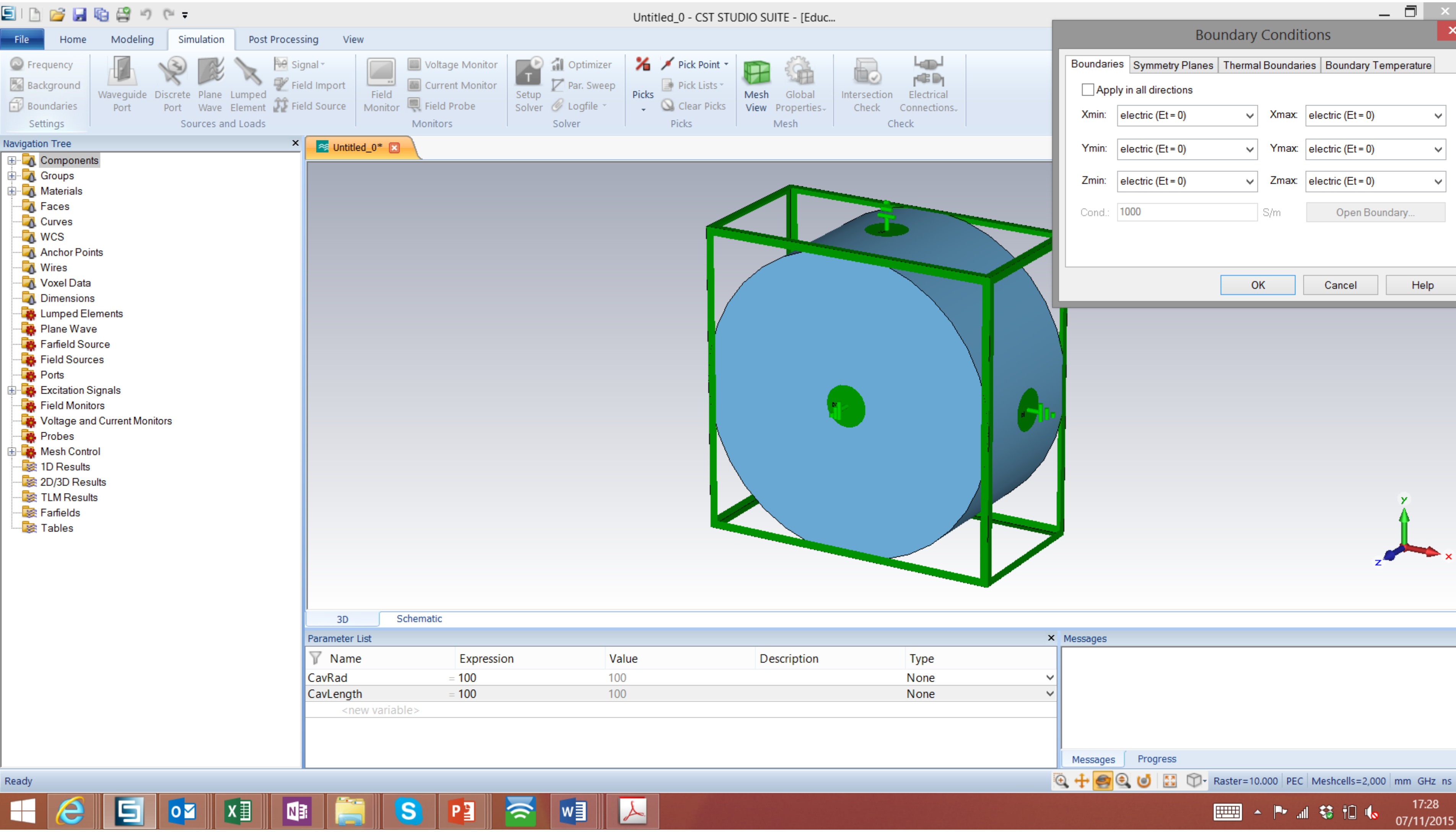

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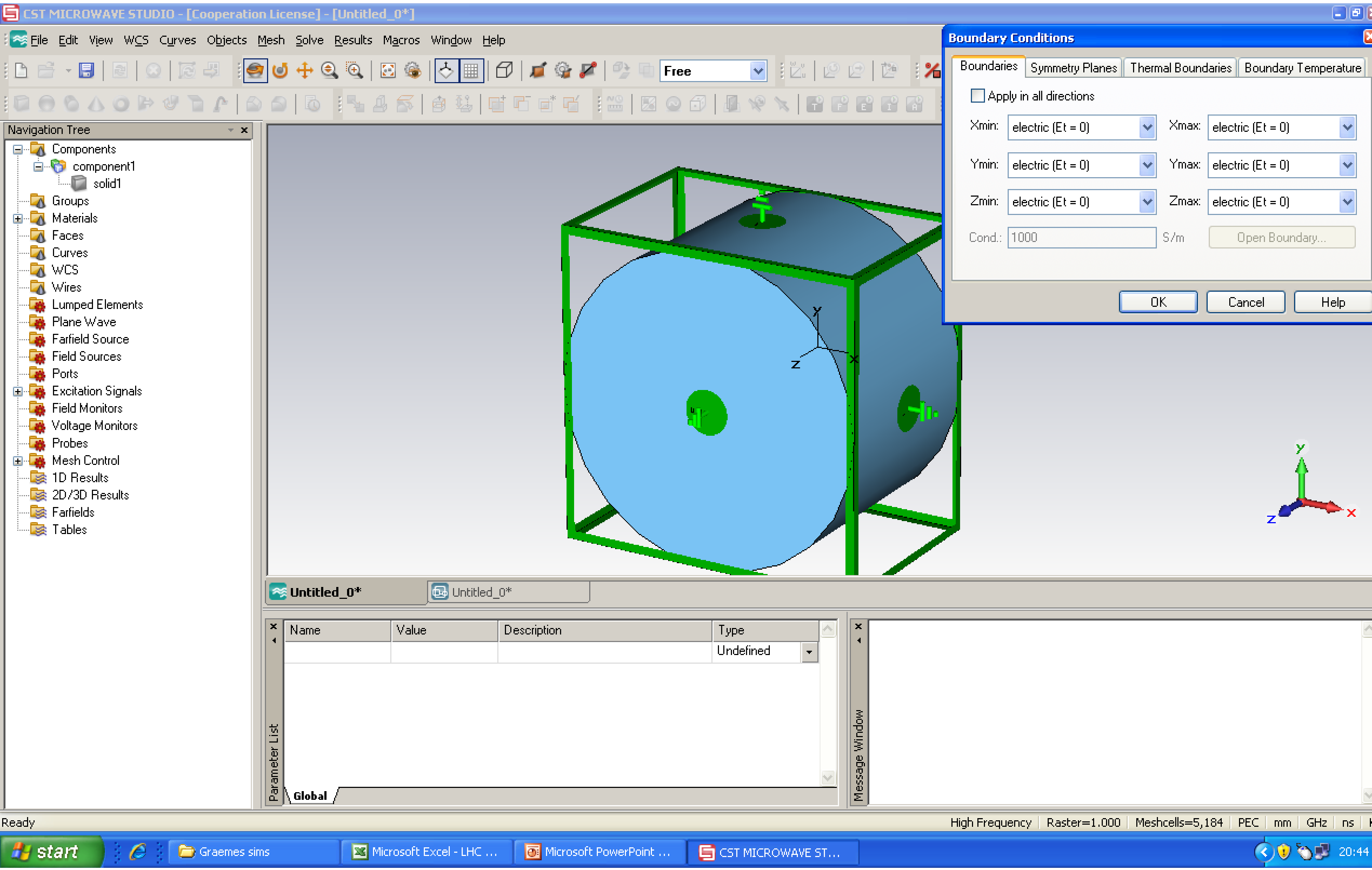

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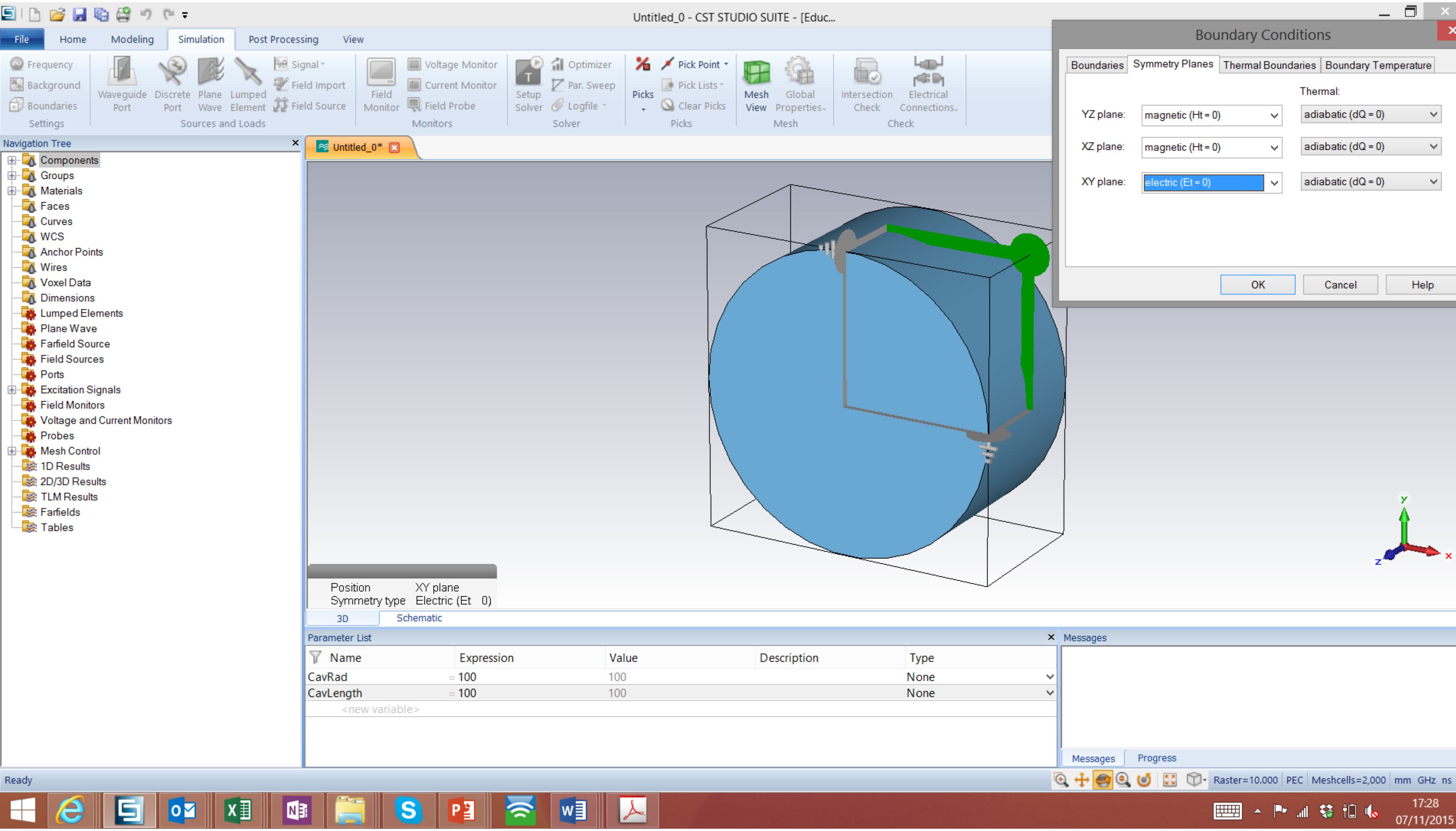
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Boundary Conditions
Boundaries
Symmetry Planes
Thermal Boundaries
Boundary Temperature
Thermal:
YZ plane:
magnetic (Ht = 0)
adiabatic (dQ = 0)
XZ plane:
magnetic (Ht = 0)
adiabatic (dQ = 0)
XY plane:
electric (Et = 0)
adiabatic (dQ = 0)
OK
Cancel
Help
Position XY plane
Symmetry type Electric (Et 0)
3D
Schematic
Parameter List
Name Expression Value Description Type
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CavLength = 100 100 None
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Messages
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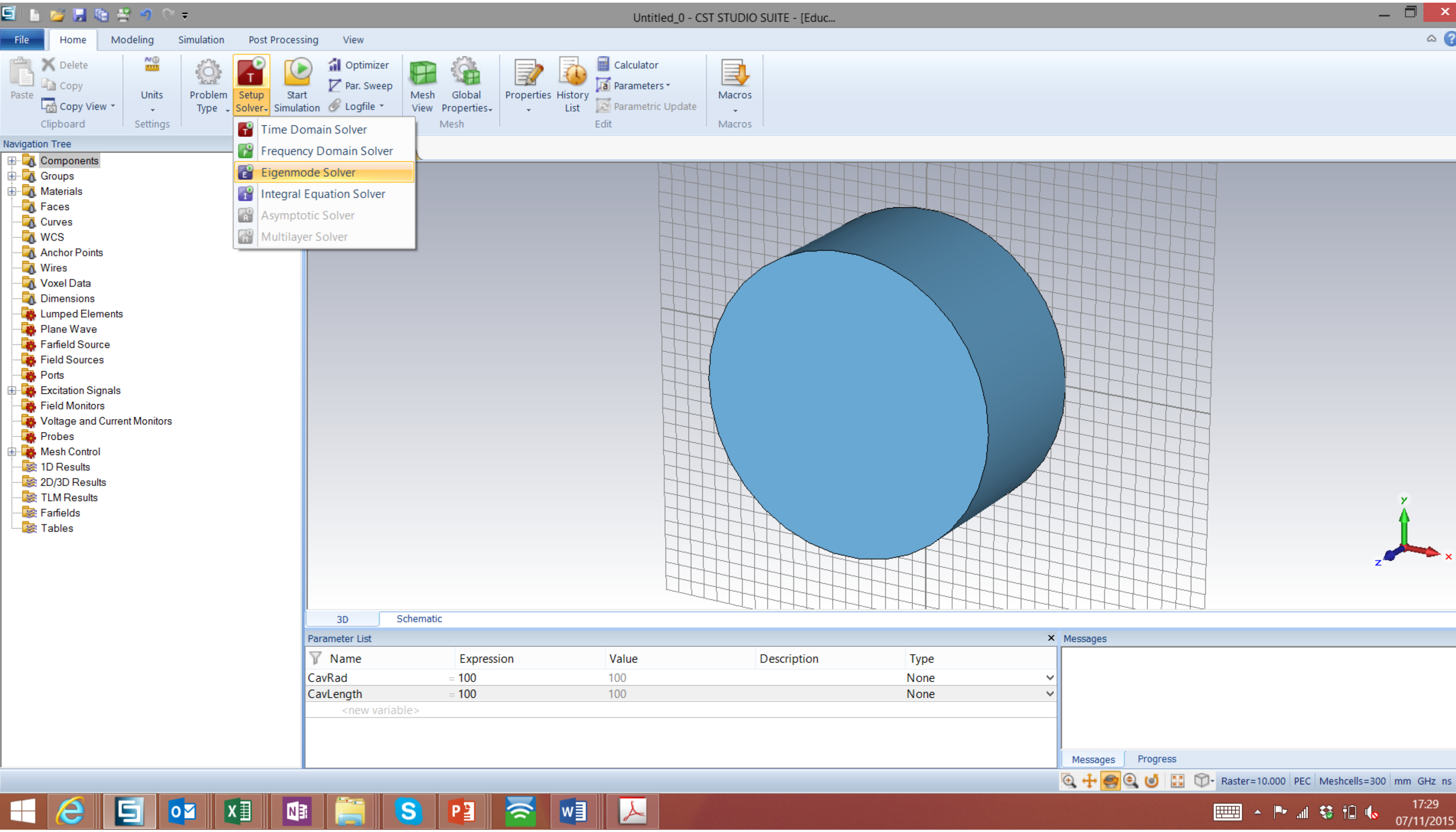
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Frequency Domain Solver
Eigenmode Solver
Integral Equation Solver
Asymptotic Solver
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Excitation Signals
Field Monitors
Voltage and Current Monitors
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1D Results
2D/3D Results
TLM Results
Farfields
Tables
3D
Schematic
Parameter List
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CavLength
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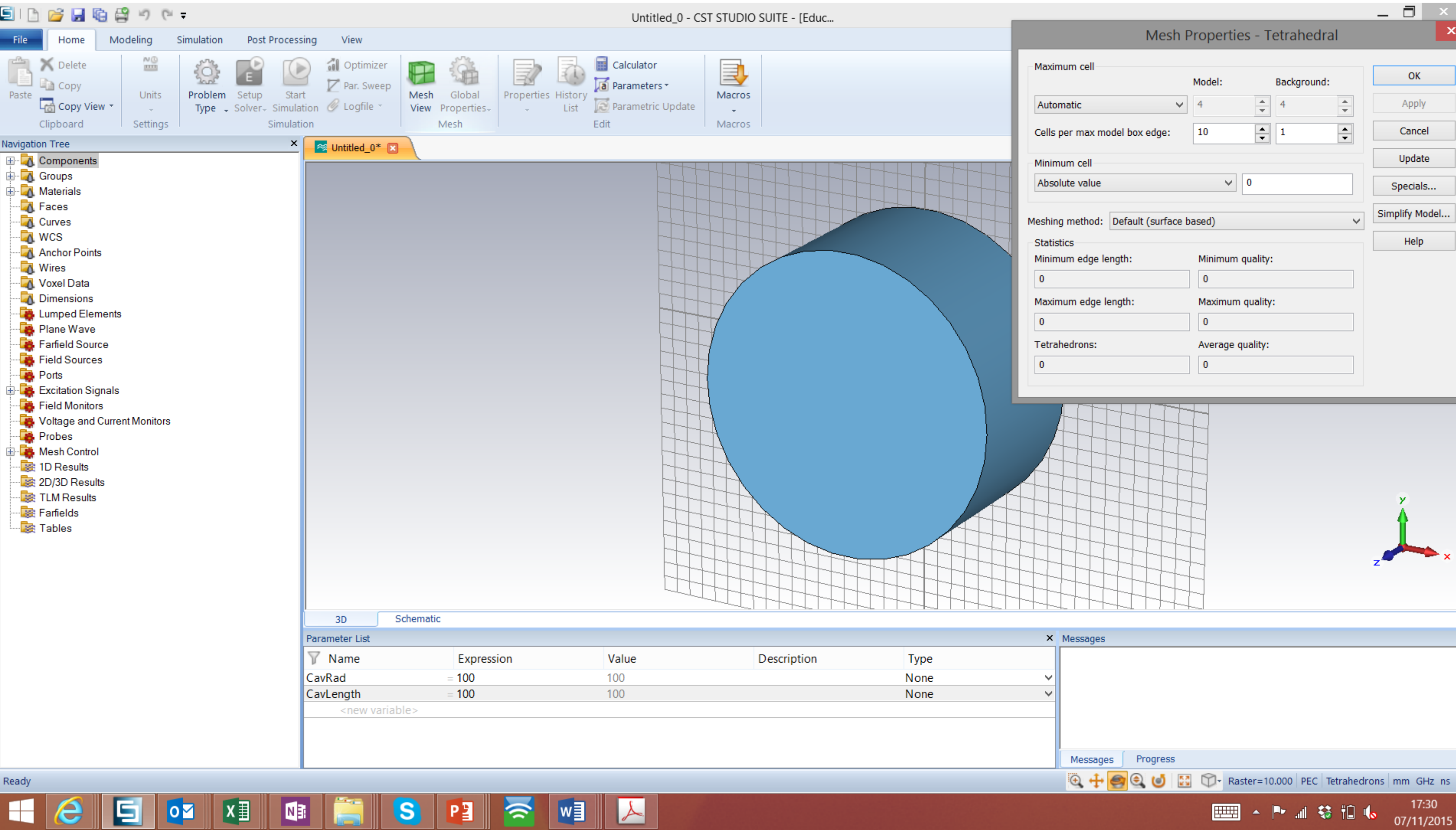
07/11/2015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Probes
Mesh Control
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2D/3D Results
TLM Results
Farfields
Tables
Untitled_0*
3D
Schematic
Mesh Properties - Tetrahedral
Maximum cell
Model:
Background:
Automatic
Cells per max model box edge:
10
1
Minimum cell
Absolute value
0
Meshing method:
Default (surface based)
Statistics
Minimum edge length:
Minimum quality:
Maximum edge length:
Maximum quality:
Tetrahedrons:
Average quality:
OK
Apply
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Update
Specials...
Simplify Model...
Help
Parameter List
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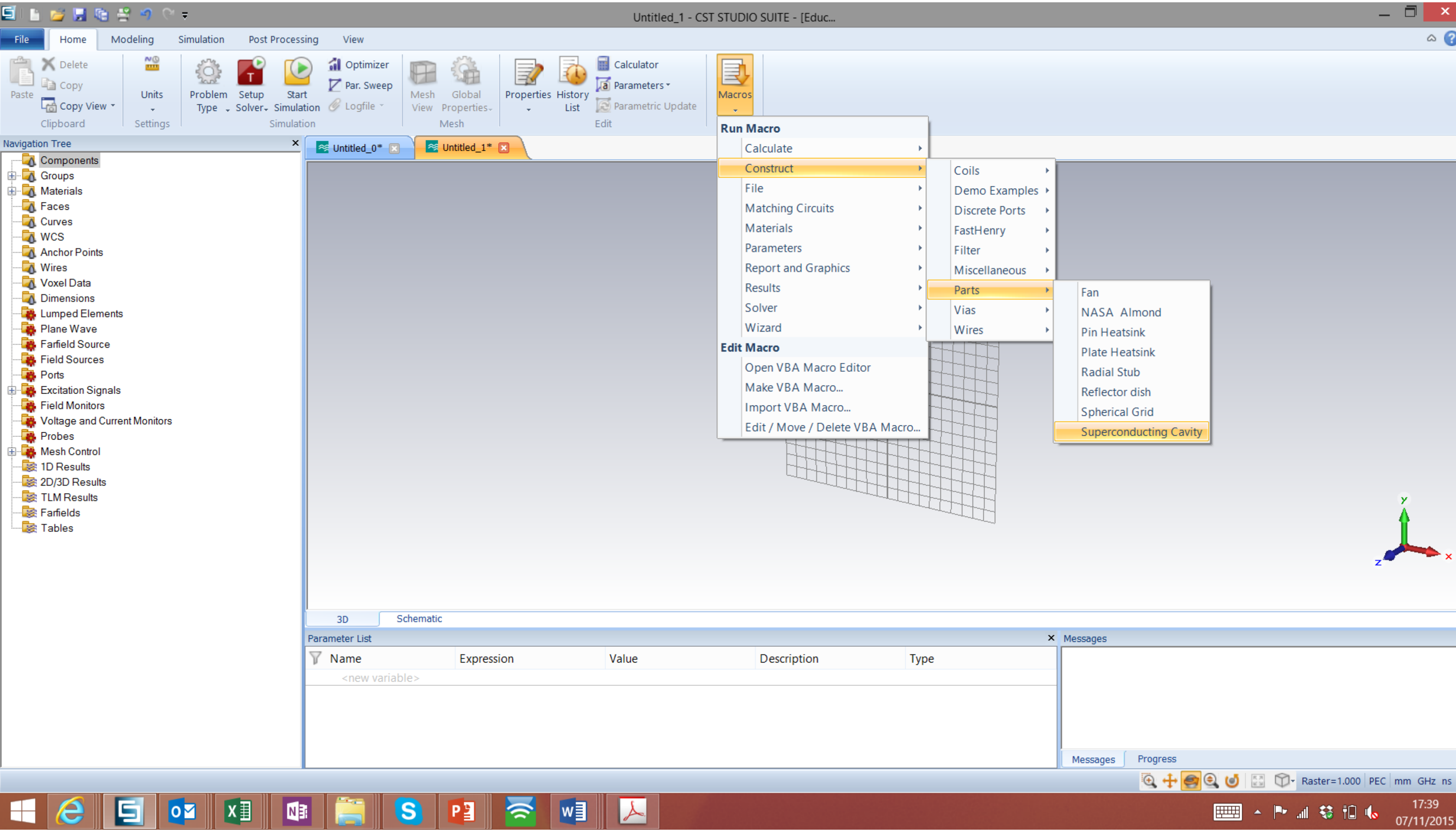
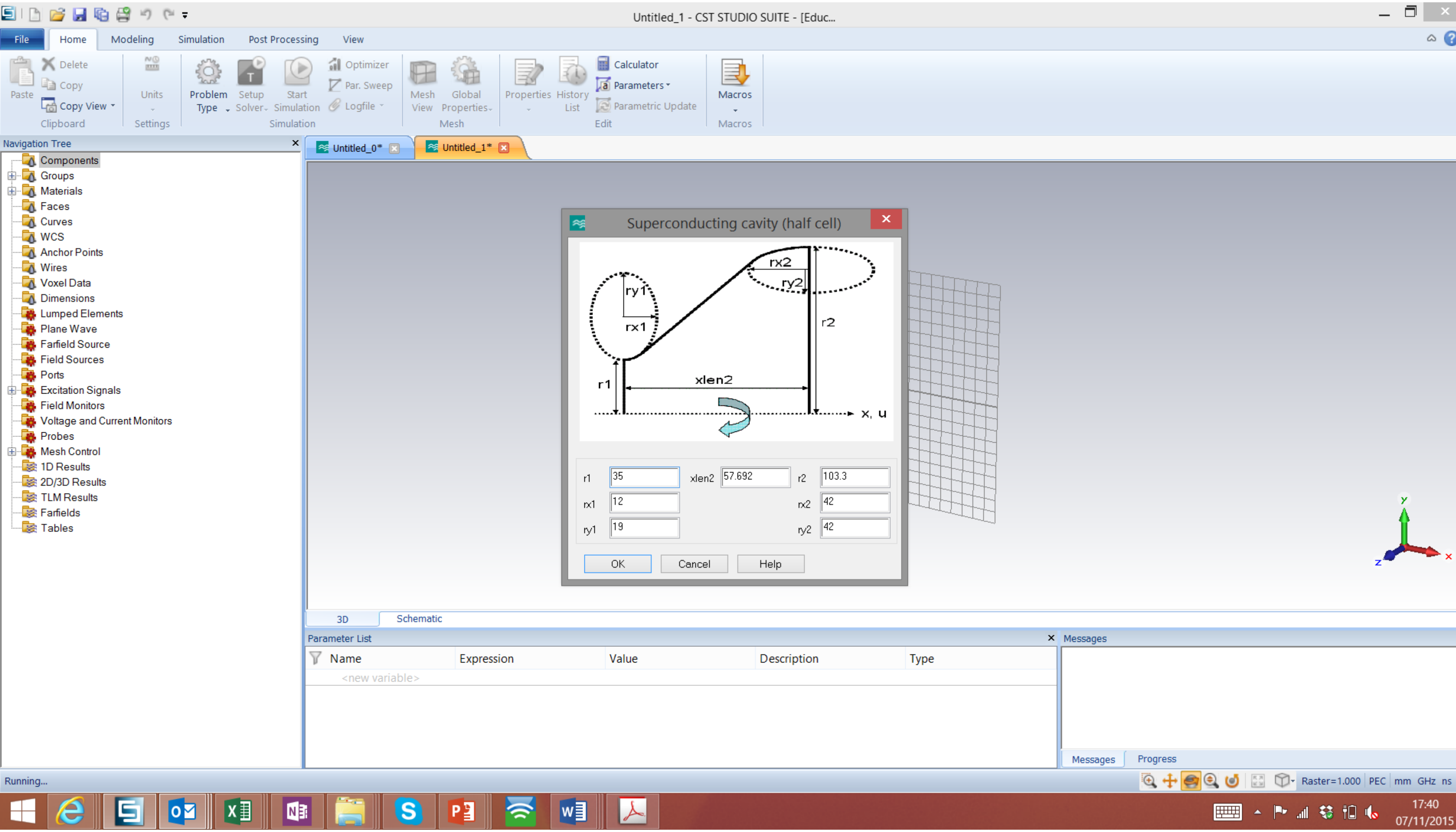


*from G. Burt, Lancaster University.



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Voltage and Current Monitors
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Mesh Control
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2D/3D Results
TLM Results
Farfields
Tables
Superconducting cavity (half cell)
rx2
ry2
ry1
rx1
r2
r1
xlen2
x, u
r1 35
xlen2 57.692
r2 103.3
rx1 12
rx2 42
ry1 19
ry2 42
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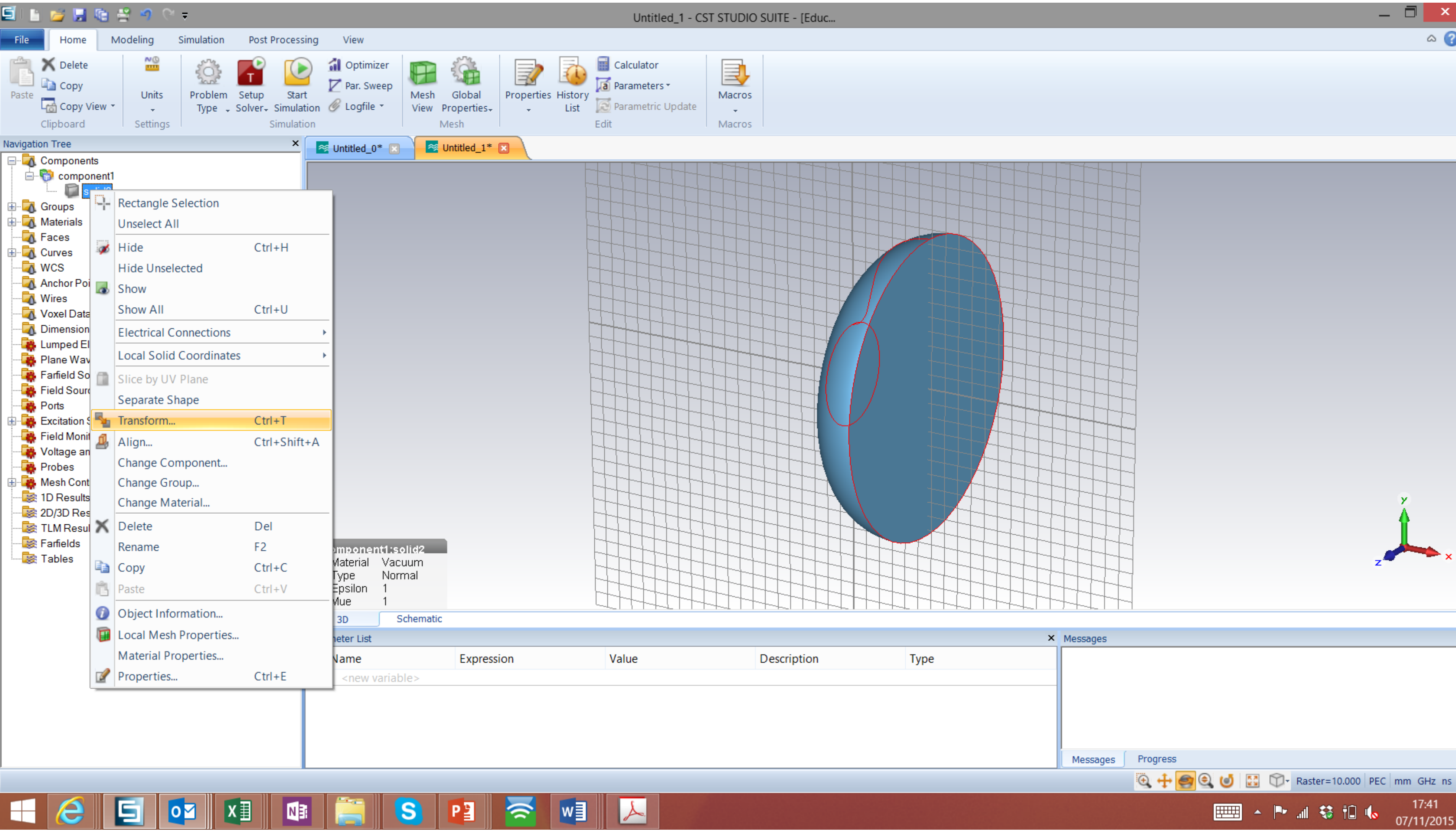
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Hide Unselected
Show
Show All Ctrl+U
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Local Solid Coordinates
Slice by UV Plane
Separate Shape
Transform... Ctrl+T
Align... Ctrl+Shift+A
Change Component...
Change Group...
Change Material...
Delete Del
Rename F2
Copy Ctrl+C
Paste Ctrl+V
Object Information...
Local Mesh Properties...
Material Properties...
Properties... Ctrl+E
mponent1:solid2
Material Vacuum
Type Normal
Epsilon 1
Mue 1
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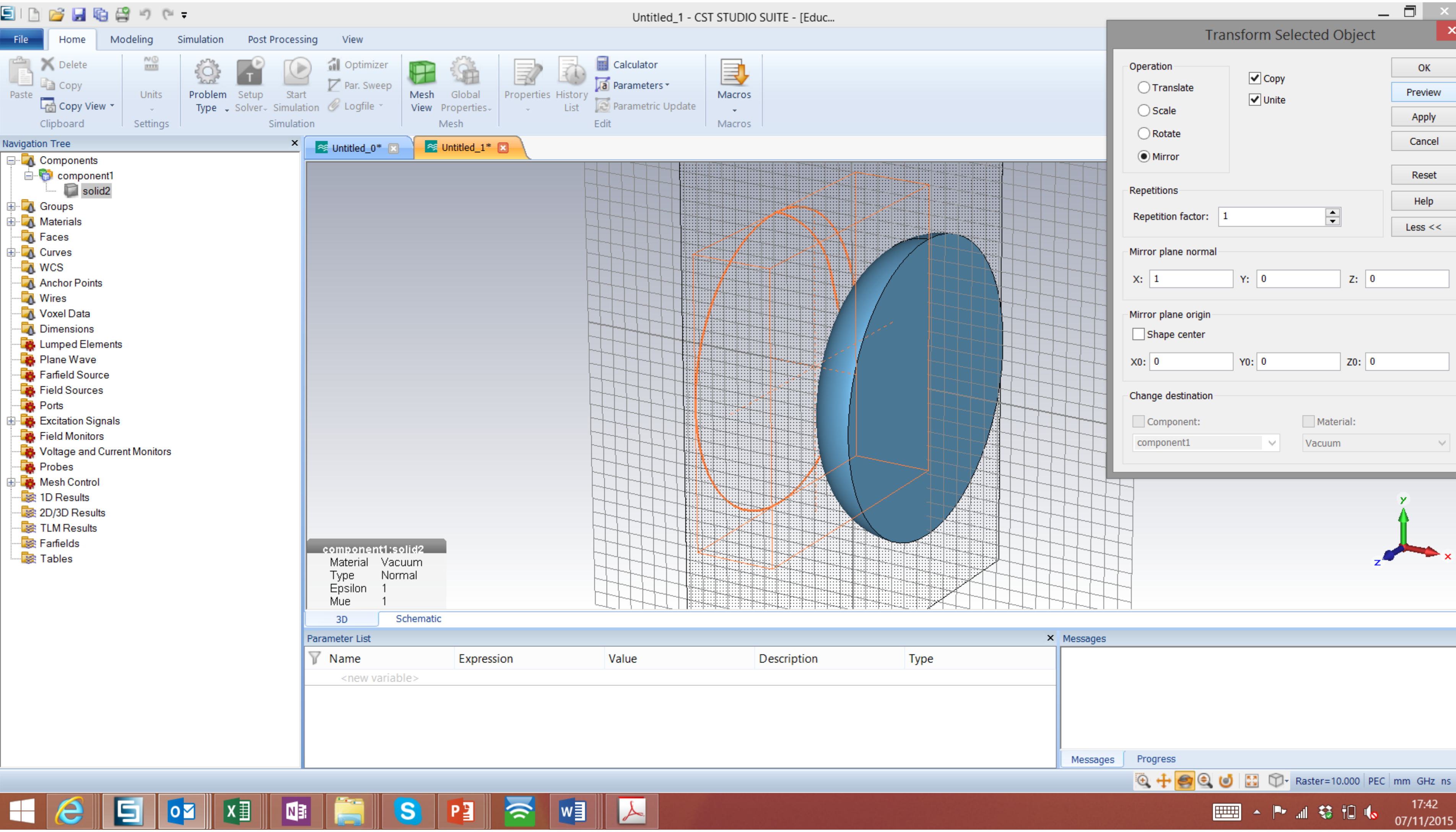
07/11/2015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Untitled_1*
component1:solid2
Material Vacuum
Type Normal
Epsilon 1
Mue 1
3D
Schematic
Transform Selected Object
Operation
Translate
Scale
Rotate
Mirror
Copy
Unite
OK
Preview
Apply
Cancel
Reset
Help
Less <<
Repetitions
Repetition factor: 1
Mirror plane normal
X: 1
Y: 0
Z: 0
Mirror plane origin
Shape center
X0: 0
Y0: 0
Z0: 0
Change destination
Component:
component1
Material:
Vacuum
Parameter List
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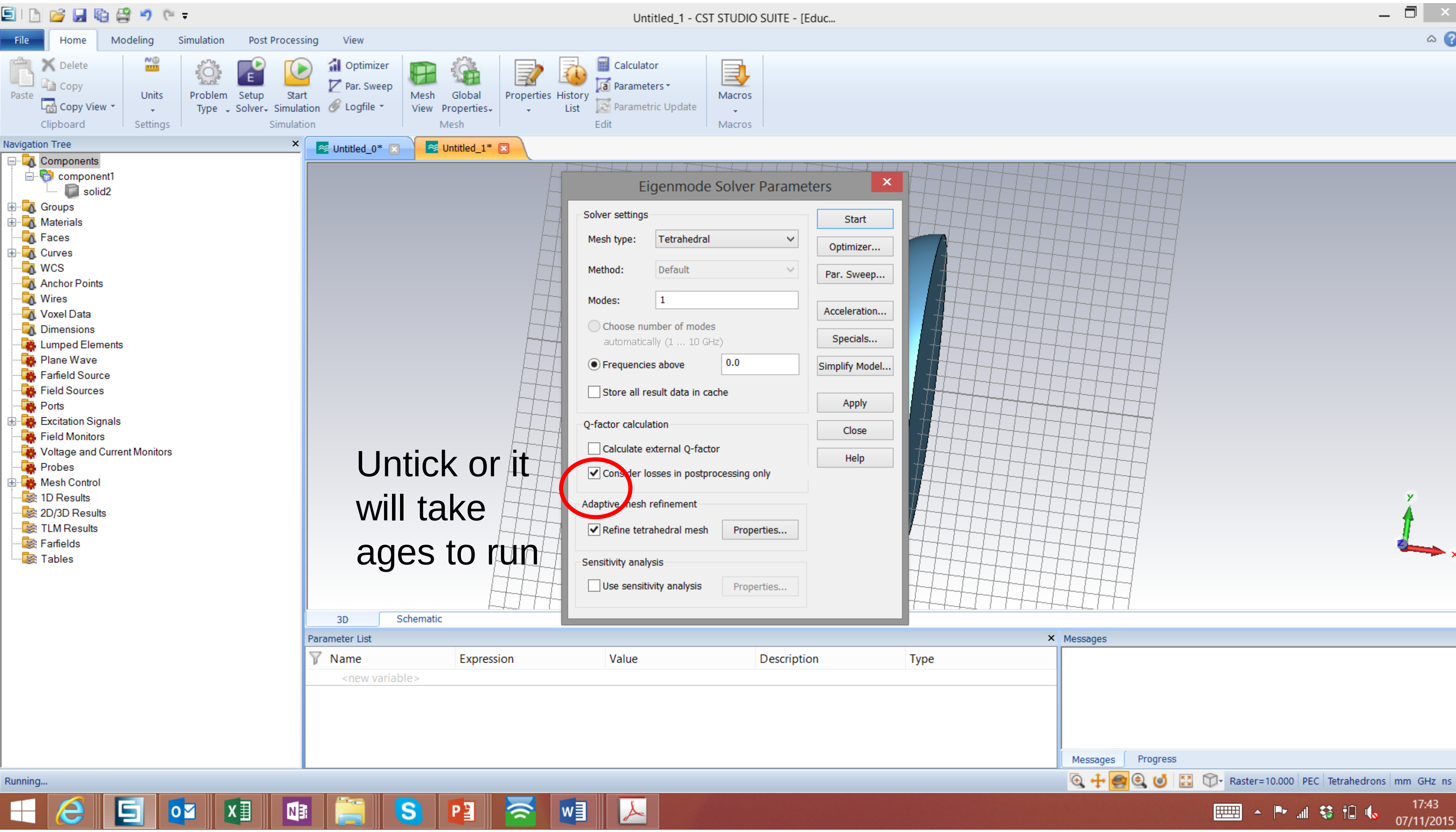
Untitled_1 - CST STUDIO SUITE - [Educ...
File
Home
Modeling
Simulation
Post Processing
View
Eigenmode Solver Parameters
Solver settings
Mesh type: Tetrahedral
Method: Default
Modes: 1
Choose number of modes automatically (1 ... 10 GHz)
Frequencies above 0.0
Store all result data in cache
Q-factor calculation
Calculate external Q-factor
Consider losses in postprocessing only
Adaptive mesh refinement
Refine tetrahedral mesh
Properties...
Sensitivity analysis
Use sensitivity analysis
Start
Optimizer...
Par. Sweep...
Acceleration...
Specials...
Simplify Model...
Apply
Close
Help
Untick or it will take ages to run
Navigation Tree
Parameter List
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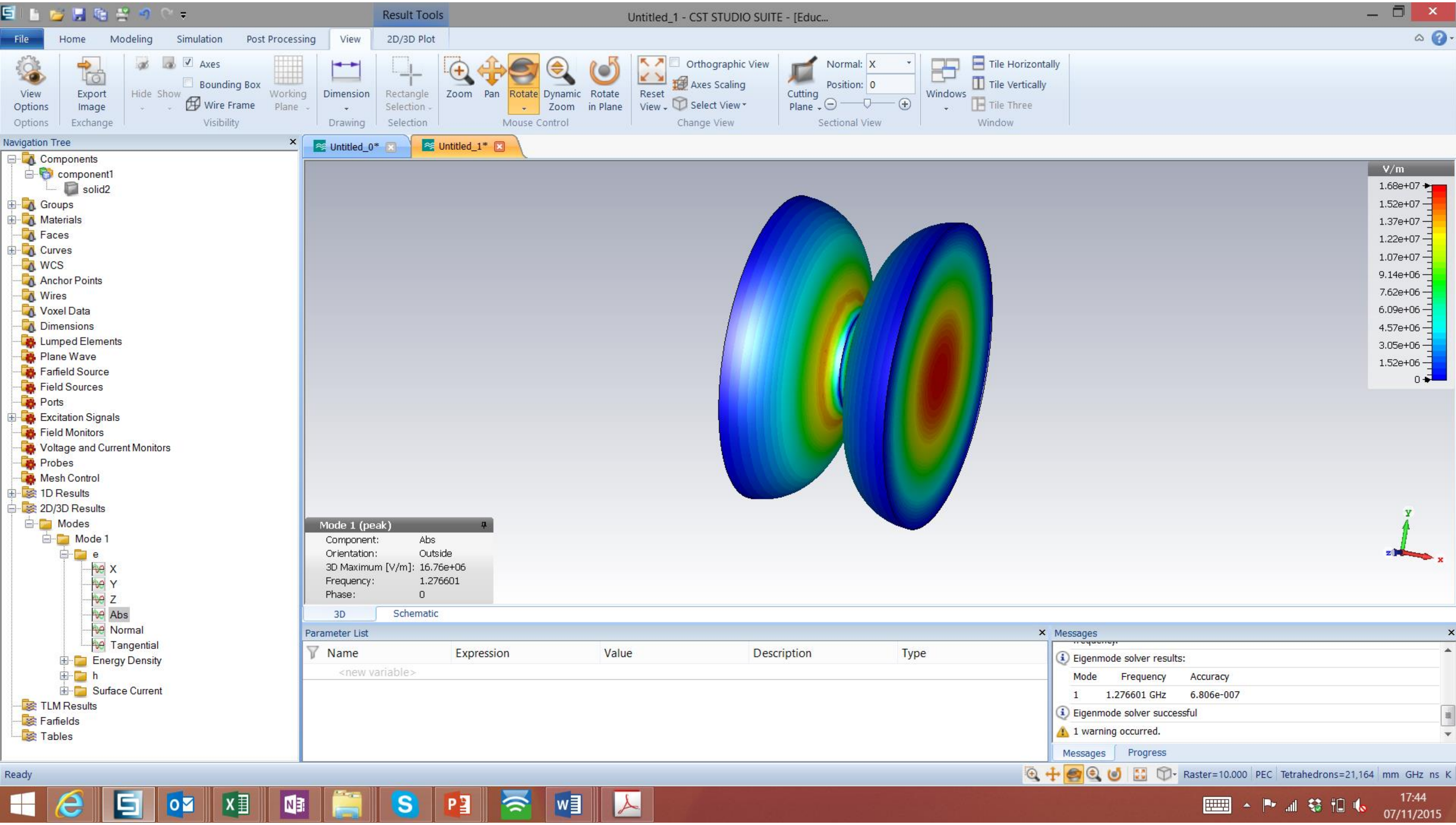
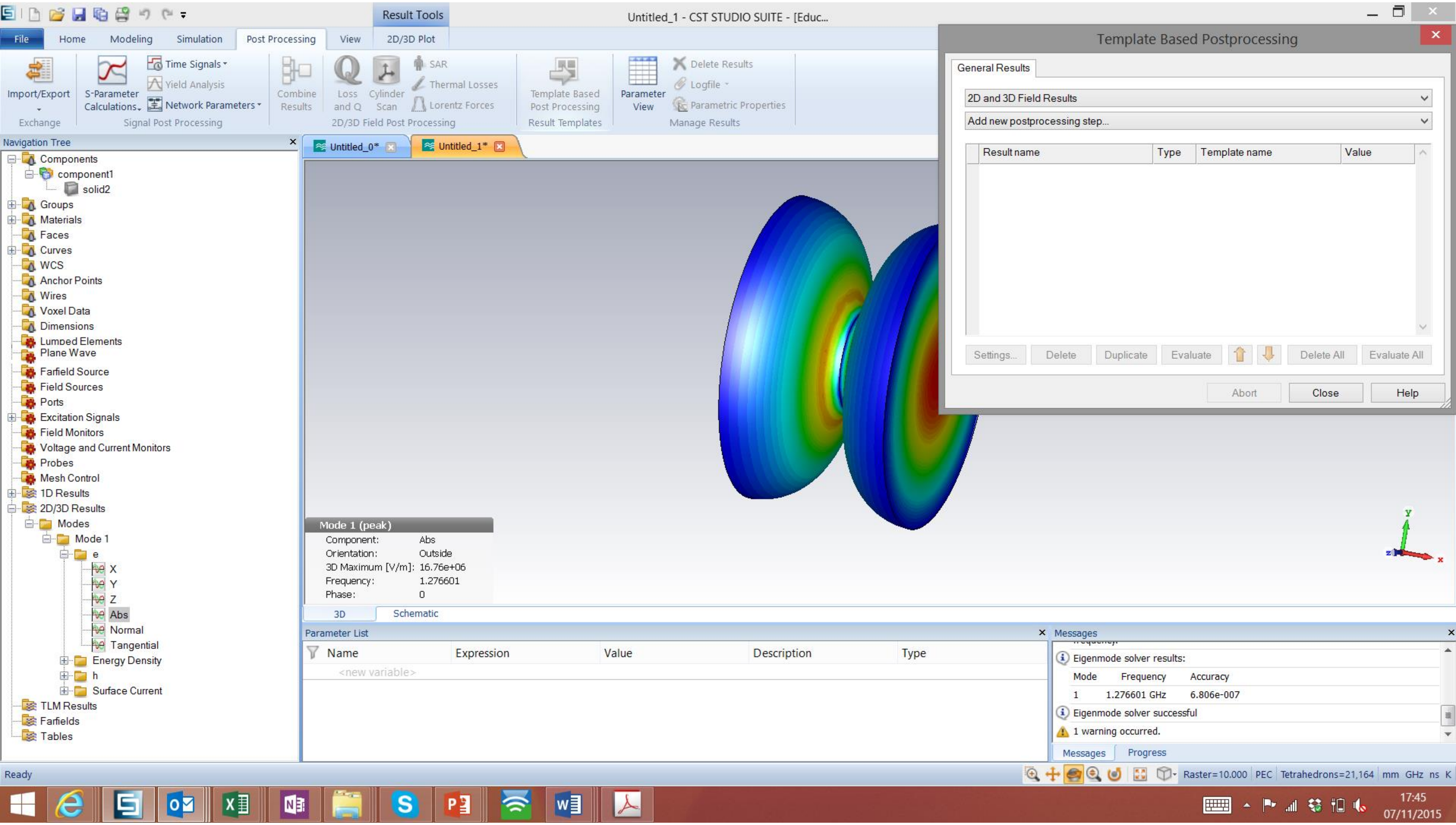
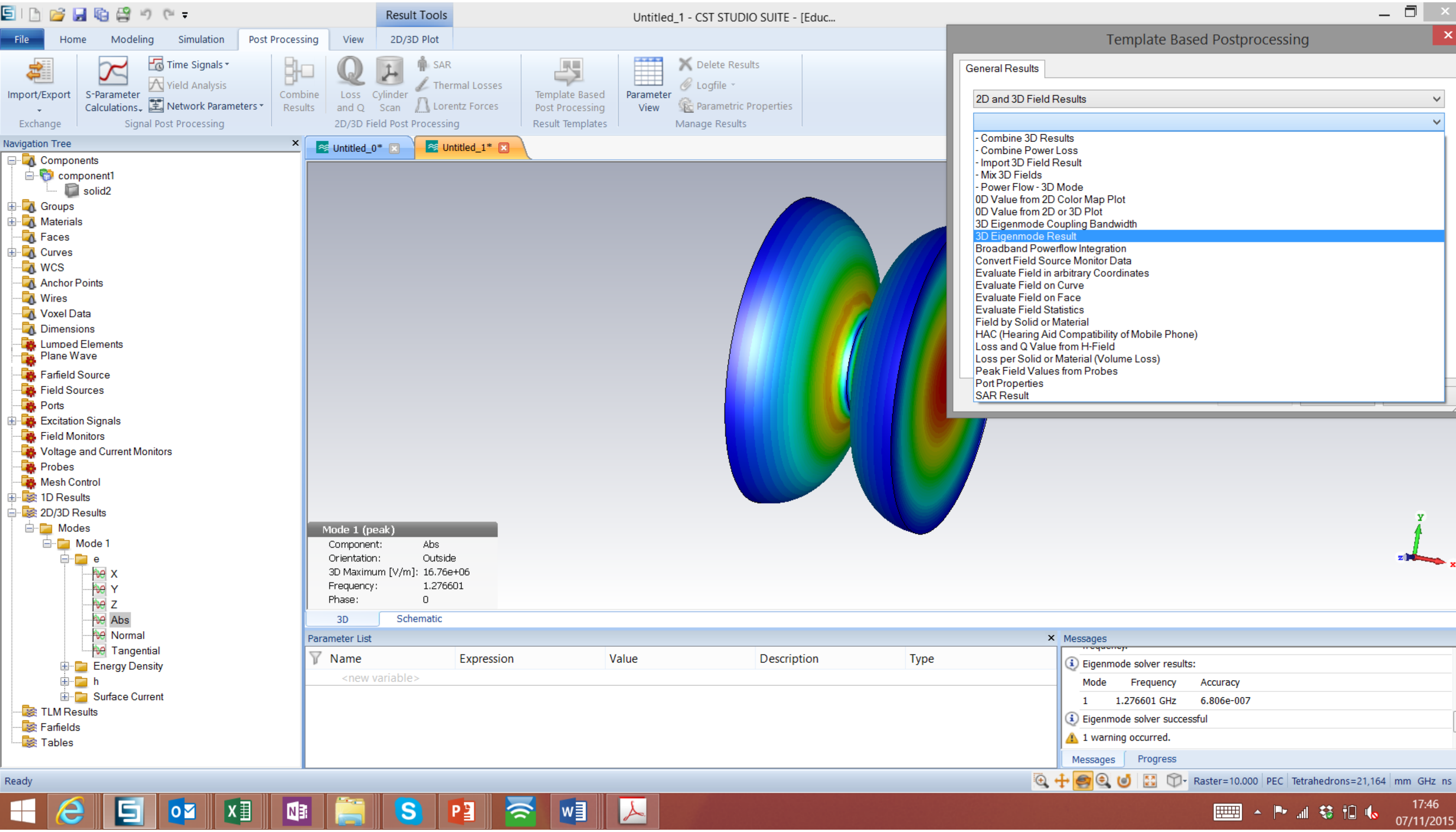
Running...



*from G. Burt, Lancaster University.



*from G. Burt, Lancaster University.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Signal Post Processing
Combine Results
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Thermal Losses
Lorentz Forces
2D/3D Field Post Processing
Template Based Post Processing
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Voltage and Current Monitors
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1D Results
2D/3D Results
Modes
Mode 1
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Z
Abs
Normal
Tangential
Energy Density
h
Surface Current
TLM Results
Farfields
Tables
Untitled_0*
Untitled_1*
Mode 1 (peak)
Component: Abs
Orientation: Outside
3D Maximum [V/m]: 16.76e+06
Frequency: 1.276601
Phase: 0
3D
Schematic
Template Based Postprocessing
General Results
2D and 3D Field Results
- Combine 3D Results
- Combine Power Loss
- Import 3D Field Result
- Mix 3D Fields
- Power Flow - 3D Mode
0D Value from 2D Color Map Plot
0D Value from 2D or 3D Plot
3D Eigenmode Coupling Bandwidth
3D Eigenmode Result
Broadband Powerflow Integration
Convert Field Source Monitor Data
Evaluate Field in arbitrary Coordinates
Evaluate Field on Curve
Evaluate Field on Face
Evaluate Field Statistics
Field by Solid or Material
HAC (Hearing Aid Compatibility of Mobile Phone)
Loss and Q Value from H-Field
Loss per Solid or Material (Volume Loss)
Peak Field Values from Probes
Port Properties
SAR Result
Parameter List
Name
Expression
Value
Description
Type
<new variable>
Messages
Eigenmode solver results:
Mode Frequency Accuracy
1 1.276601 GHz 6.806e-007
Eigenmode solver successful
1 warning occurred.
Messages
Progress
Ready
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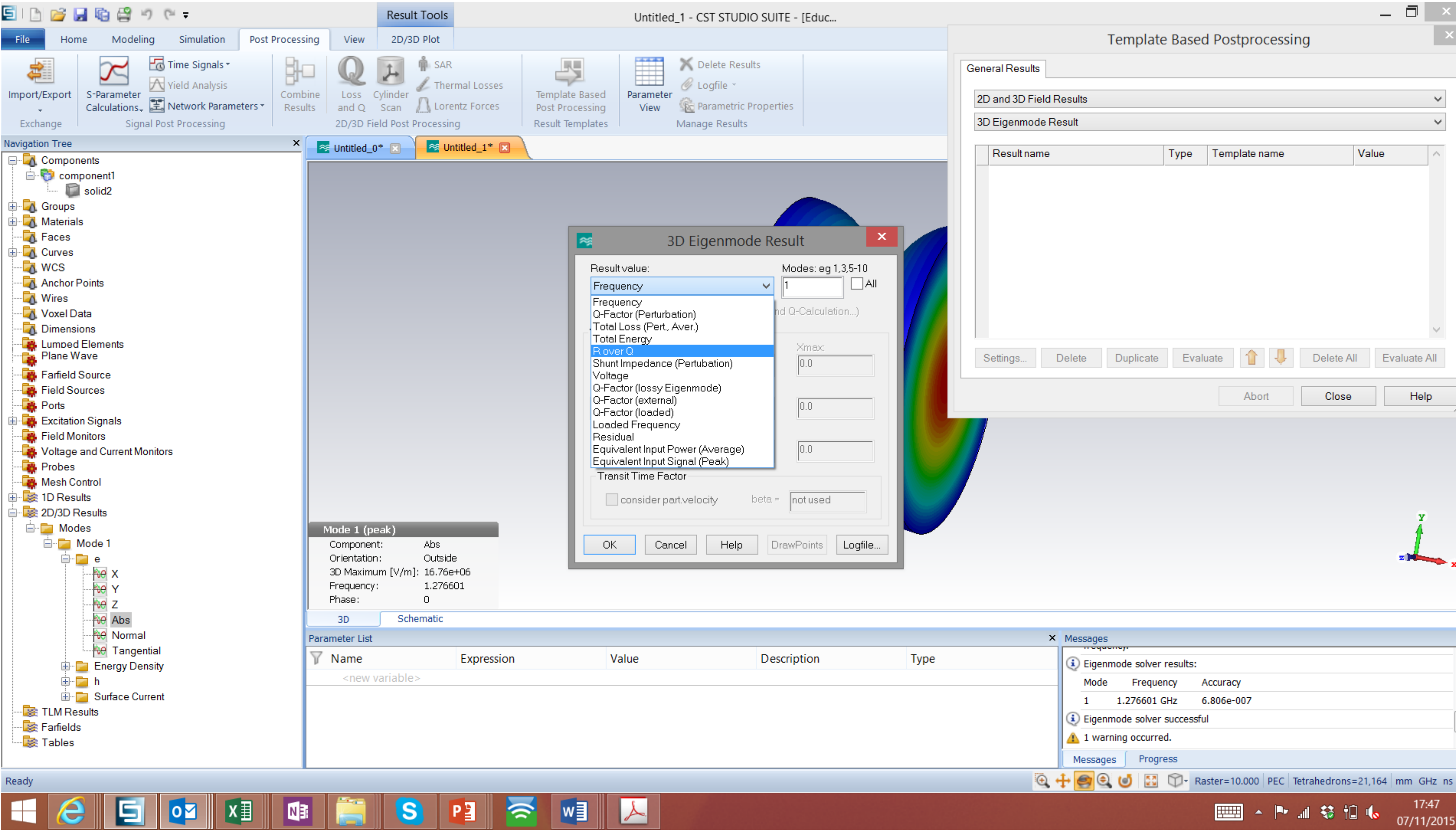
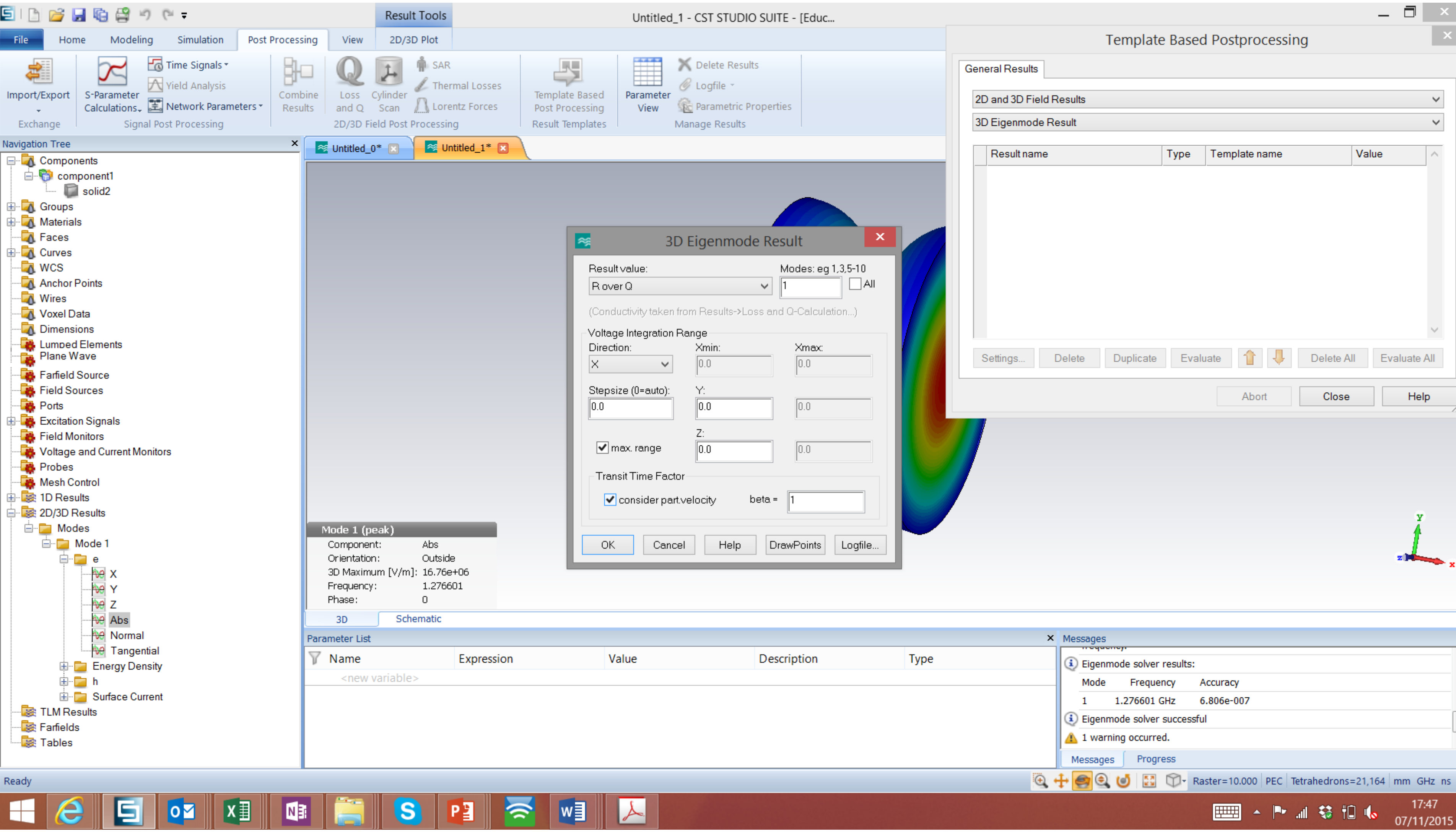
Tetrahedrons=21,164
mm GHz ns K
17:46
07/11/2015



*from G. Burt, Lancaster University.



*from G. Burt, Lancaster University.

Wake Fields and Wake Potentials

- Any variation in the cavity profile, material, or material properties will perturb the configuration
- Beam loses part of its energy to establish EM (wake) fields that remain after the passage of the beam
- Wake duration depends on the geometry and material of the structure
  - Wakes persist for duration of bunch passage
  - Wakes last longer than the time between bunches

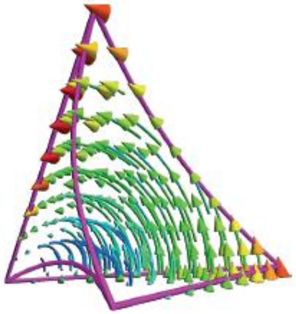
$$\boldsymbol{W_z(\vec{r},\vec{r}',s) = -\frac{1}{q}\int_{z_1}^{z_2} dz\left[E_z(\vec{r},z,t)\right]_{t=(z+s)/c}}$$

$$\boldsymbol{W_\perp(\vec{r},\vec{r}',s) = \frac{1}{q}\int_{z_1}^{z_2} dz\left[\vec{E}_\perp + c\left(\hat{z} \times \vec{B}\right)\right]_{t=(z+s)/c}}$$

*from S. U. de Silva, ODU.

Calculation Method

A charged particle bunch introduces an electric current density $\vec{J}$.
Combining Ampere's and Faraday's laws



$$\nabla \times (\nabla \times \vec{E}) + \mu\varepsilon \frac{\partial^2 \vec{E}}{\partial t^2} + \mu\sigma_{eff} \frac{\partial \vec{E}}{\partial t} = -\mu \frac{\partial \vec{J}}{\partial t}$$

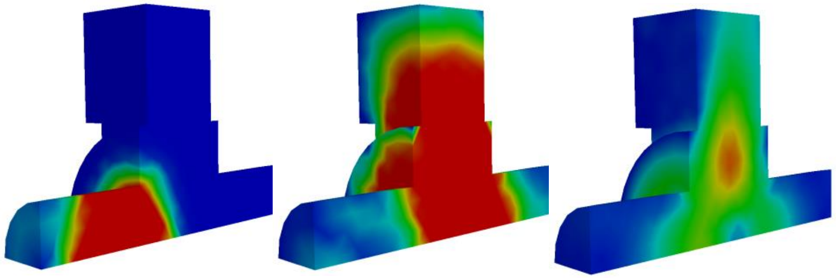
The domain is then discretized into curved tetrahedral elements and $\int$ E $d\tau$ is represented as an expansion in hierarchical Whitney vector basis functions $N_i(x)$

$$\int E\, d\tau = \sum_{i=1}^{N_p} e_i(t) \cdot N_i(x)$$

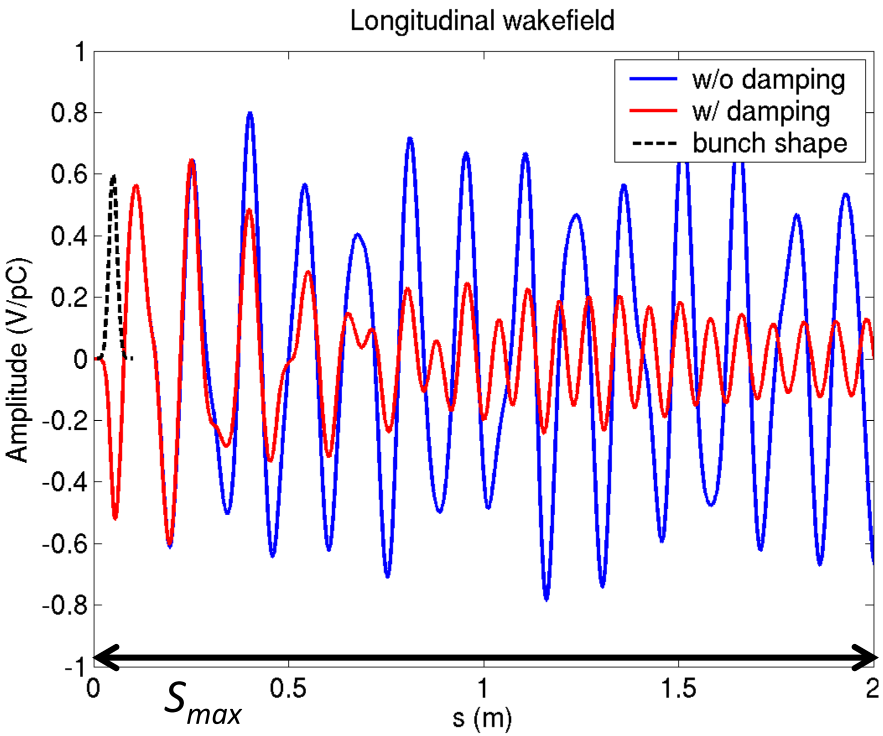
*from S. U. de Silva, ODU.

Wake-Field Simulation

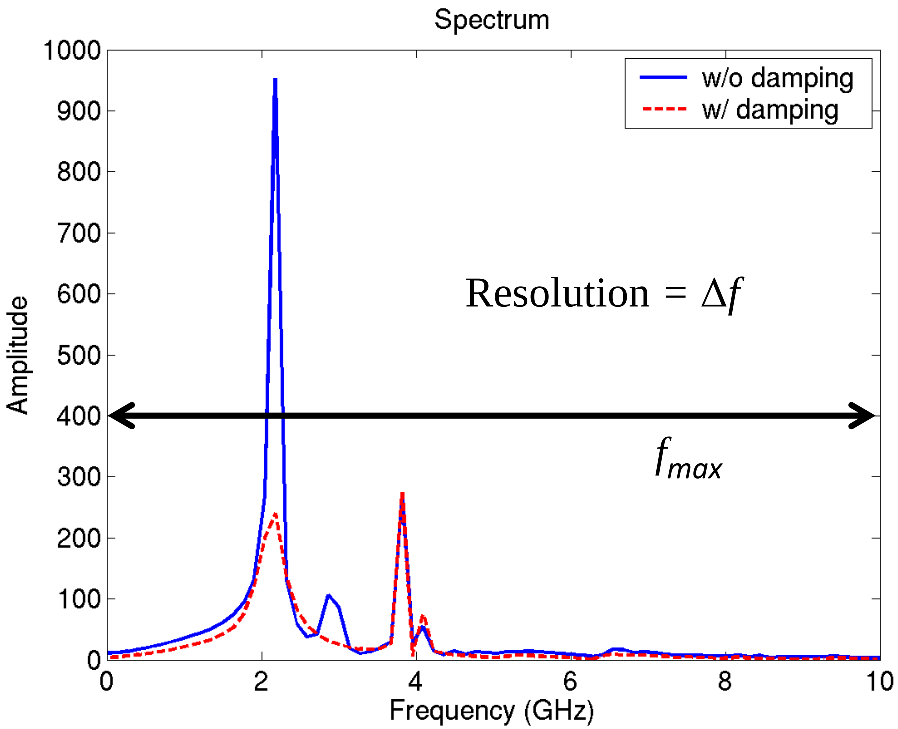
- Determine wake potential, impedance and loss factors



Field snapshots from beam transit



Longitudinal wakefield

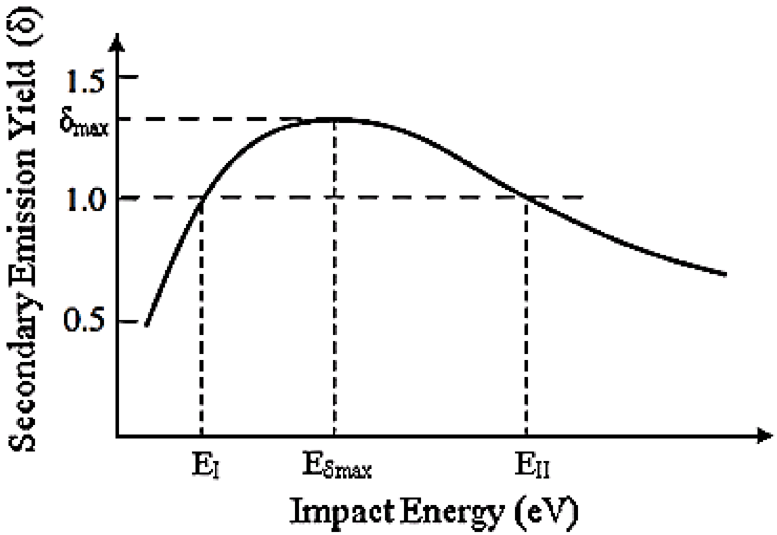


Impedance spectrum

*from S. U. de Silva, ODU.

Multipacting

For Nb: $E_I > 150\ eV$ and $E_{II} < 2000\ eV$



- **Multipacting Condition:**

-Large amount of secondary electrons emitted.

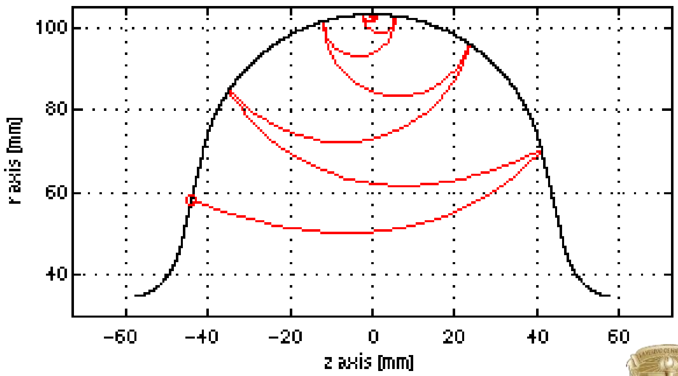
- **Resonant Condition:**

-Sustainable resonant trajectories.

-Impact energies (SEY) >1.

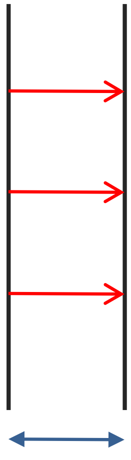
In terms of the cyclotron freq.:

$$\frac{2f}{2n-1} = \frac{eB}{2\pi m}$$



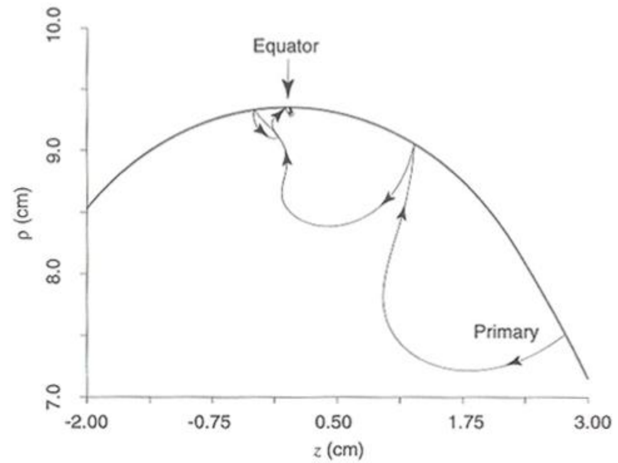
Multipacting

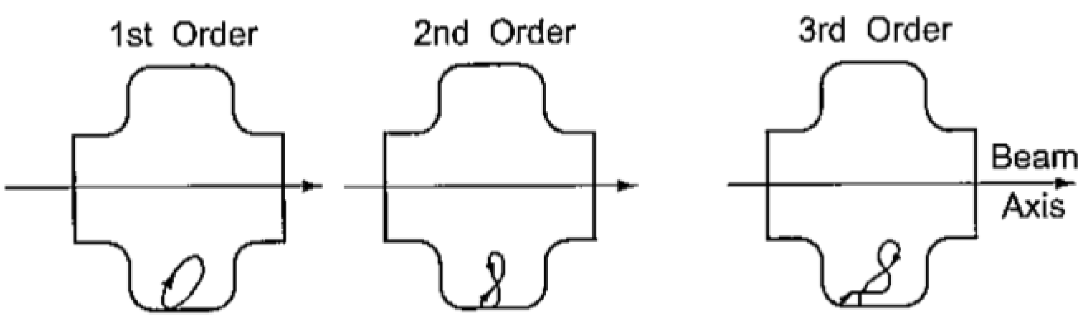
n = multipacting order.



$$V_n = \frac{m\omega^2 d^2}{(2n-1)\pi e}$$

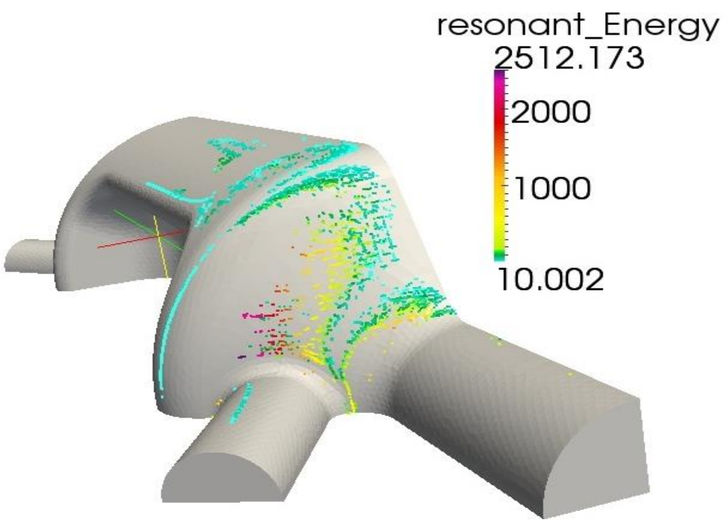
$$E_n = \frac{2m\omega^2 d^2}{(2n-1)^2\pi^2}$$

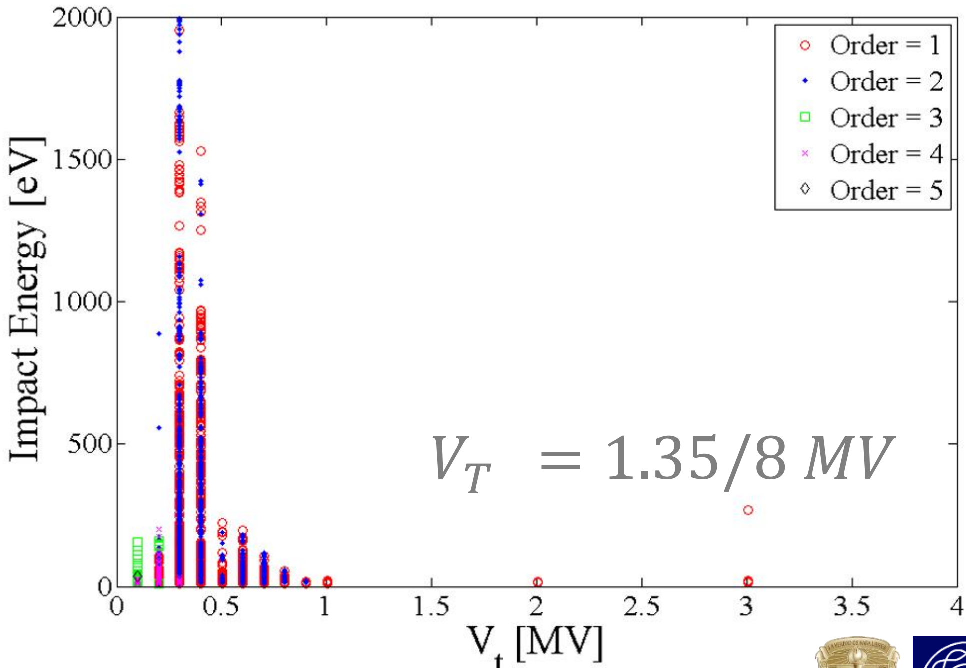




Multipacting Analysis

- Important for maintaining operation gradients, avoiding thermal breakdowns.
- Using SLAC's TRACK3P code from the ACE3P suit for numerical simulations.





Extras

Simulation Software

- CST (Computer Simulation Technology) Suite
  - Microwave Studio - 3D EM simulation of high frequency components
    - *Eigenmode solver, Frequency domain solver*
  - Particle Studio - analysis of charged particle dynamics in 3D electromagnetic fields
    - *Stationary particle tracking solver, Wake-field solver, Particle in cell (PIC)*
  - Mphysics Studio - thermal and mechanical stress analysis
    - *Structural mechanics solver, Thermal transient / stationary solvers*
  - Other packages: EM Studio, Cable Studio, PCB Studio, Design Studio
- Is a commercial software suite (CST AG, Germany)
  - With GUI
  - Supports distributed computing
  - Currently runs on stand alone computers

*from S. U. de Silva, ODU.

Simulation Software

- ACE3P (Advanced Computational Electromagnetics 3D Parallel) Suite
- From Advanced Computations Department at SLAC National Accelerator Laboratory
- Modules:

Frequency Domain:	**Omega3P**	– Eigensolver (Damping)
	S3P	– S-Parameter
Time Domain:	**T3P**	– Wakefields & Transients
Particle Tracking:	**Track3P**	– Multipacting & Dark Current
EM Particle-in-cell:	**Pic3P**	– RF Guns & Sources (e.g. Klystron)
Multi-physics:	**TEM3P**	– EM, Thermal & Structural Effects

Courtesy: K. Ko, C. Ng, Z. Li - SLAC

Simulation Software

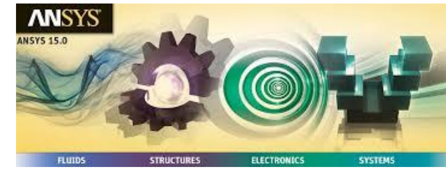
- **Cubit / Trelis** – Model and mesh generation
  - Cubit – Sandia National Laboratories
  - Trelis – Computational Simulation Software, LLC (csimsoft)

- **NERSC** – For computation
  - National Energy Research Scientific Computing Center: Scientific computing facility for Office of Science, U.S.DOE situated at Berkeley National Laboratory

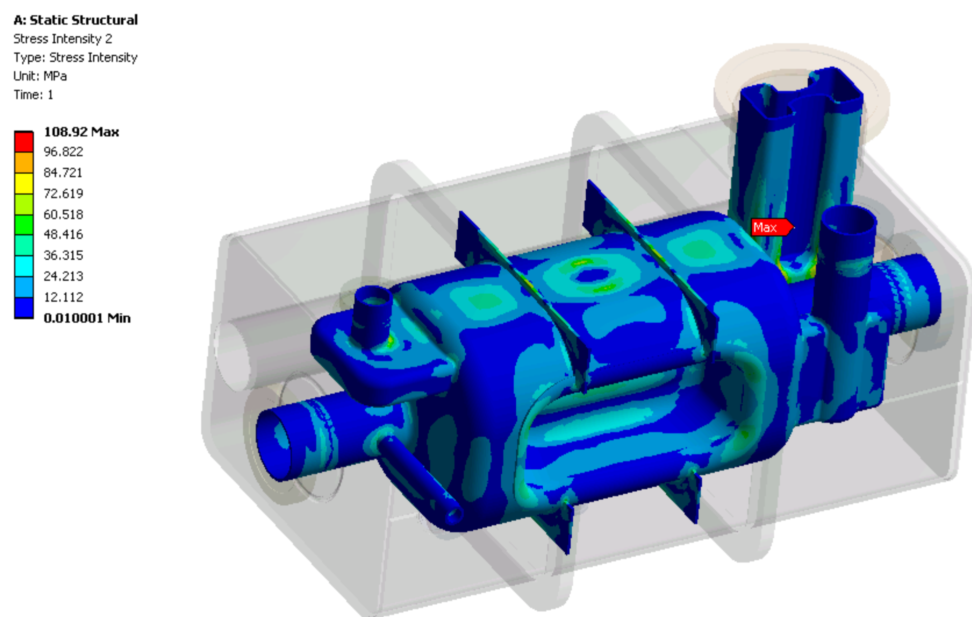
- **Paraview** – Visualization
  - Open-source, multi-platform data analysis and visualization application

*from S. U. de Silva, ODU.

Simulation Software



- Mechanical and thermal analysis
  - ANSYS with HFSS – ANSYS Inc.
  - For structural analysis of cavities and cryomodule components
  - Challenges: Extracting deformed structural model to be used in CST or other EM simulation software



- Cavity integration into cryomodule
  - With ancilliary components, support structures including production details
  - Using CAD software – NX by Siemens

*from S. U. de Silva, ODU.

SIEMENS

Simulation Software

- Beam dynamics study
  - ASTRA (A Space-charge TRacking Algorithm) – DESY, Germany
    - *Space charge tracking algorithm*
  - ELEGANT – Argonne National Laboratory
    - *6-D (x, x', y, y', z, ΔE) tracking with matrices and/or canonical integrators, and supports a variety of time-dependent elements*
  - Etc.
- Use a large data set of EM 3D field data generated by CST Microwave Studio or Superfish/Poisson (LANL)

*from S. U. de Silva, ODU.