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Ansys High Frequency Structure Simulator (HFSS) Tutorial

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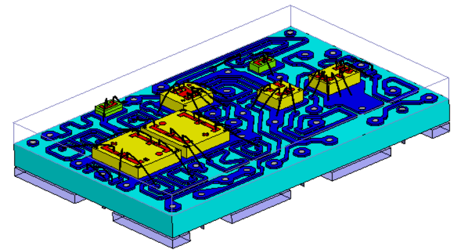
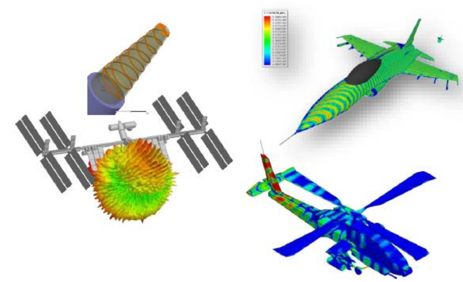
PACIFIC NORTHWEST NATIONAL LABORATORY

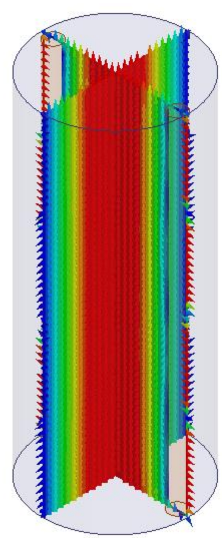
8/21/18

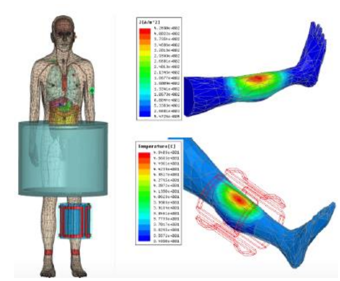
Agenda

- Overview of HFSS
  - Capabilities and key features
  - Example measurement comparisons
- Cylindrical cavity tutorial
  - Eigenmode solver
  - Parametric geometry
  - Curvilinear elements
  - Modal frequencies
  - Q-factors
  - Field plots
  - Field calculator









Overview of HFSS

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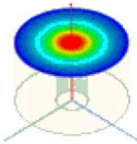
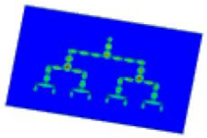
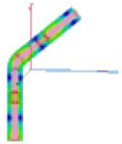
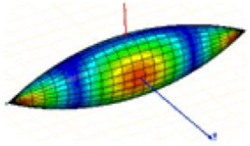
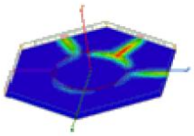
- Full-wave frequency-domain 3-D field solver based upon finite element method
  - Industry-standard accuracy
  - Adaptive meshing of arbitrary geometry
  - Fully parametric modeling
  - Optimization and HPC
  - Multi-physics via Ansys Workbench
- Widely used for RF/microwave design
  - Antenna design and platform integration
  - Filters and waveguide structures
  - Electronic packages and PCBs
  - Connectors and transitions
  - EMC/EMI
  - Radar cross-section
- Integrated into Ansys Electronics Desktop
  - Part of Ansys Electromagnetics Suite

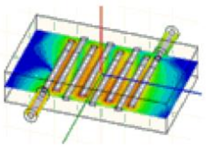

Coaxial Resonator

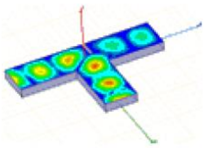

Corporate Feed

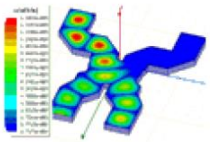

Parametric Sweep of Coax Bend


Ogive – IE


Ring Hybrid


Bandpass Filter


Tee and Optimum Tee


Combiner

Recent Capability Additions to HFSS

- Base license includes multiple solvers
  - Frequency-domain 3D finite element solver
  - Frequency-domain 3D finite element eigenmode solver
  - Transient finite 3D element solver
  - Frequency-domain 3D integral equation solver
  - Frequency-domain FEBI hybrid solver
  - Frequency-domain 2.5D planar integral equation solver
  - Linear circuit solver
- Base license enables use of 4 processor cores
  - HPC, Optimetrics, and Distributed Solver licenses increase computing capabilities
- HFSS offers two different interfaces to same solver to accommodate different workflows
  - 3D view (for CAD)
  - 3D Layout view (for ECAD such as Cadence, Mentor Graphics)

HFSS R19 User Interface within Ansys Electronics Desktop

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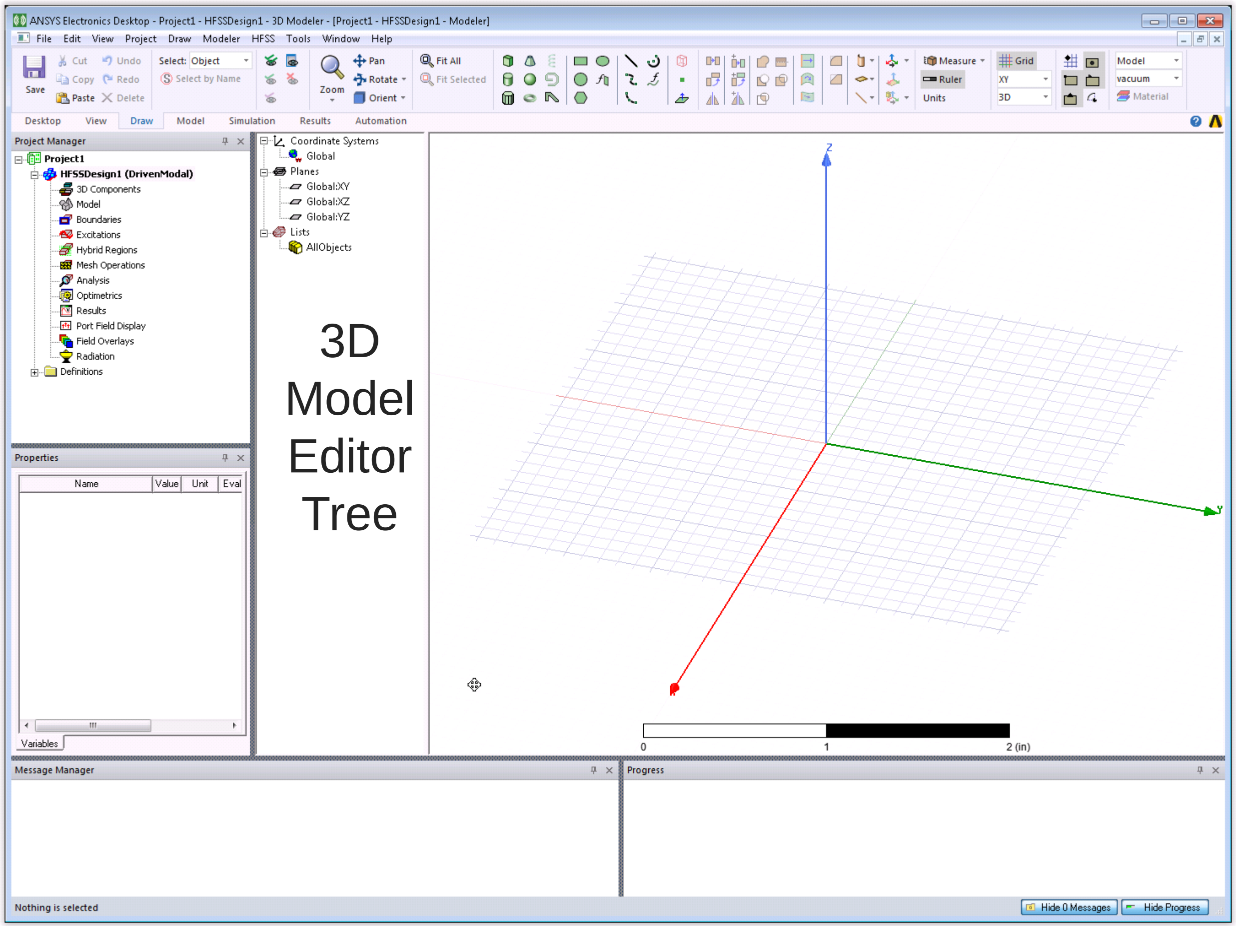
Ribbon / Toolbars

Project Manager

3D Model Editor Tree

3D Model Editor Graphics

Properties



Message Manager

Progress Window

Frequency-domain FEM Solution Types

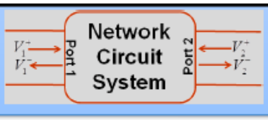
- Eigenmode solution
  - Solves for natural resonances of structure based on geometry, materials, and boundaries
  - Provides modal frequencies, unloaded Q-factors, and fields
  - Can solve for up to 20 modes at once
- Driven solution
  - Port or incident field used to excite the structure
  - *Driven modal* method commonly used for RF/microwave designs
  - *Driven terminal* method commonly used for multi-conductor transmission lines (no waveguides, symmetry boundaries, or Floquet ports)
  - Provides S-parameters and fields

Driven Modal

- Fields based transmission line interpretation
- Port's signal decomposed into incident and reflected waves
- Excitation's magnitude described as an incident power

Modal Propagation

•Energy propagates in a set of orthogonal modes
•Modes can be TE, TM and TEM w.r.t. the port's normal
•Mode's field pattern determined from entire port geometry
•Each Mode has its own column and row in the S, Y, and Z parameters

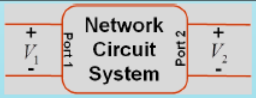


Driven Terminal

- Circuit Based transmission line interpretation
- Port's signal interpreted as a total voltage (Vtotal = Vinc + Vref)
- Excitation's magnitude described as either a total voltage or an incident voltage
- Supports Differential S-Parameters

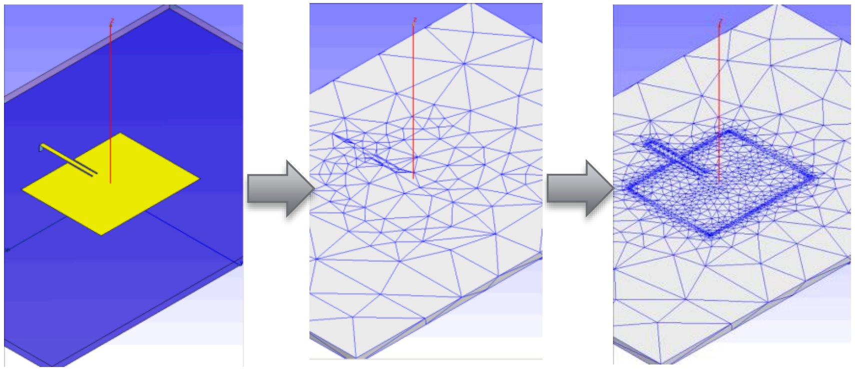
Terminal Propagation

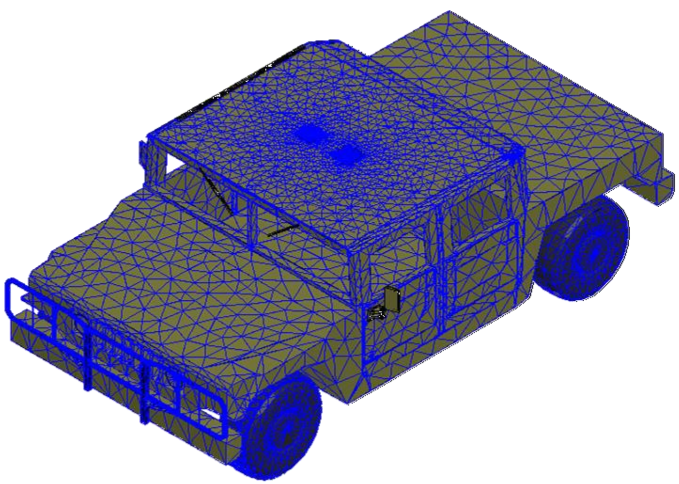
•Each conductor touching the port is considered a terminal or a ground
•Energy propagates along each terminal in a single TEM mode
•Each Terminal has its own column and row in the S, Y and Z parameters
•Does not support symmetry boundaries or Floquet Ports



Adaptive Mesh Algorithm

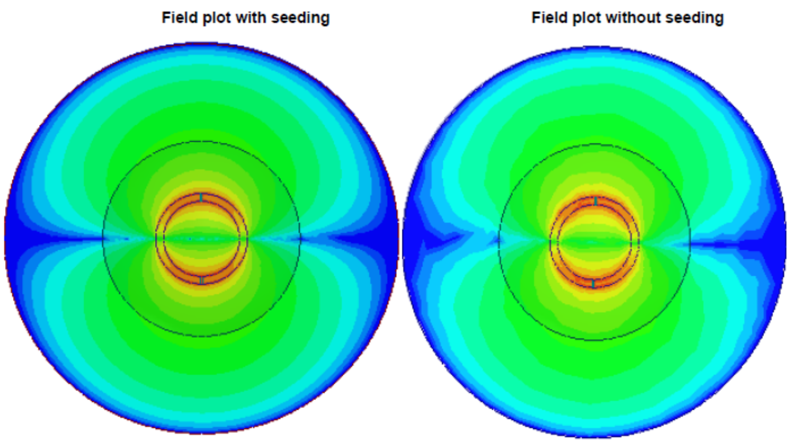
- Tetrahedral mesh automatically generated and refined below user-defined electrical length
  - Tetrahedral element shape conforms to arbitrary geometries
- Iterative algorithm solves fields and refines mesh until user-defined convergence threshold value is reached
  - Can be performed for set of user-specified frequencies (broadband adaptive meshing)
  - Driven modal: S-parameter convergence
  - Eigenmode: Frequency convergence
- Produces graded mesh with fine discretization only where needed to accurately represent field behavior
  - Efficient use of computational resources
  - Tunes mesh to capture EM performance

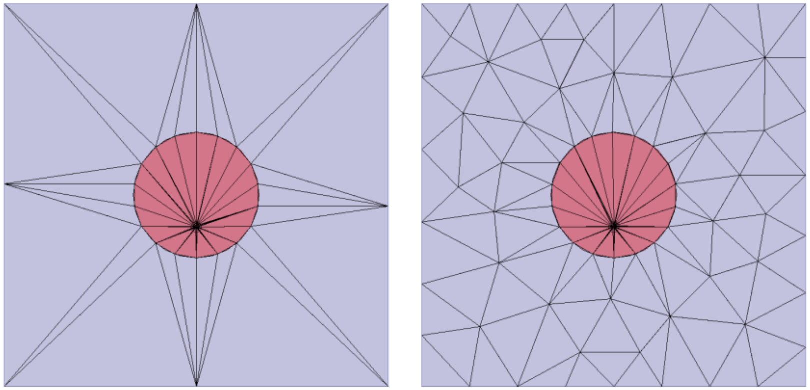




Mesh Controls

- Mesh seeding allows user to directly influence initial mesh
  - Reduce number of adaptive passes
  - Focus mesh elements in critical areas
  - Not required for accurate results
  - Can improve field plots
  - Seeding radiation boundary can improve far-field data
- Lambda refinement
  - Ensures that initial mesh is refined to fraction of electrical wavelength
  - Electrical size depends on solver basis order
    - Zero: λ/10, First: λ/3, Second: 2λ/3, Mixed: 2λ/3



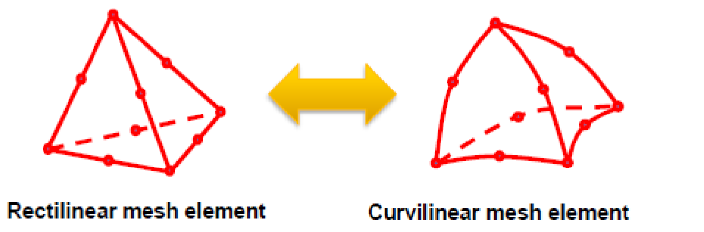


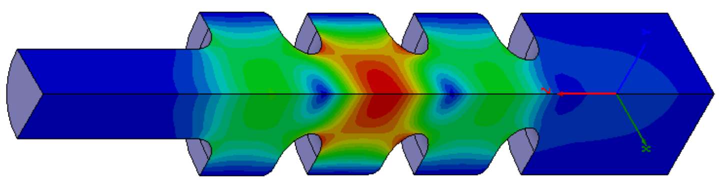
Initial geometric mesh

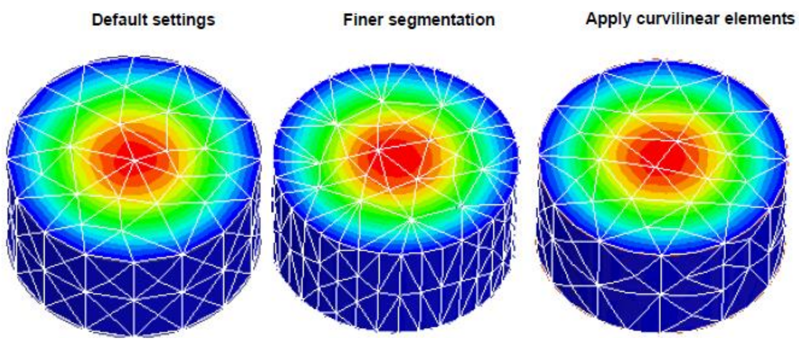
Electrical mesh after lambda refinement

Curvilinear Mesh Elements

- Global mesh approximation setting for all true surfaces in model
- Higher order (curvilinear) elements used to represent the geometry
  - Pulls midpoints of tetrahedra surfaces to true surface
- Pillbox resonator with analytical f_R = 22.950 GHz for TM_{010} mode
  - Default setting: 23.269 GHz
  - Finer segmentation: 23.012 GHz
  - Curvilinear elements: 22.950 GHz



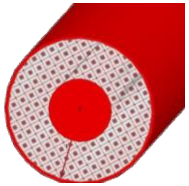


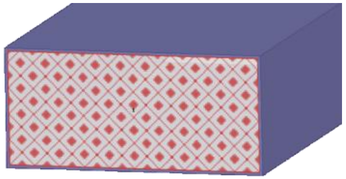


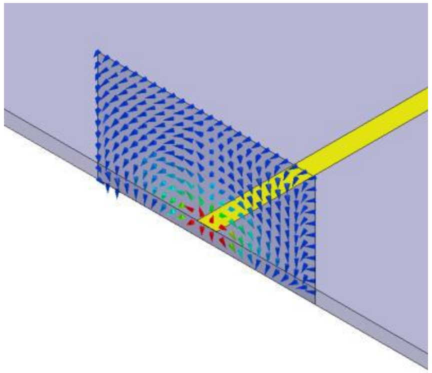
6024 DOF	6140 DOF	4966 DOF
1.38% error	0.03% error	0.00% error

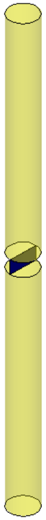
Port Excitations for Driven Solutions

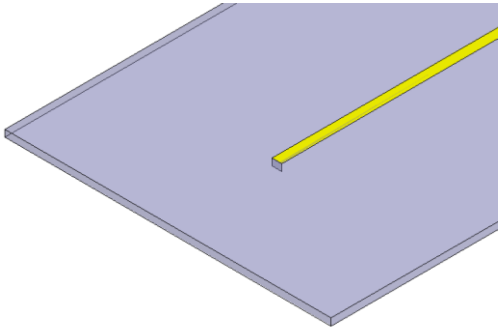
- Wave ports
  - 2D FEM solver calculates requested number of modes (treated as t-line cross-section)
  - Solves for impedances and propagation constants
  - Supports multiple modes and de-embedding
  - Simple for closed t-lines
  - Must allow room for fields of open t-lines
  - Must touch external boundary or backed by conducting object
- Lumped ports
  - User-assigned constant impedance
  - Uniform electric field on surface
  - Single TEM mode with no de-embedding
  - Can be internal to model











Frequency Sweeps for Driven Solutions

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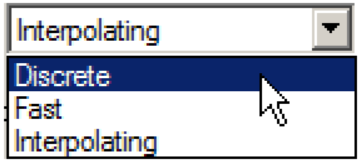
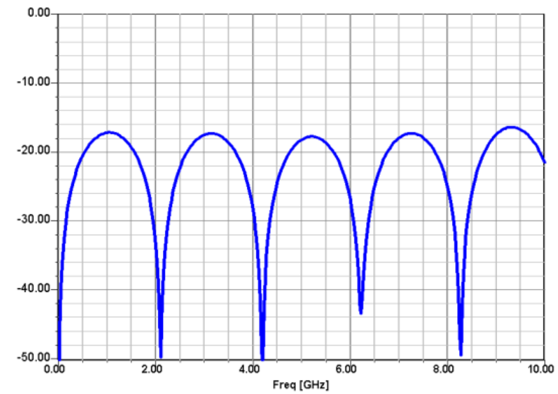
- Discrete sweep
  - Solves adapted mesh at every frequency
  - Matrix data and fields at every frequency
- Fast sweep
  - Adaptive Lanczos-Padé Sweep (ALPS) solver extrapolates rational polynomial function for electric field over specified range from center frequency field solution
  - Usually valid over less than 10:1 BW
  - Matrix data and fields at every frequency
- Interpolating sweep
  - Solves minimum number of frequencies to create rational polynomial fit for S-parameters
  - Useful for very broadband S-parameters
  - Matrix data at every frequency



$$S = \frac{\beta_q (s-z_q)(s-z_{q-1})\ldots(s-z_1)}{\alpha_q (s-p_q)(s-p_{q-1})\ldots(s-p_1)}$$



FEM Solvers for Driven Solutions

- Direct matrix solver is default technique
  - Exactly solves matrix equation Ax = b
  - Multi-frontal sparse matrix solver to find inverse of A (LU decomposition)
  - Solves for all excitations b simultaneously
- Iterative matrix solver is optional technique for driven solutions
  - Reduces RAM usage and often runtime
  - Solves matrix equation Max = Mb where M is preconditioner
  - Begins with initial solution and recursively updates solution until tolerance is reached
  - Iterates for each excitation b
  - More sensitive to mesh quality, reverts to direct solver if it fails to converge

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

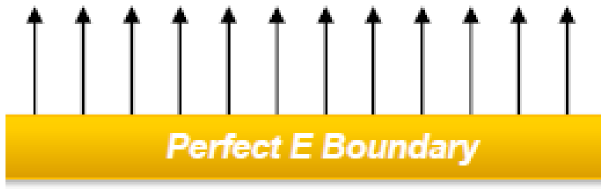
$$\nabla \cdot D = \rho$$

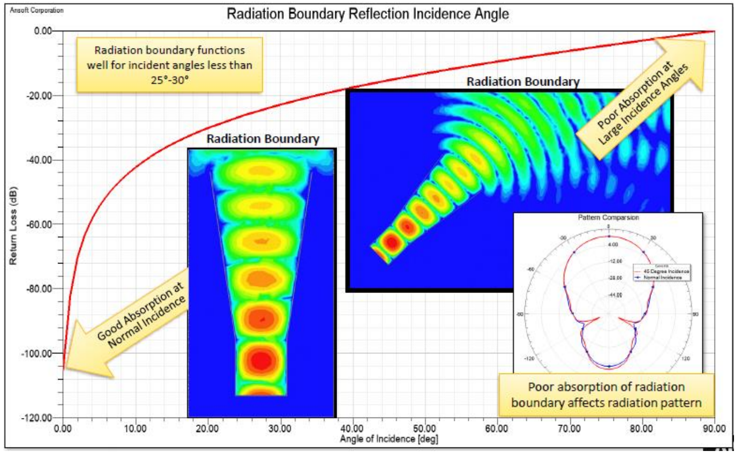
$$\nabla \cdot B = 0$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ 0 & a_{22} & a_{23} & a_{24} \\ 0 & 0 & a_{33} & a_{34} \\ 0 & 0 & 0 & a_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix}$$

Boundary Conditions

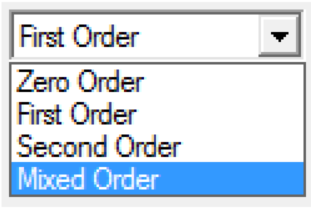
- Can be used to simplify geometry or make meshing more efficient
- Material properties for surfaces
  - Finite conductivity (imperfect conductor)
  - Perfect electric or magnetic conductor
- Surface approximations for components
  - Lumped RLC
  - Layered impedance
- Radiation
  - Absorbing boundary condition
  - Perfectly matched layers (PML)
  - FE-BI boundary
- Any object surface that touches the background is automatically defined as Perfect E (perfect conductor) boundary

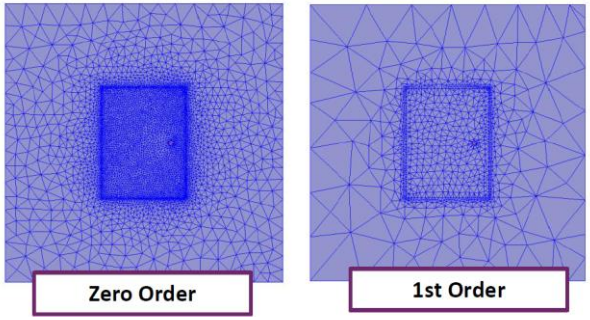




FEM Basis Functions

- Basis functions are n-order polynomials that describe how E-field varies along mesh elements edge, face, or volume
- Hierarchical basis functions
  - Zero ***or*** first ***or*** second order basis functions
  - Higher-order elements have increased accuracy but more unknowns (6, 20, 45)
- Mixed order basis functions
  - Zero ***and*** first ***and*** second order basis functions
  - hp-FEM method refines element order p and element size h
  - Automatically distributes element order based on element size to optimize use of resources
- Choice of ideal basis function is problem dependent
  - Mixed order efficiency is comparable to or better than best of single order basis functions

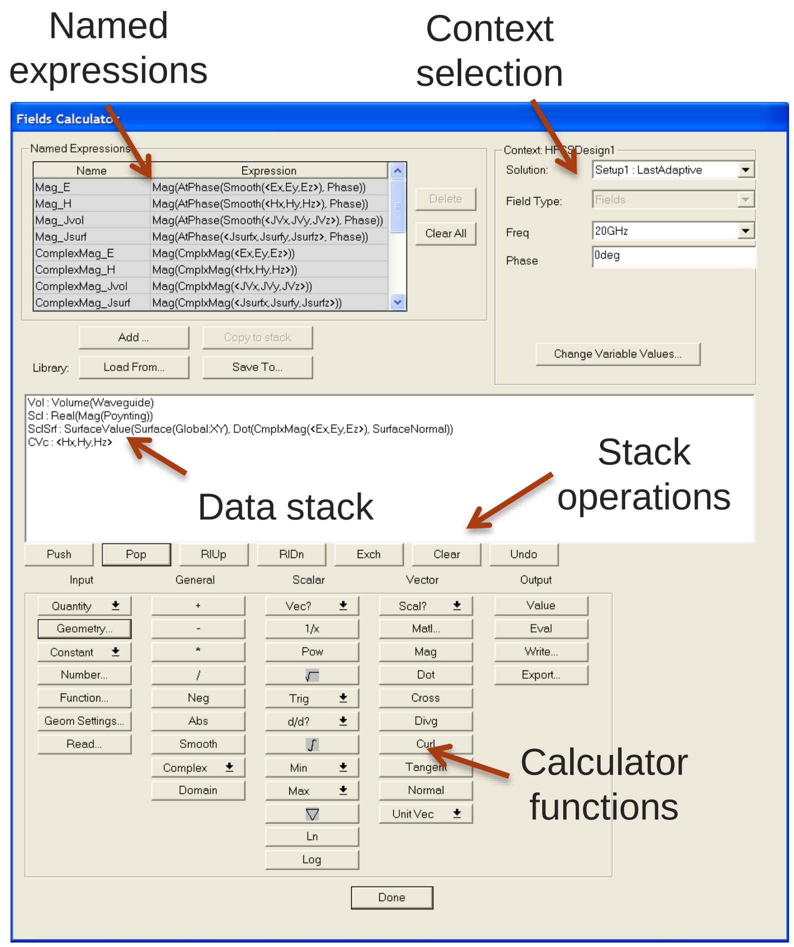




Order	Tetrahedra	RAM	Solution Time	Adaptive Passes
0	449,445	2.9 GB	21 min	16
1st	28,559	681 MB	2.5 min	11
2nd	20,782	1.8 GB	9.5 min	9
Mixed	**17,385**	**355MB**	**1.3 min**	**11**

Fields Calculator

- Tool for performing math operations on saved field data
  - E, H, J, and Poynting data
  - Geometric, complex, vector, and scalar data
  - Uses peak phasor representations of steady-state fields
  - Perform operations using model or non-model geometry
  - Generate numerical, graphical, geometrical, or exportable data
- Reverse Polish notation
- Frequently used expressions can be included in user library and loaded into any project
  - Eliminates need to re-create expressions used across projects



$$\frac{1}{2}\iint_{s} \mathrm{Re}\{\vec{E}\times\vec{H}^{*}\}\bullet\vec{ds}$$

$$\frac{1}{2}\sigma\iiint_{v} |E|^{2}\,dv$$

Quality Factor of Eigenmode Solutions

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- Provided with solution data for each requested mode
  - Obtained from complex frequency

$$Q_u = \frac{|freq|}{2 * imag(freq)}$$

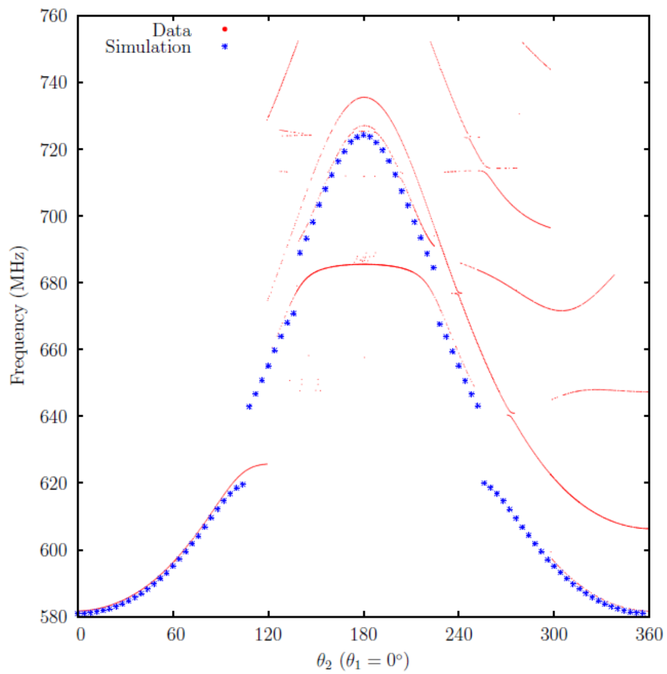
- Can also be calculated using fields calculator

$$Q_u = \frac{\int_{\Omega} |\mathbf{H}|^2 \, d\Omega}{\frac{S}{2} \oint_{\Gamma} |\mathbf{n} \times \mathbf{H}|^2 \, d\Gamma + tg\delta \int_{\Omega} |\mathbf{H}|^2 \, d\Omega}$$

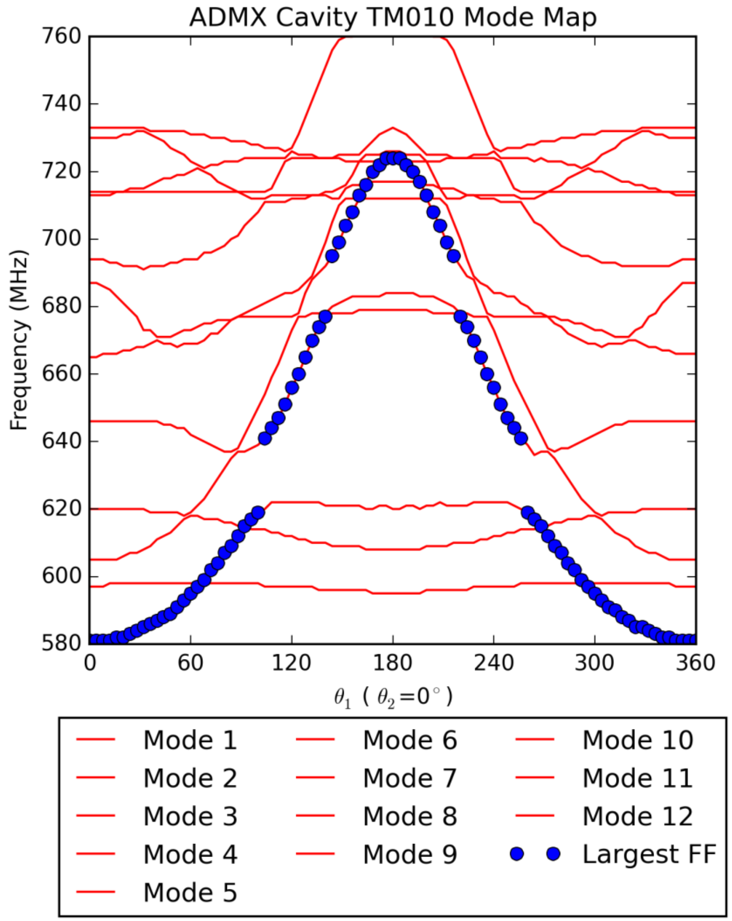
Calculator Operation	Resulting Stack Display (top entry only unless noted)
Qty→H	CVc : <Hx, Hy, Hz>
Push	*(above entry duplicated)*
Cmplx→Conj	CVc : Conj(<Hx, Hy, Hz>)
Dot	CSc : Dot(<Hx, Hy, Hz>, Conj(...
Cmplx→Real	Scl : Real(Dot(<Hx, Hy, ...
Geom→Volume→{select cavity volume}	Vol : ObjectList(cav_total) *(above is example; user entry may differ)*
∫	Scl : Integrate(ObjectList(cav... *(above represents energy stored in cavity volume)*
Push	*(above entry duplicated)*
Num→Scalar→{enter loss tan for volume}	Scl : {numerical value} *(loss tangent for dielectric fill within cavity volume)*
*	Scl : *(Integrate(ObjectList(... *(above represents energy lost in dielectric material losses)*
Qty→H	CVc : <Hx, Hy, Hz>
Geom→Surface→{select cavity surfaces}	Srf : ObjectFaces(cav_tot_faces) *(above is example; user entry may differ)*
Unit Vec→Normal	Vec : Normal(ObjectFaces(cav_...
Cross	CVc : Cross(<Hx, Hy, Hz>, Norm...
Push	*(above entry duplicated)*
Cmplx→Conj	CVc : Conj(Cross(<Hx, Hy, Hz>, ...
Dot	CSc : Dot(Cross(<Hx, Hy, Hz>, ...
Cmplx→Real	Scl : Real(Dot(Cross(<Hx, ...
Geom→Surface→{select cavity surfaces}	Srf : ObjectFaces(cav_tot_faces)
∫	Scl : Integrate(ObjectFaces(...
Num→Scalar→2	Scl : 2
Const→Pi	Scl : 3.14159265358979
Const→Frequency	Scl : {current freq, in Hz}
*	Scl : {numerical result, pi*f}
Num→Scalar→{enter μ_r for walls}	Scl : {entered value, unitless}
*	Scl : {numerical result, pi*f*mur}
Const→Mu0	Scl : 1.25663706144E-006
*	Scl : {numerical, pi*f*mur*mu0}
Num→Scalar→{enter wall conductivity}	Scl : {entered value, s/meter}
*	Scl : {numerical, pi*f*mur*mu0*σ}
√	Scl : {numerical, sqrt of above}
*	Scl : {numerical result, 2*above}
1/x	Scl : {numerical result} *(above is skin depth/2)*
*	Scl : *(Integrate(ObjectFaces... *(above is energy lost in walls)*
+	Scl : +(*(Integrate(ObjectFaces...
/	Scl : /(+(*(Integrate(...
Eval	Scl : {numerical result} *(above is Q of homogeneous fill and wall conductivity cavity, unitless)*

Example Comparison with Measurement

- Excellent agreement for ADMX cylindrical cavity
  - HFSS solution includes 12 modes in vicinity of TM_{010} mode
  - Blue markers indicate mode with largest form factor at each rod location

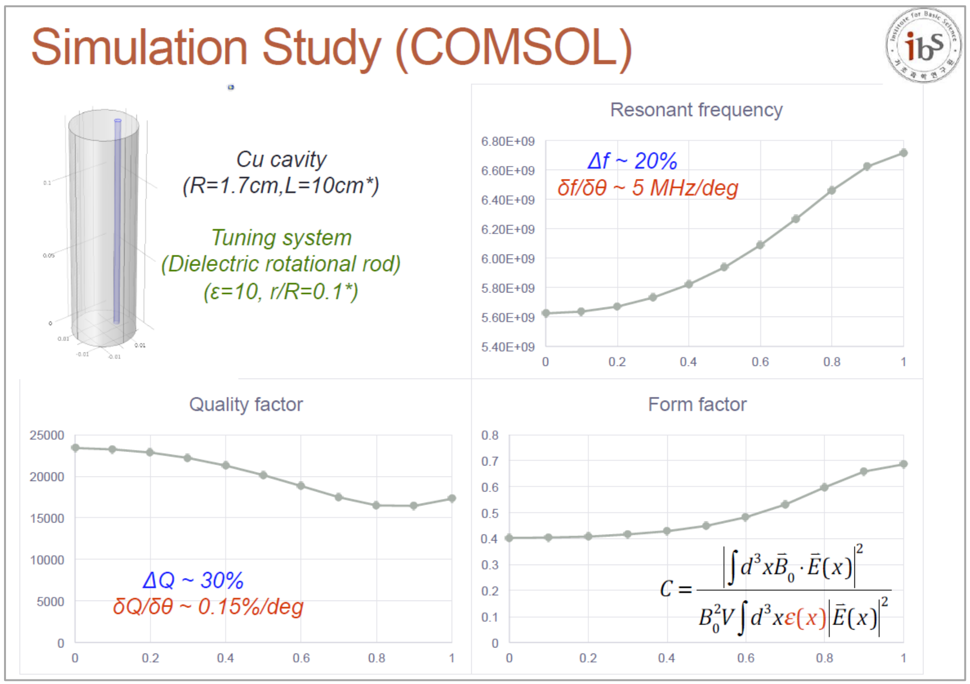


Measured and COMSOL results
(Lyapustin 2015)

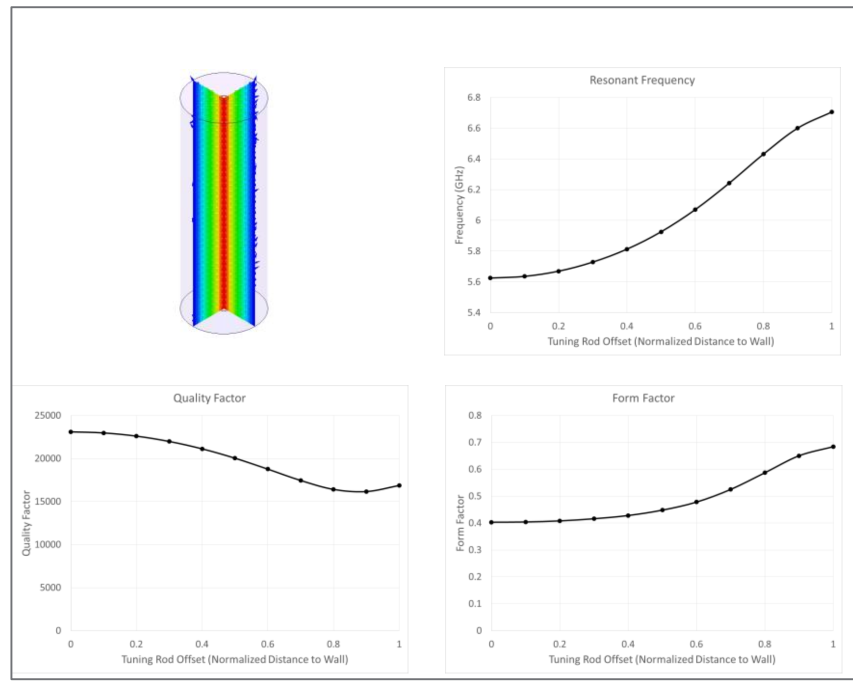


Example Comparison with COMSOL

- Model presented by SungWoo Youn at January 2017 Workshop on Microwave Cavities and Detectors for Axion Research
- Dielectric rod moved from center to wall in 1.5 mm increments

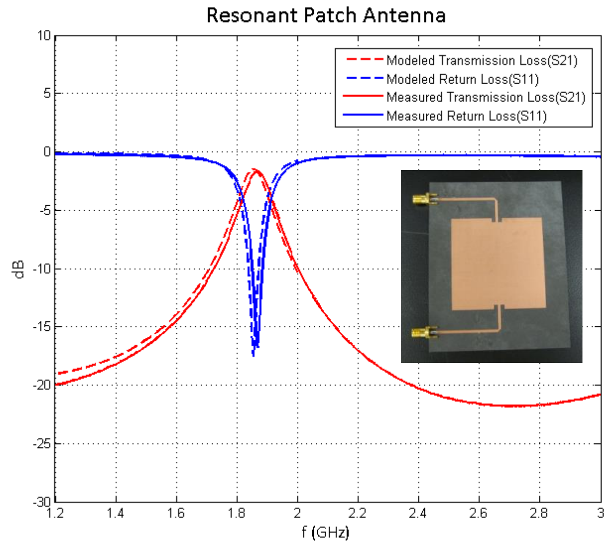


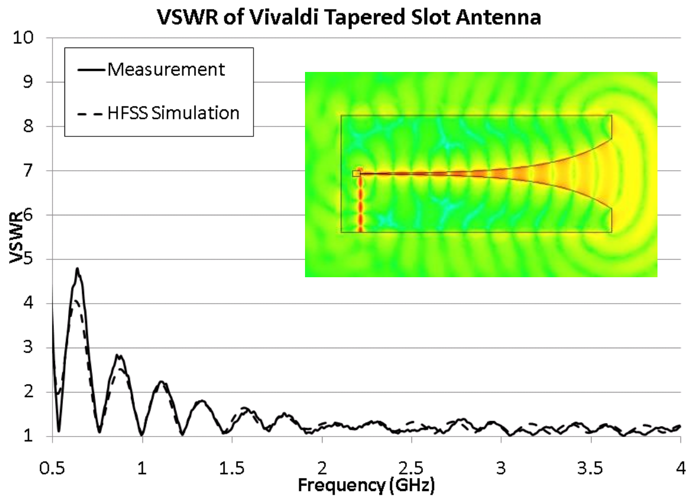
Youn 2017

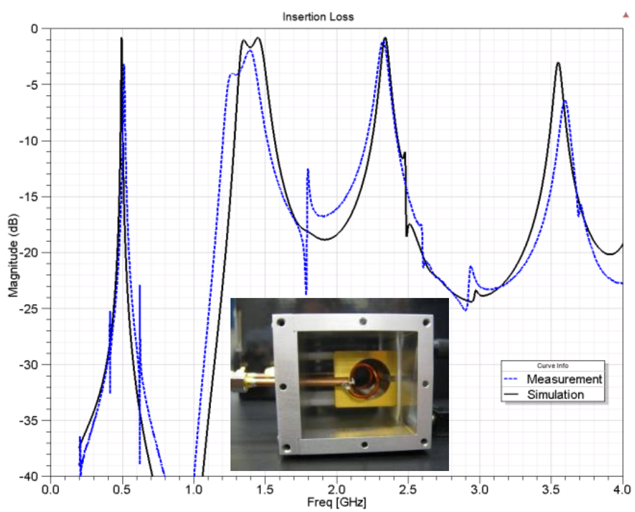


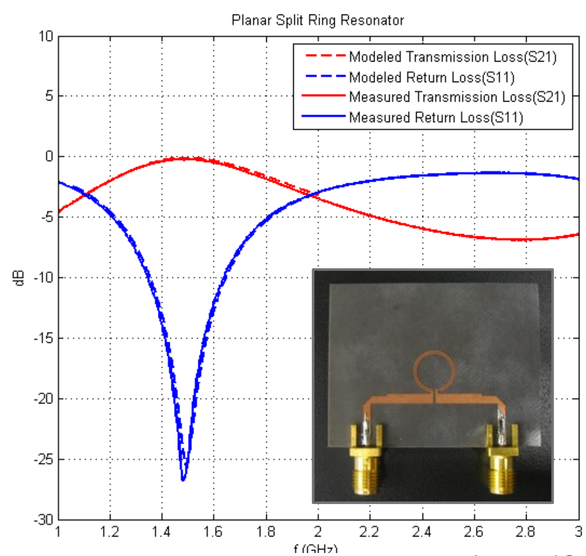
HFSS Results

Other Comparisons with Measurements









Cylindrical Cavity Example

Cylindrical Cavity Example

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- Empty copper cavity
  - Radius = 21 cm
  - Height = 100 cm
- Expected results for TM_{010} mode
  - f_R = 546.42 MHz
  - Q-factor = 61,391 (Li and Jiang, 2006)
  - Form factor C = 0.69 (Peng *et al.*, 2000)
  - Form factor C = 0.692 (Stern *et al.*, 2015)

$$f_{010} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{p'_{01}}{r}\right)^2 + \left(\frac{0\times\pi}{d}\right)^2}$$

$$f = \frac{c}{2.61r}$$

$$Q_u = \left(\frac{H}{R+H}\right)\left(\frac{R}{\delta}\right) \qquad Q_0 = Q_c = \frac{2V}{S\sqrt{\frac{2}{\omega\mu\sigma}}}$$

$$C = \frac{\left|\int_V d^3x\, \vec{E}_\omega \cdot \vec{B}_0\right|^2}{B_0^2 V \int_V d^3x\, \epsilon |\vec{E}_\omega|^2}$$

1: Create HFSS Project

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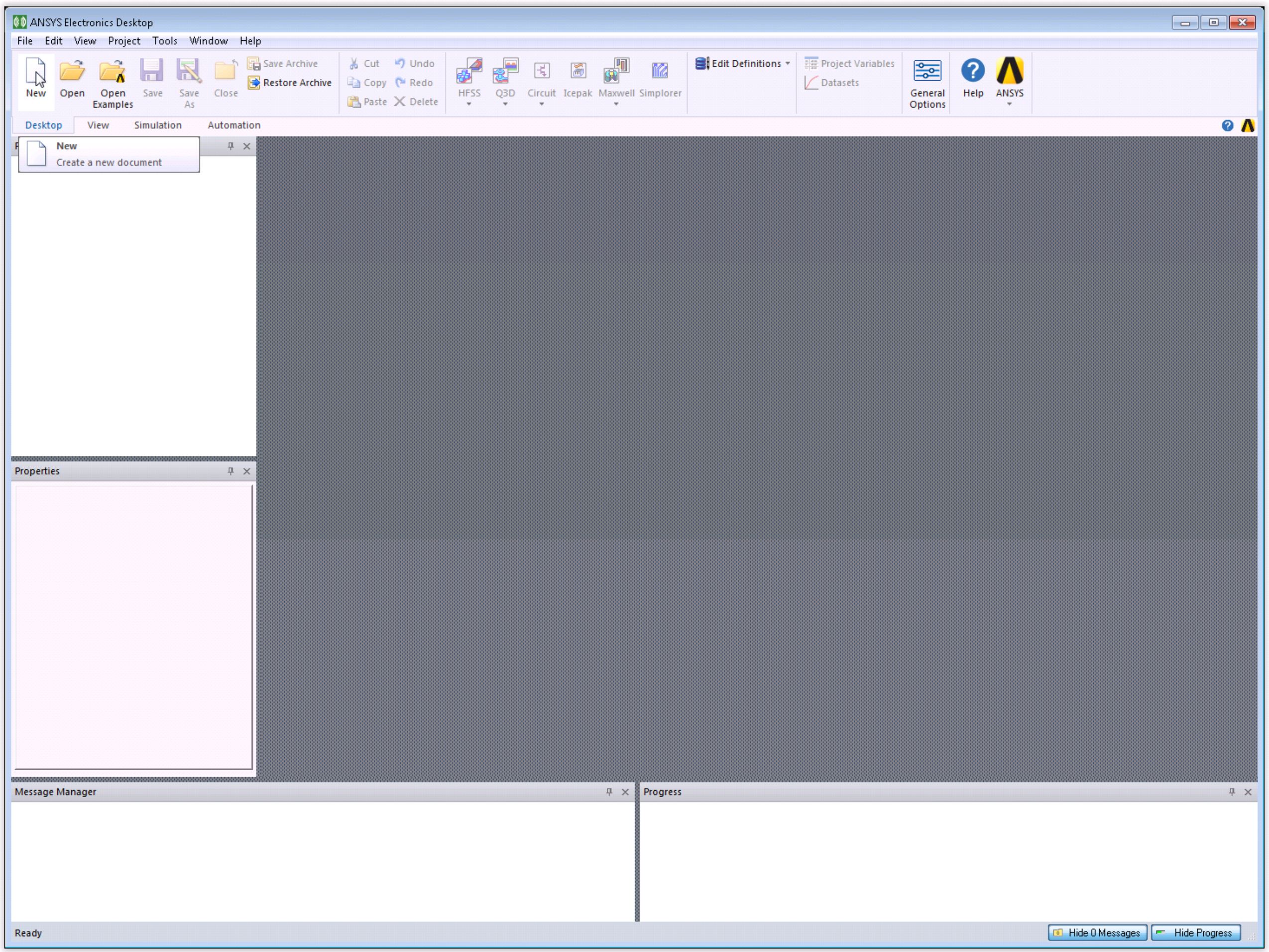
- Insert into Electronics Desktop using ***New***



2: Set Eigenmode Solution Type

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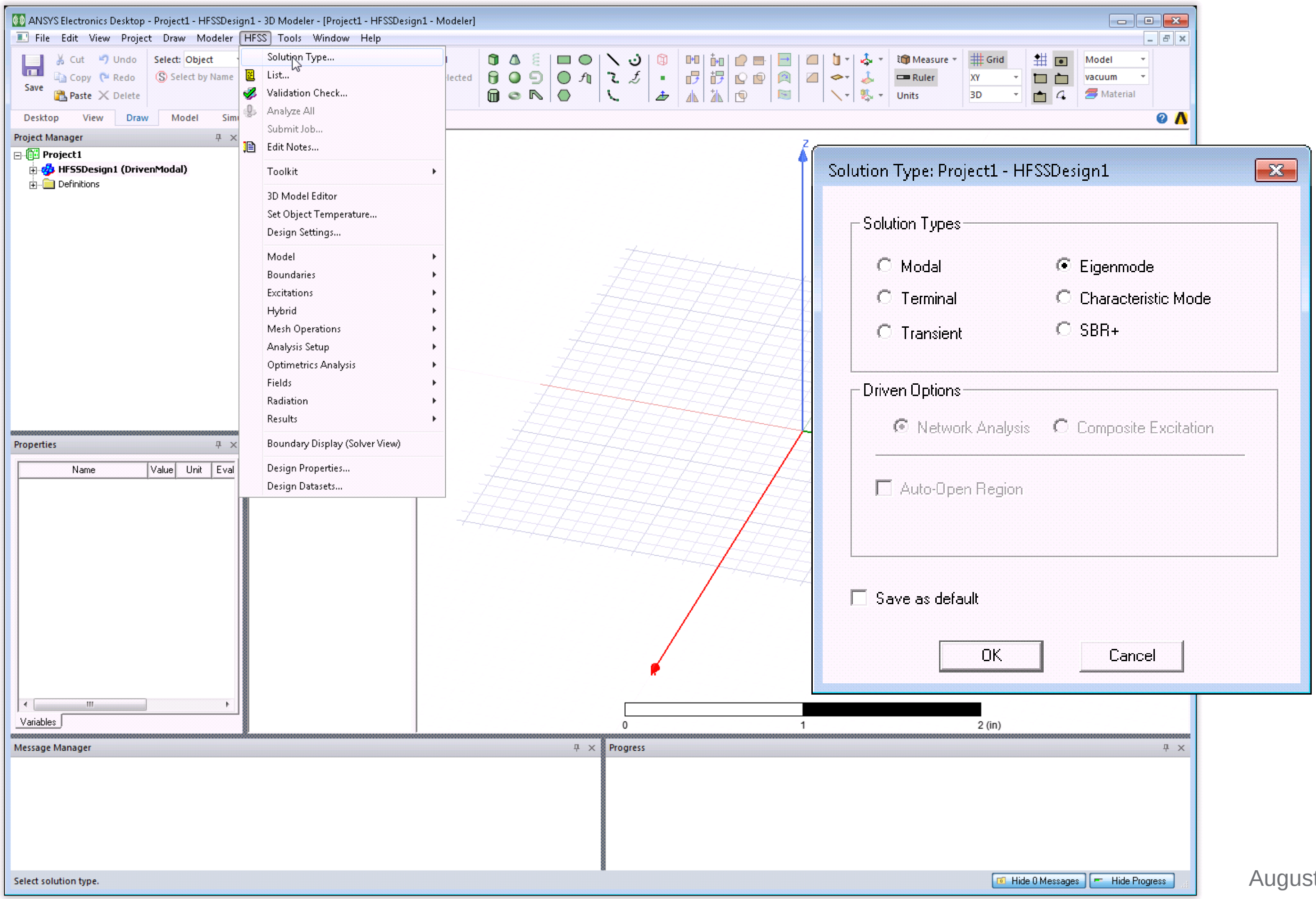
- Select ***HFSS > Solution Type > Eigenmode***



3: Set Model Units

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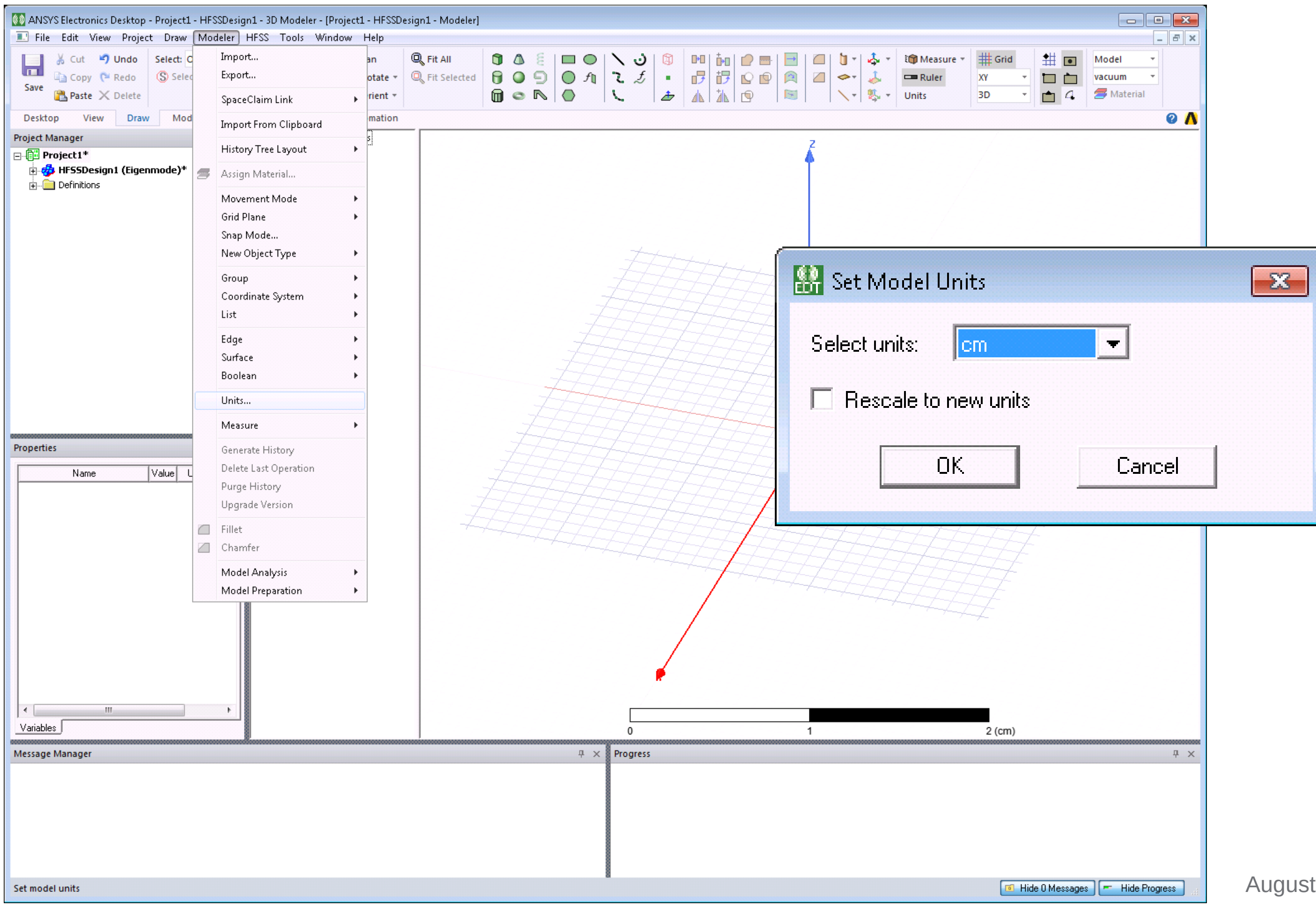
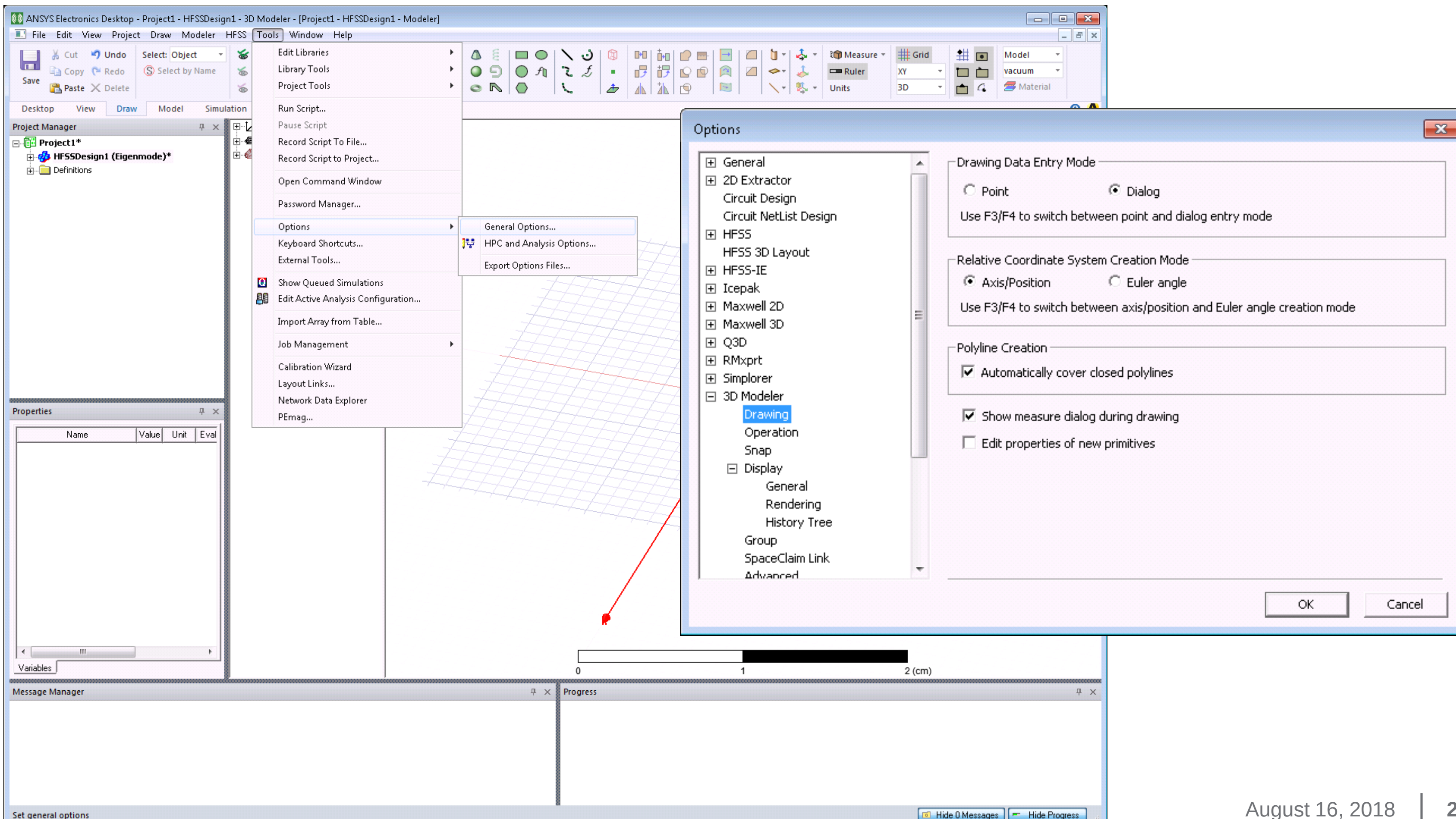
- Select ***Modeler > Units > cm***



4: Set Dialog Data Entry Mode

- Select ***Tools > Options > General Options > 3D Modeler > Drawing > Dialog***



5: Set Default Transparency of 0.7

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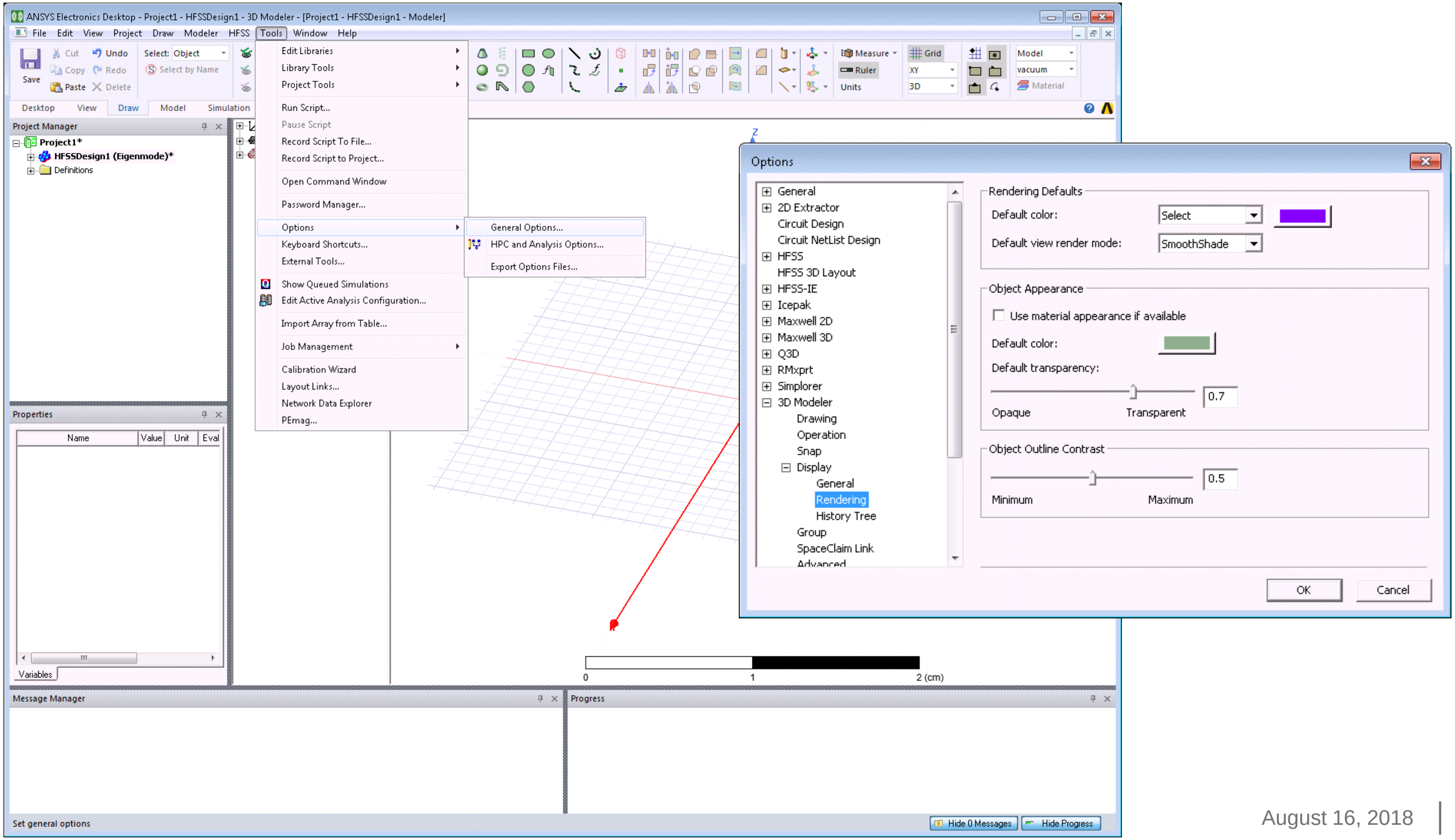
- Select ***Tools > Options > General Options > Display > Rendering***



6: Create Parameterized Cavity

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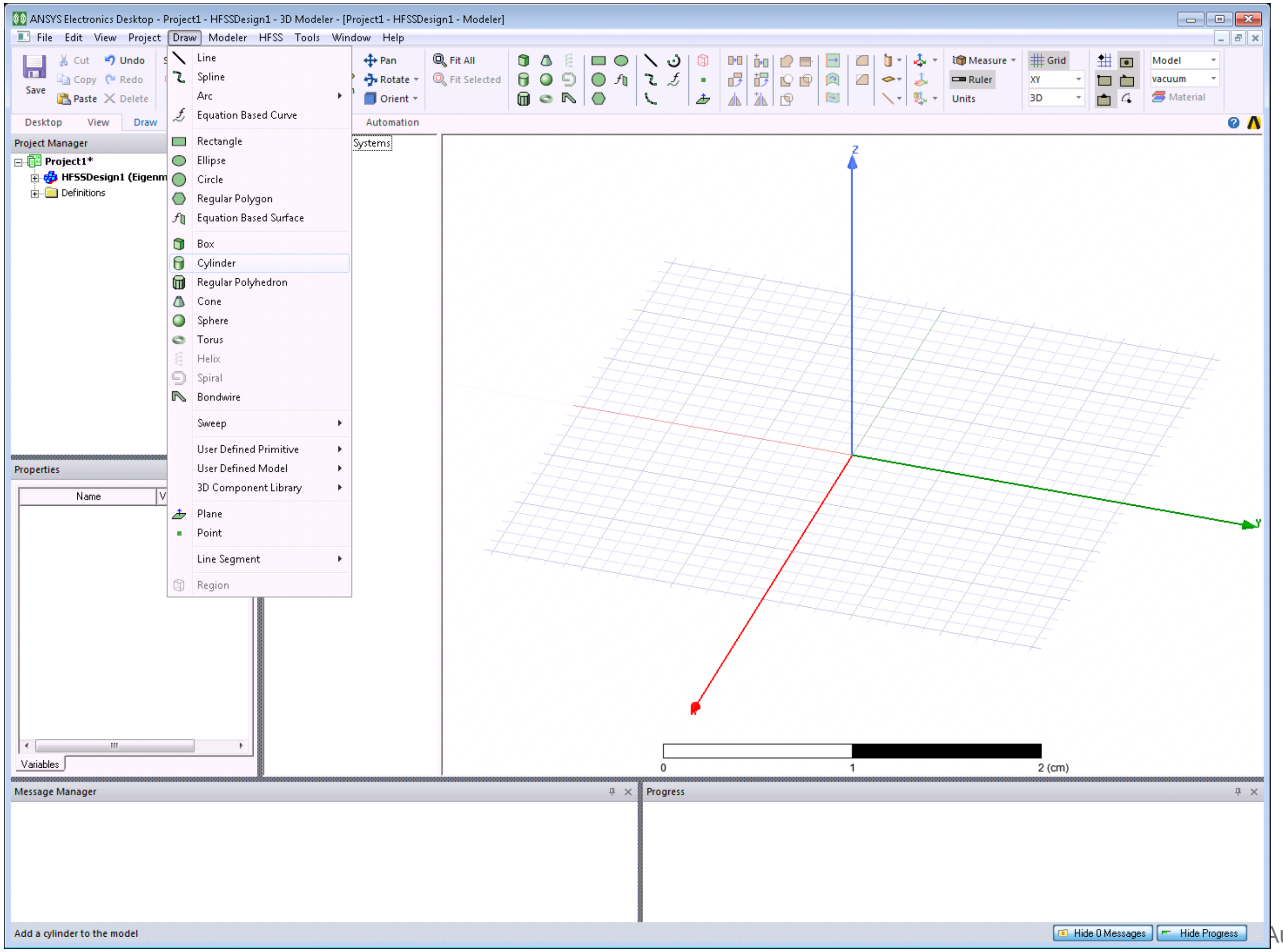
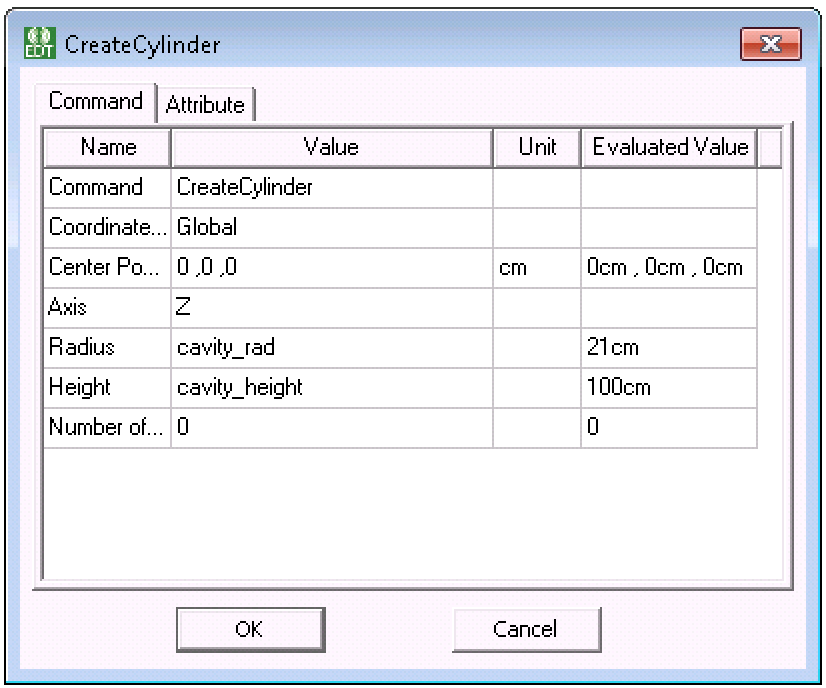
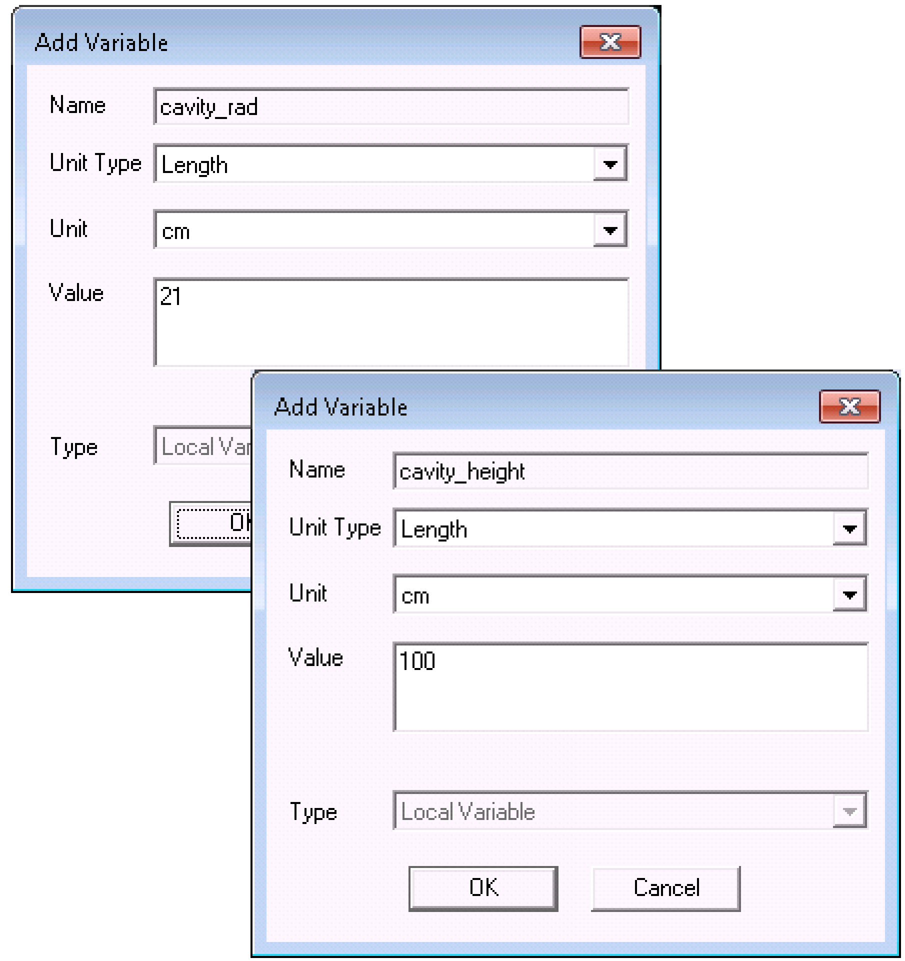
- Select ***Draw > Cylinder***



6: Create Parameterized Cavity

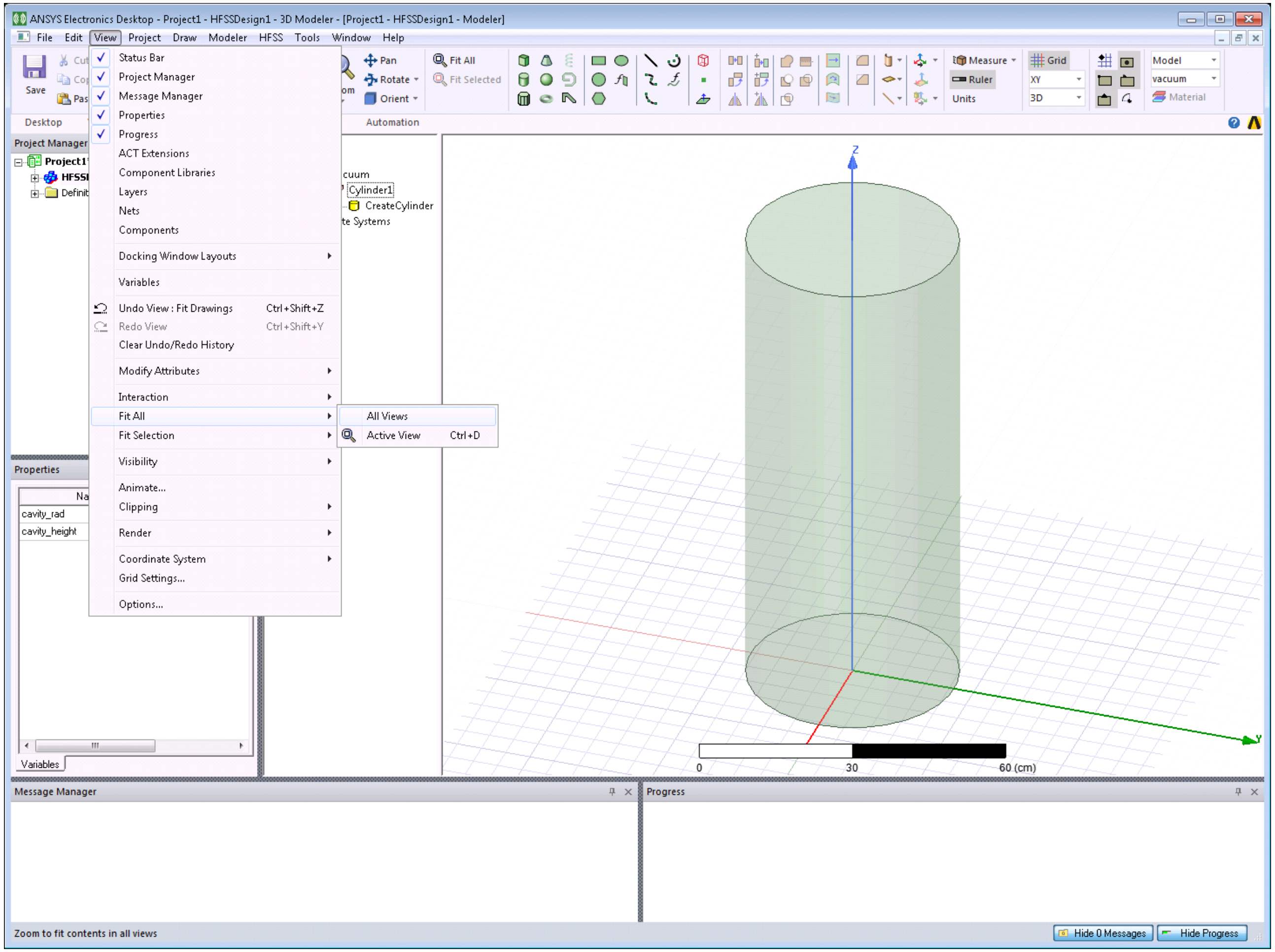
- Cavity_rad = 21 cm
- Cavity_height = 100 cm





6: Create Parameterized Cavity

- Fit cavity to view using ***View > Fit All > All Views***



7: Assign Cavity Wall Conductivity

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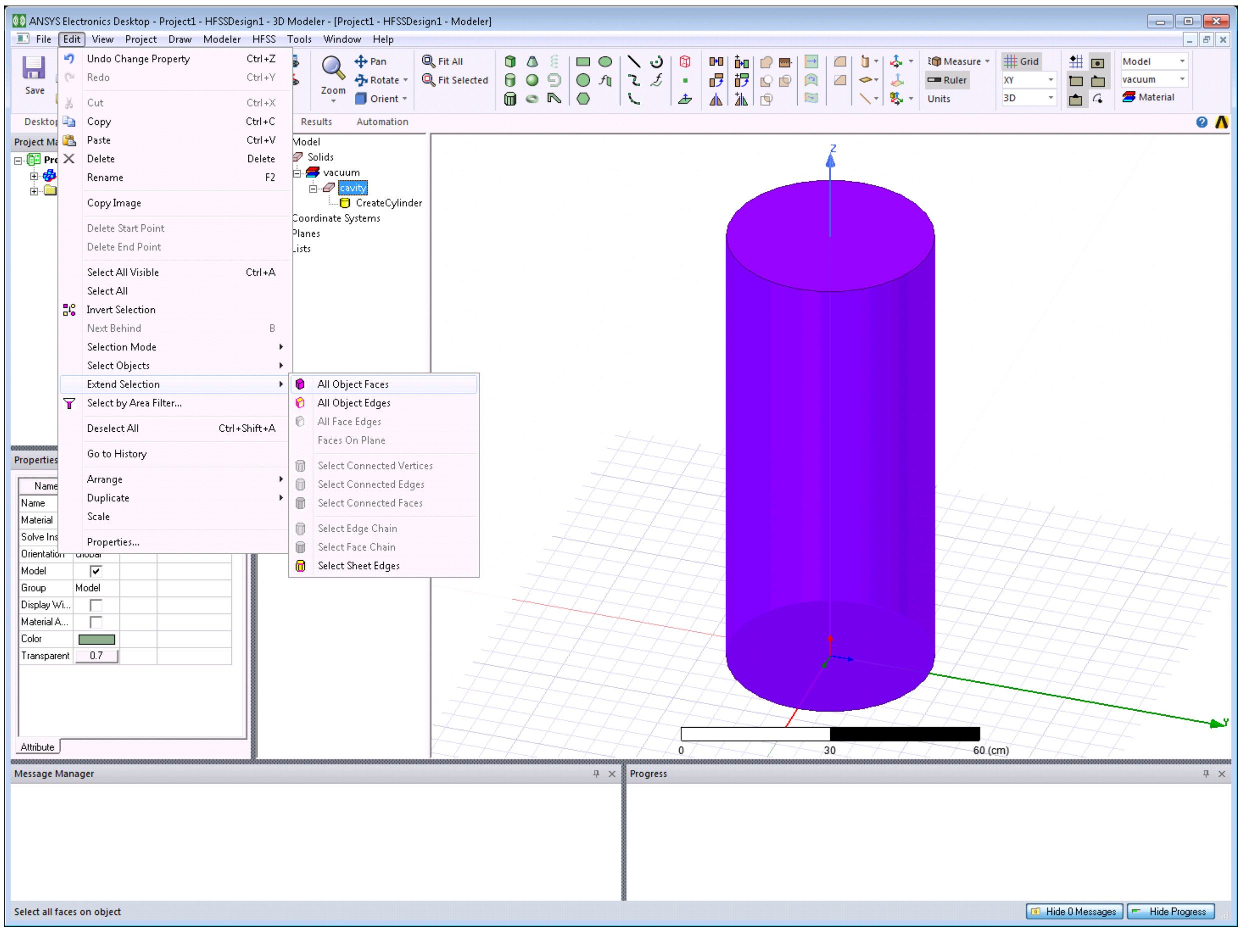
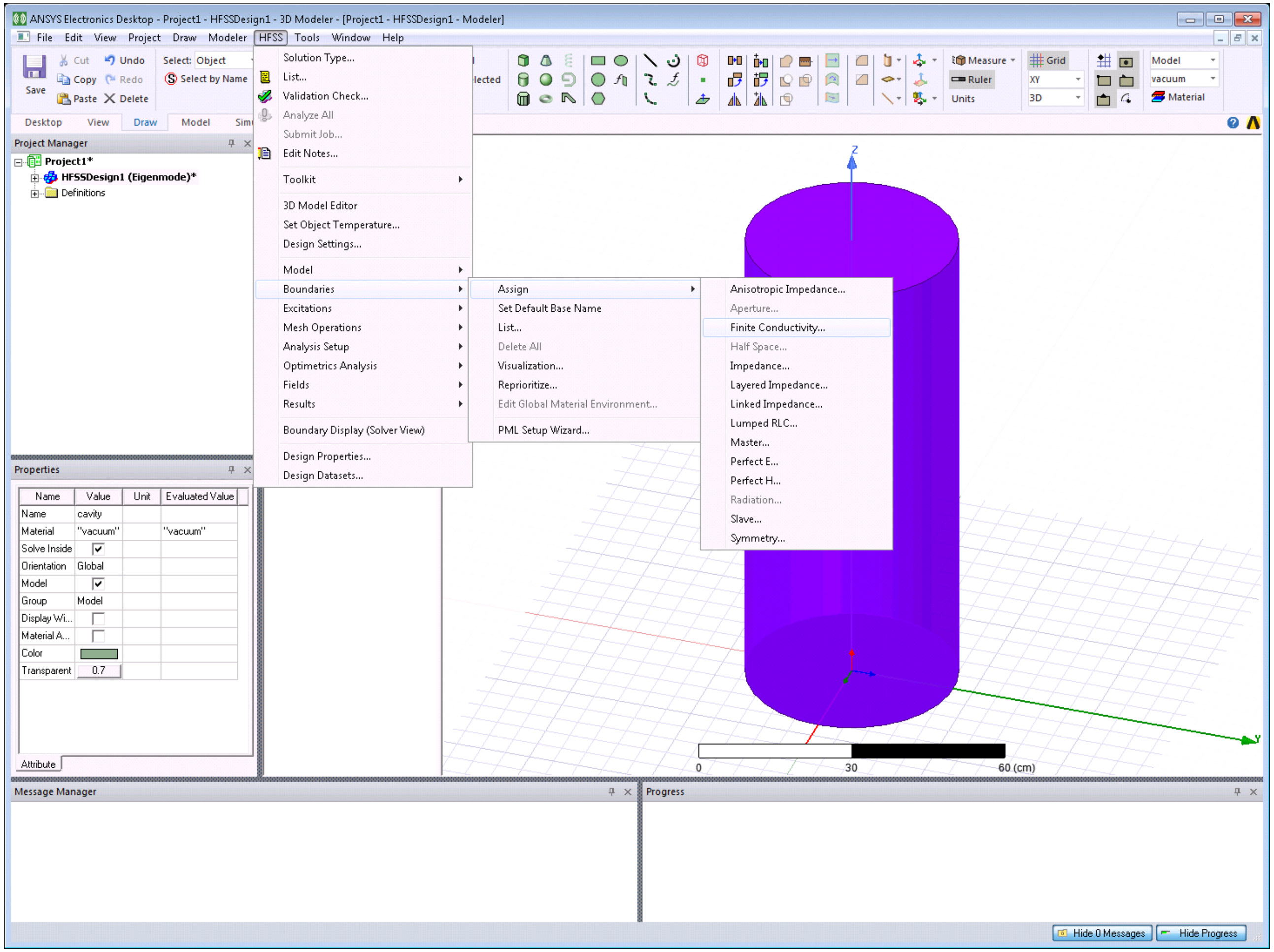
- Select cavity in 3D modeler tree and ***Edit > Extend Selection > All Object Faces***



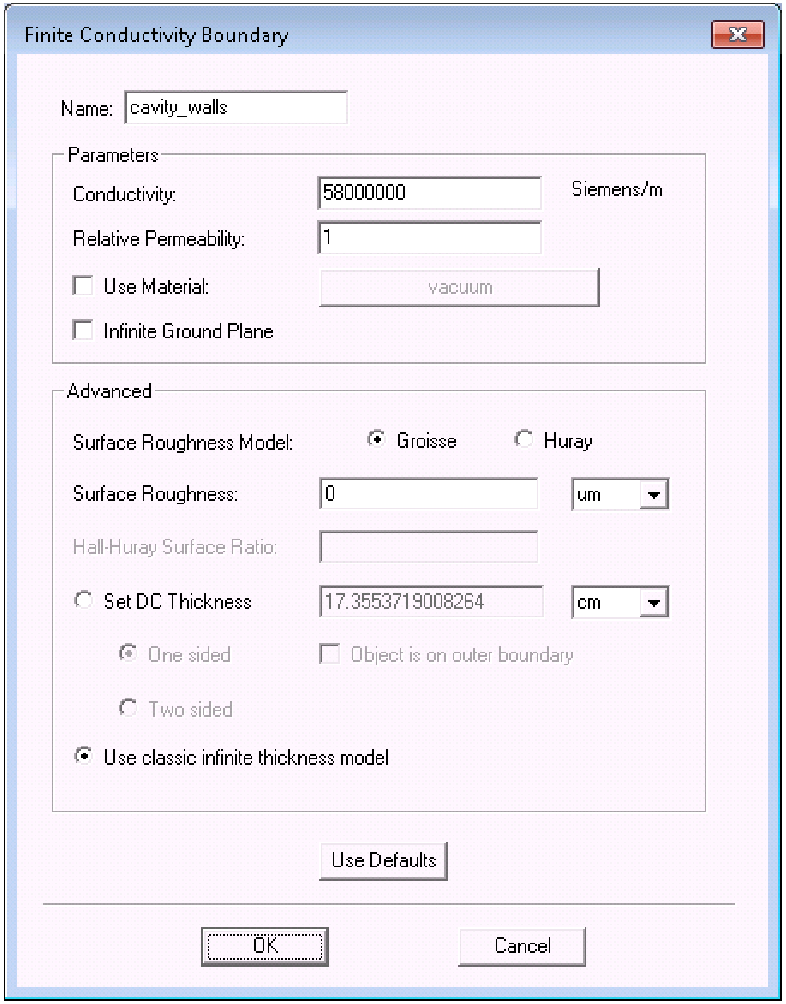
7: Assign Cavity Wall Conductivity

- Select ***HFSS > Boundaries > Assign > Finite Conductivity***



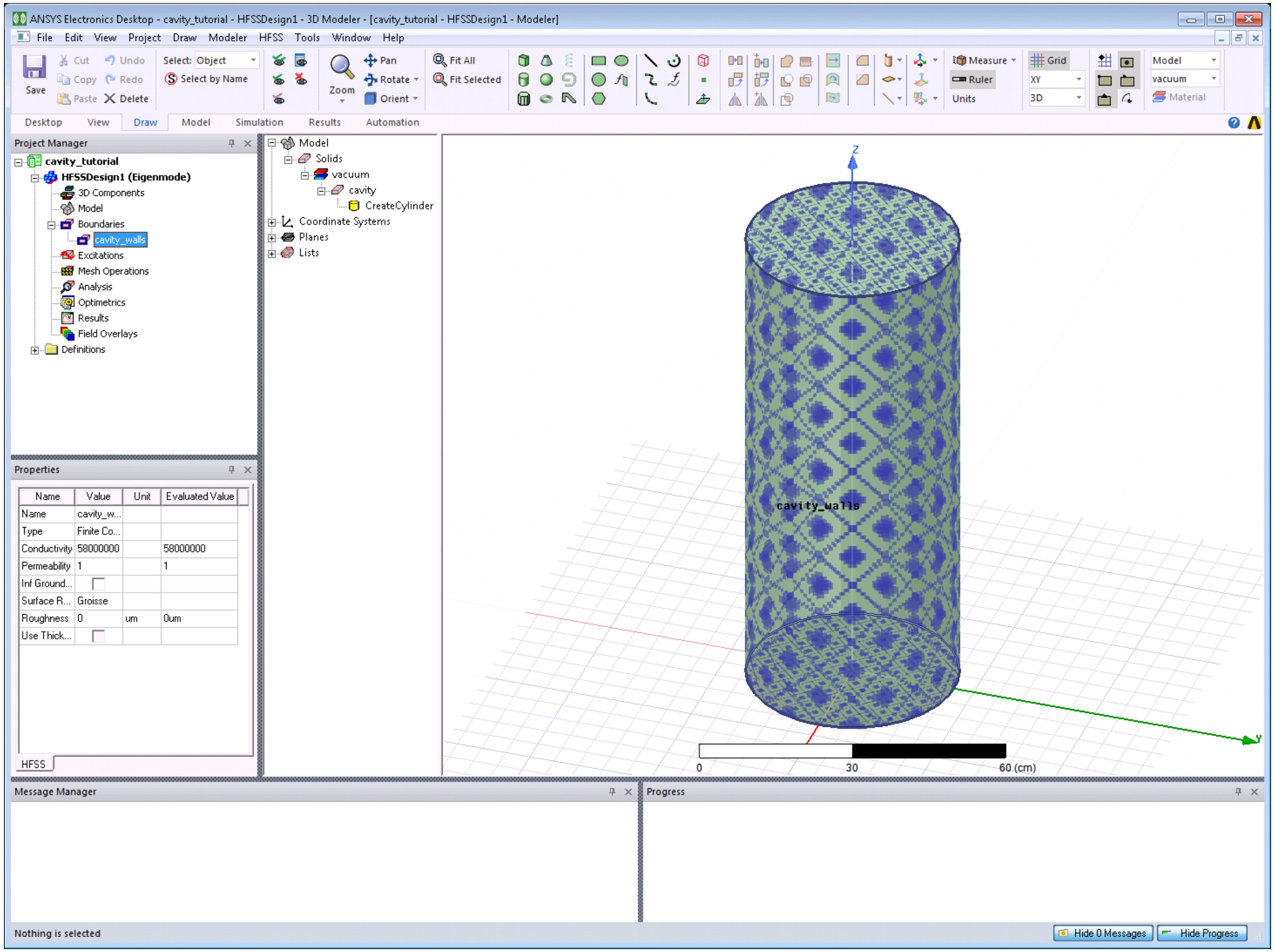
7: Assign Cavity Wall Conductivity

- Enter name “cavity_walls” and use default 5.8E7 S/m



7: Assign Cavity Wall Conductivity

- Should have boundary condition as shown here



8: Apply Curvilinear Mesh Elements

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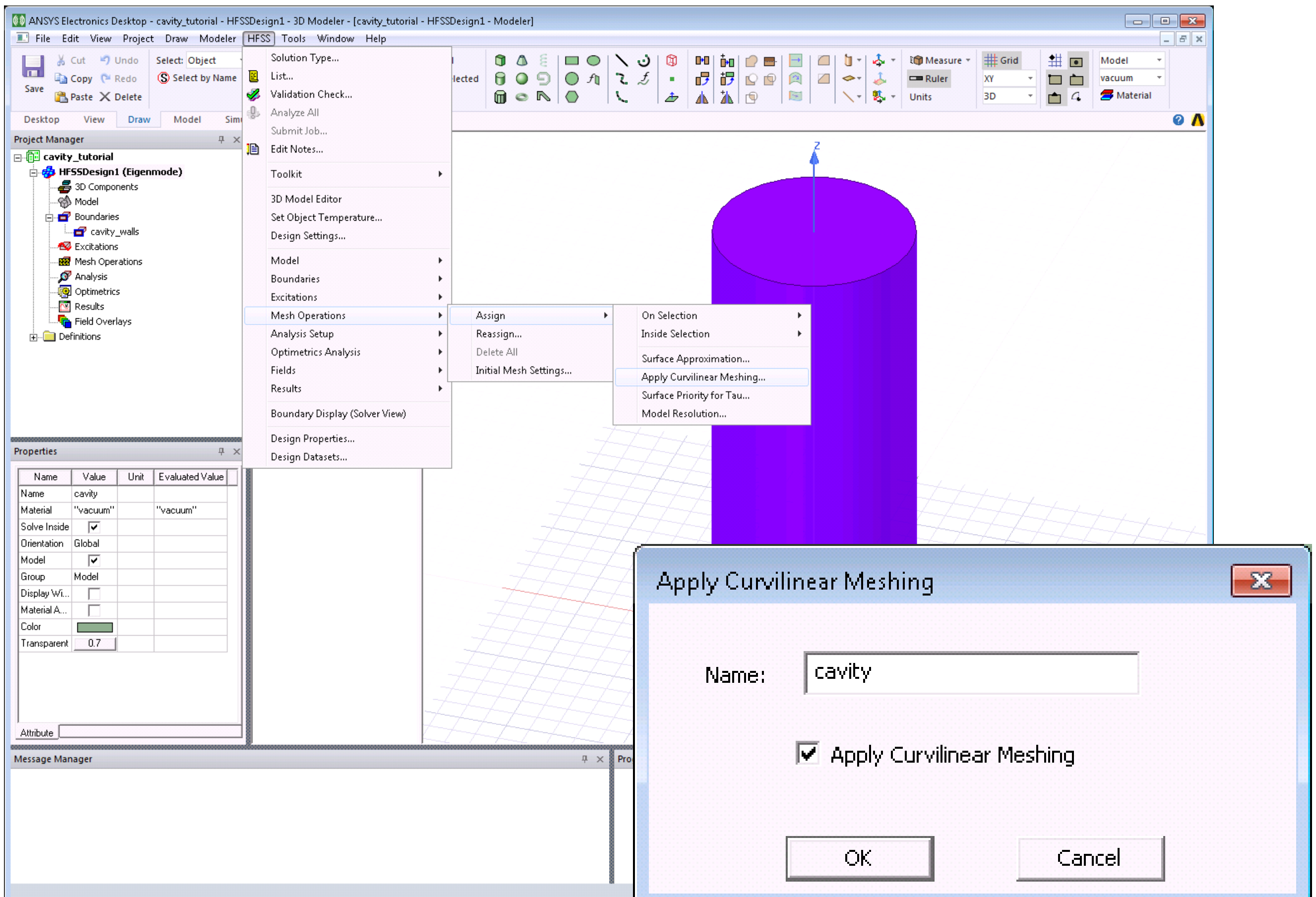
- Select cavity in 3D modeler tree and apply curvilinear elements
- Select ***HFSS > Mesh Operations > Assign > Apply Curvilinear Meshing***



8: Apply Curvilinear Mesh Elements

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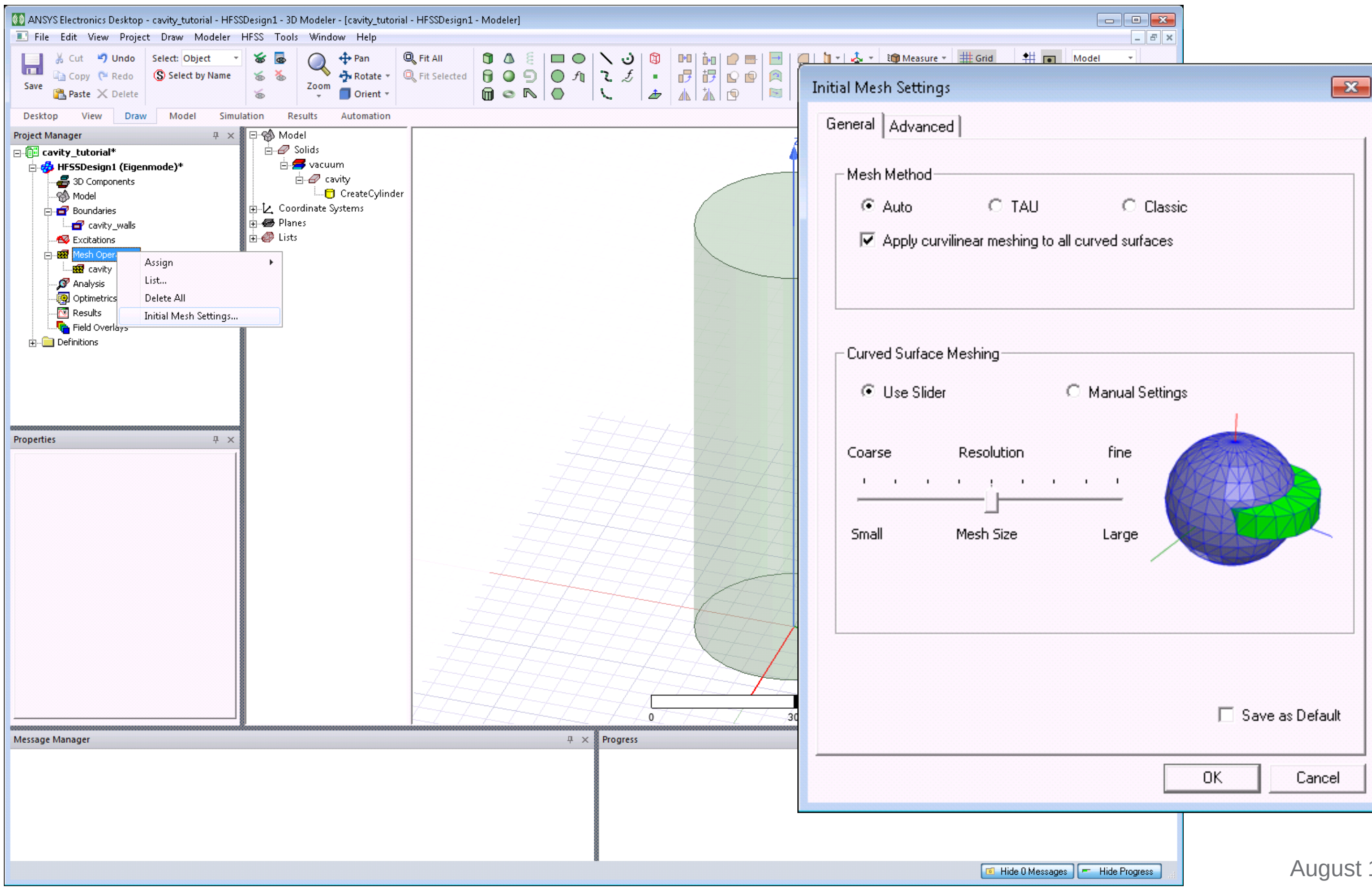
- Can also apply curvilinear elements as global setting
- Right-click ***Mesh Operations > Initial Mesh Settings***



9: Add Solution Setup

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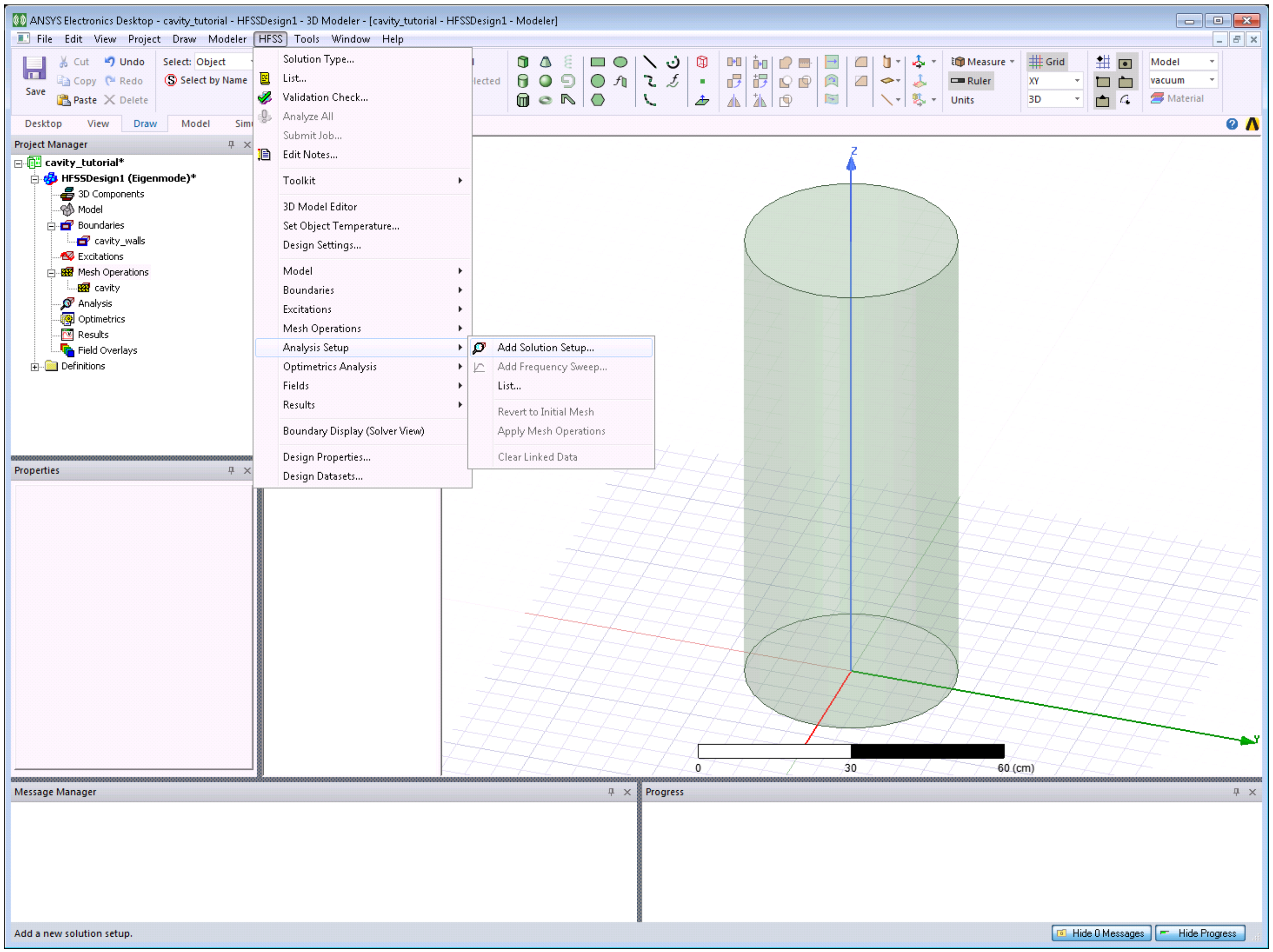
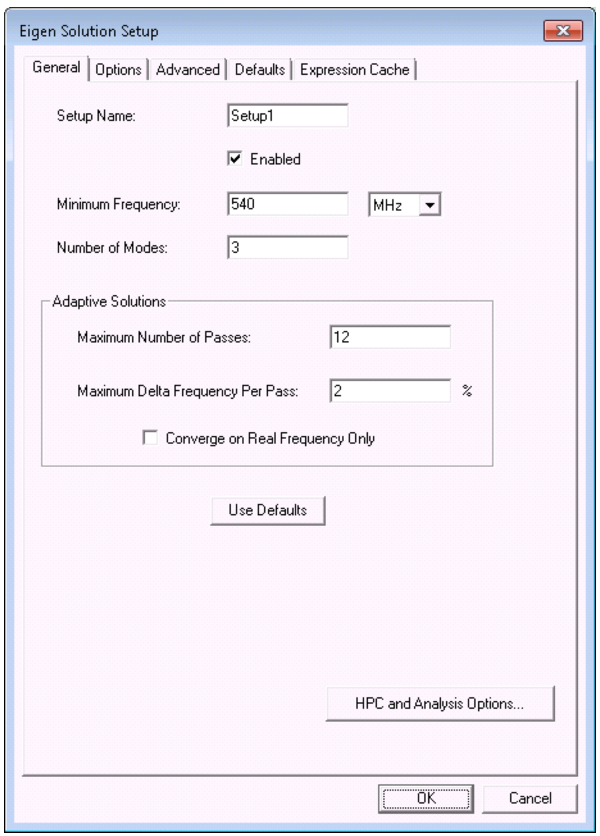
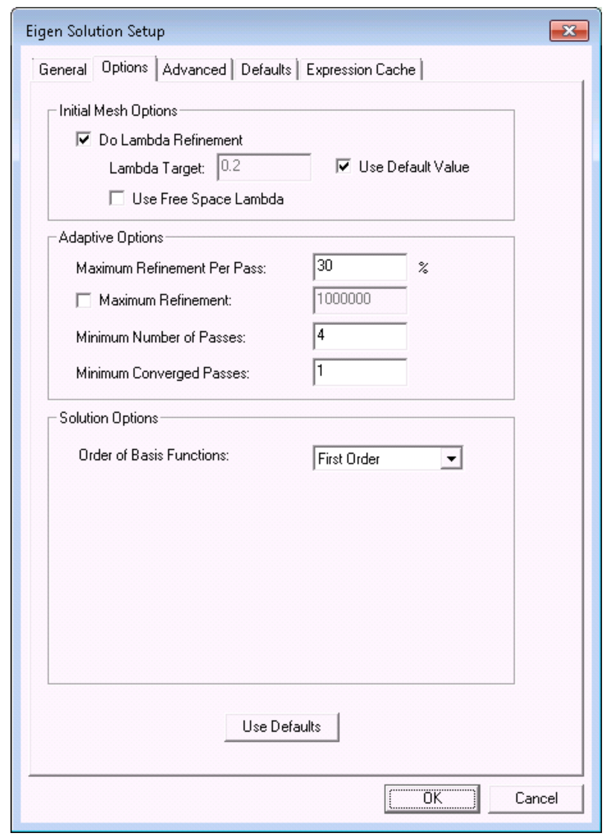
- Select ***HFSS > Analysis Setup > Add Solution Setup***



9: Add Solution Setup

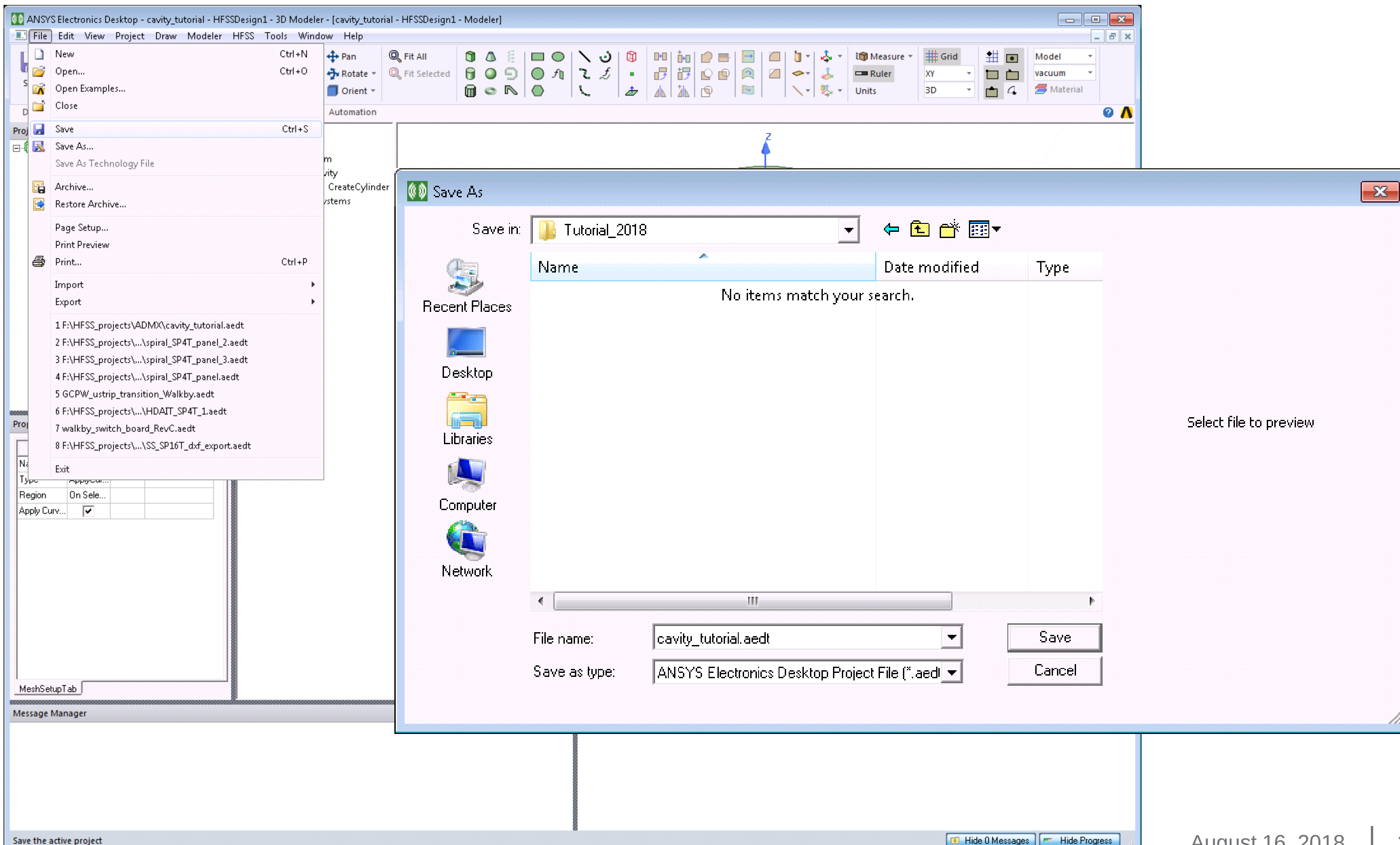
- Enter Minimum frequency = 540 MHz, Number of Modes = 3, Maximum Number of Passes = 12, Max Delta Frequency / Pass = 2%, Minimum Passes = 4





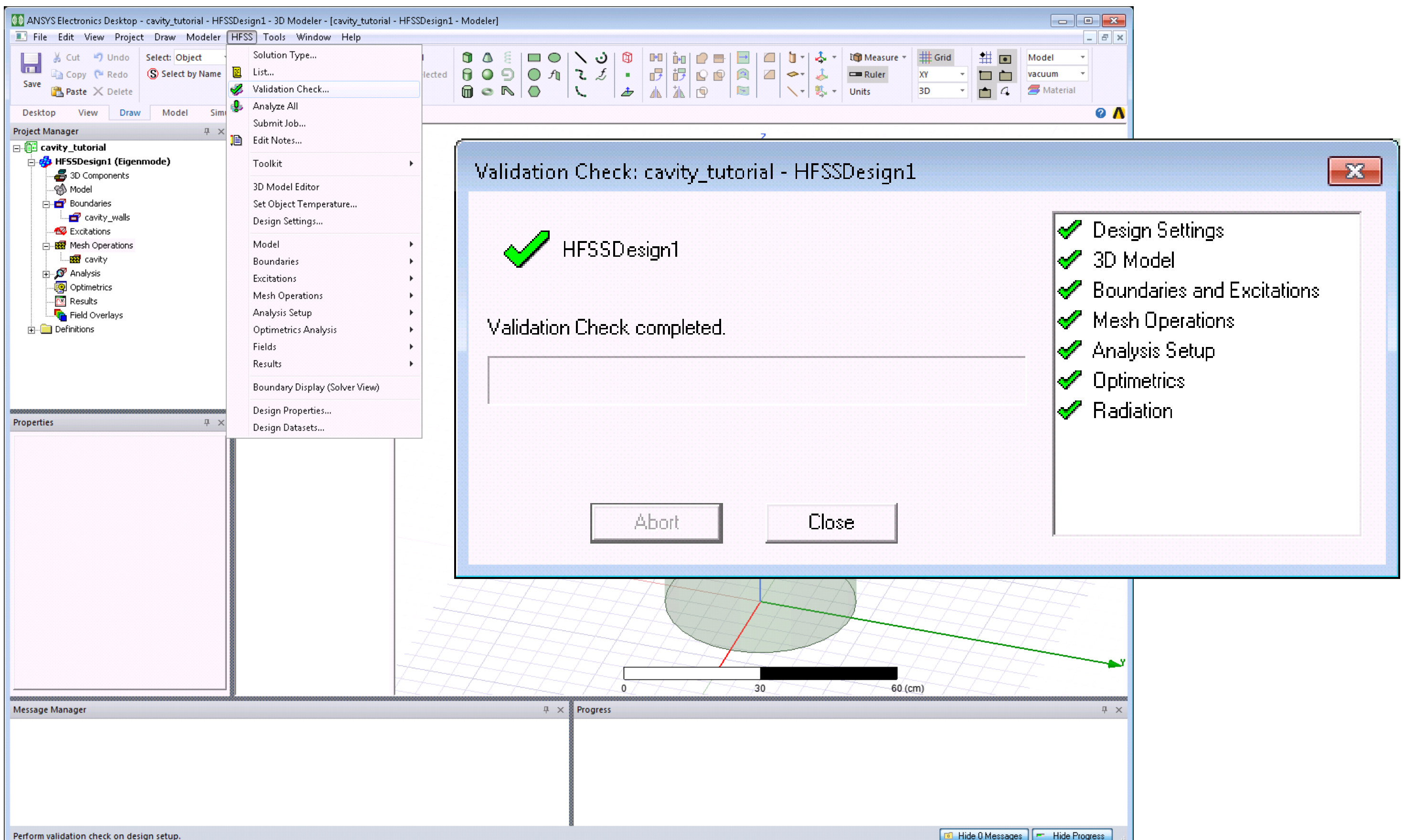
10: Save Project

- Select ***File > Save*** and save project as “cavity_tutorial.aedt”



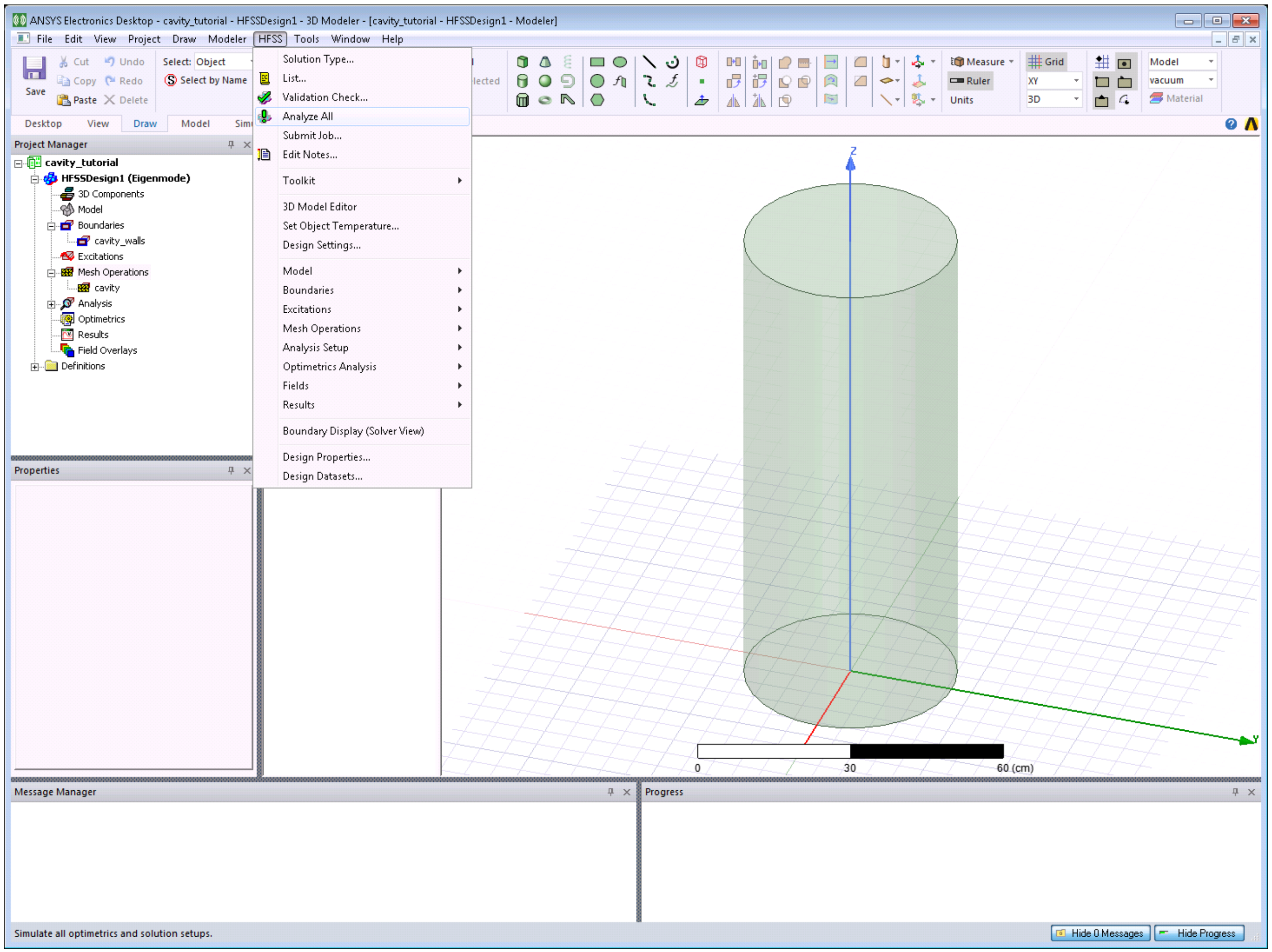
11: Perform Validation Check

- Select ***HFSS > Validation Check***
- Confirms that required steps to solve model have been performed



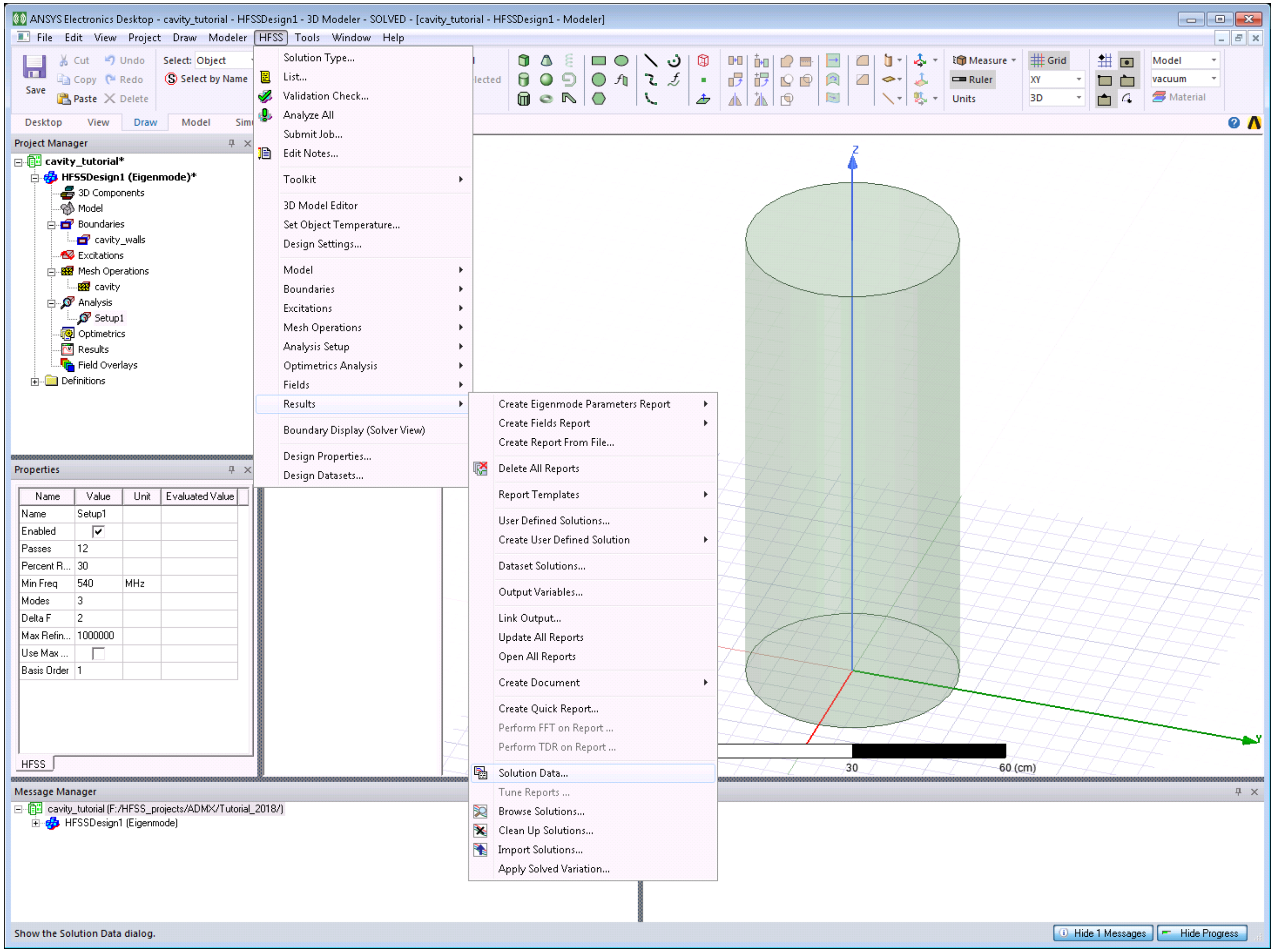
12: Solve Model

- Select ***HFSS > Analyze All***



13: View Solution Data

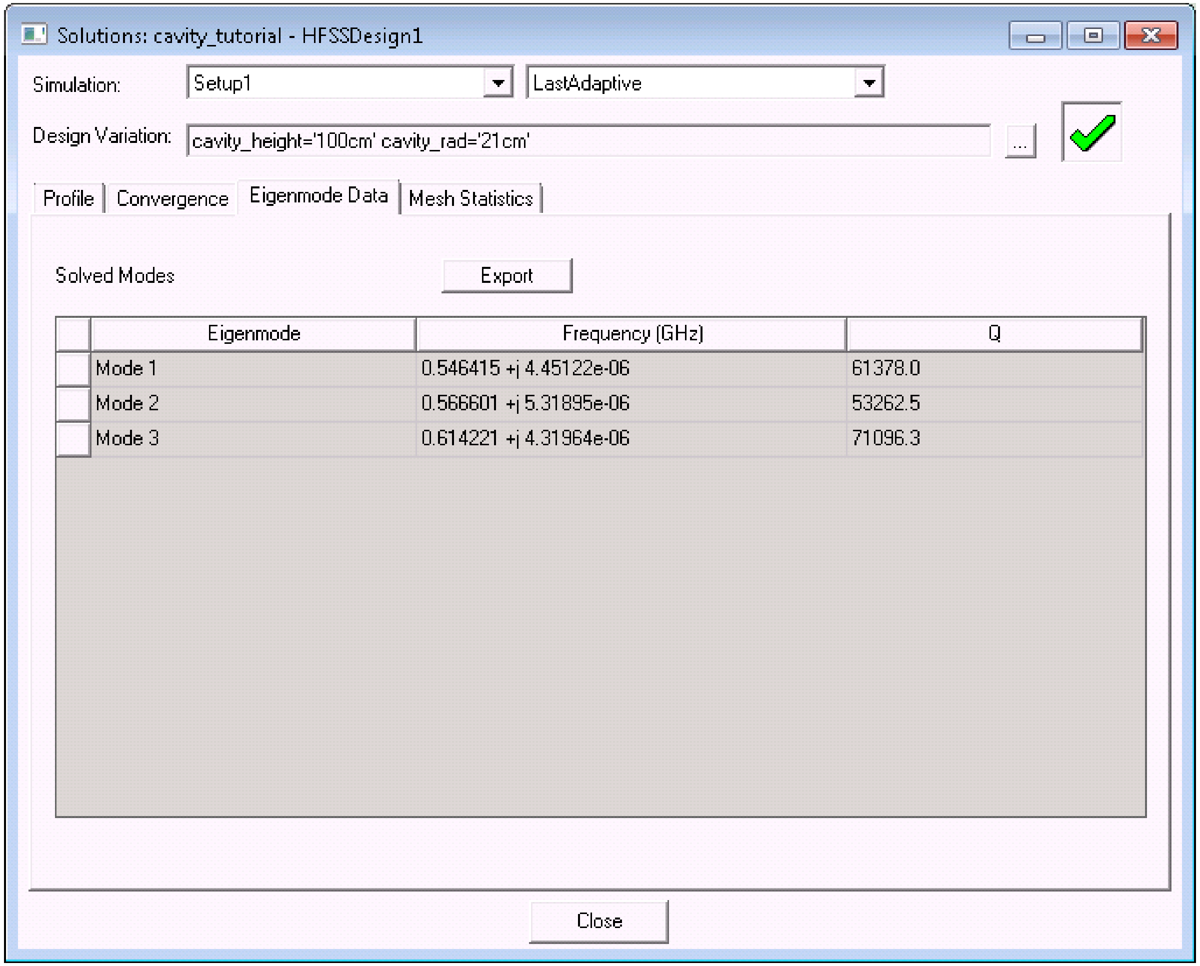
- Select ***HFSS > Results> Solution Data***



13: View Solution Data

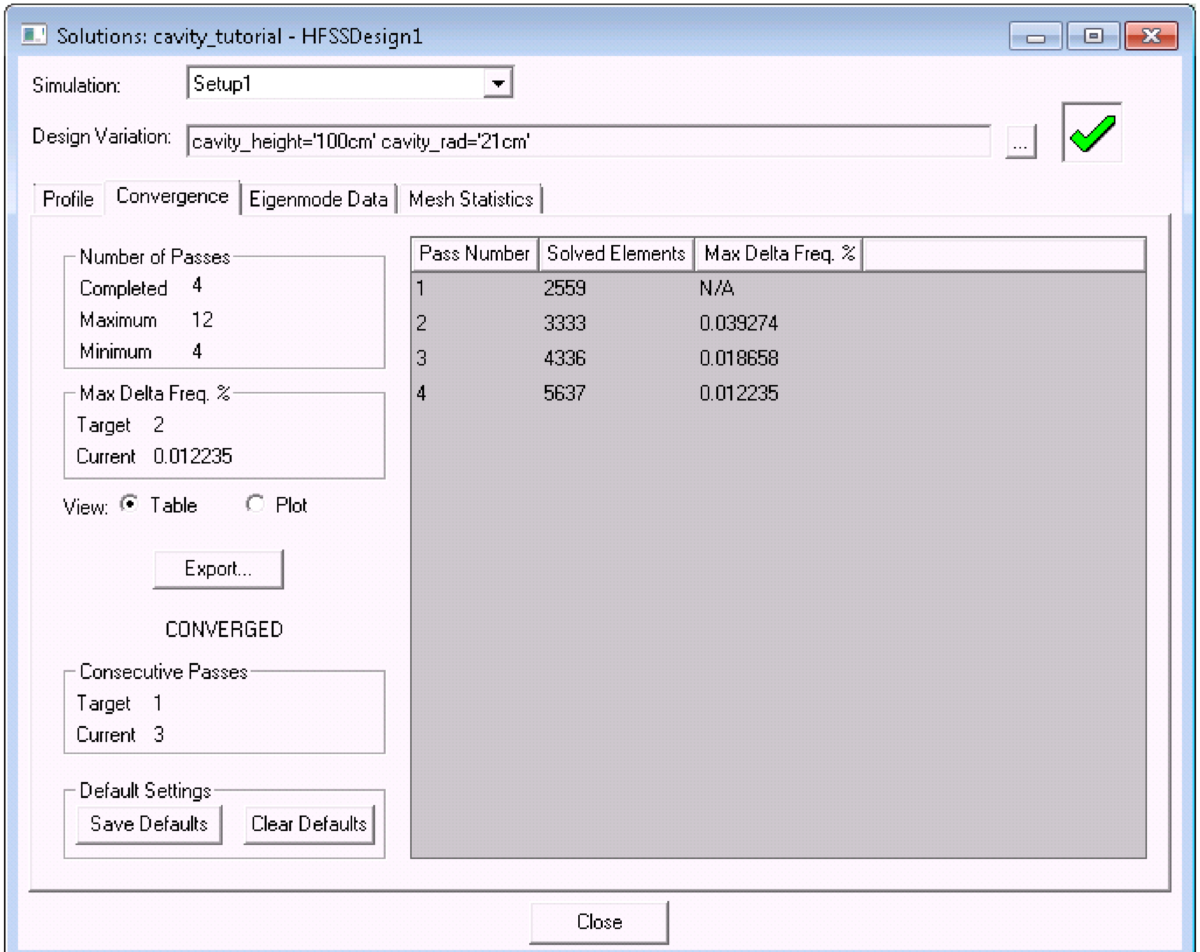
- Select ***Eigenmode Data*** tab to view modal frequencies and Q-factors

TM_{010}
TM_{011}
TE_{113}



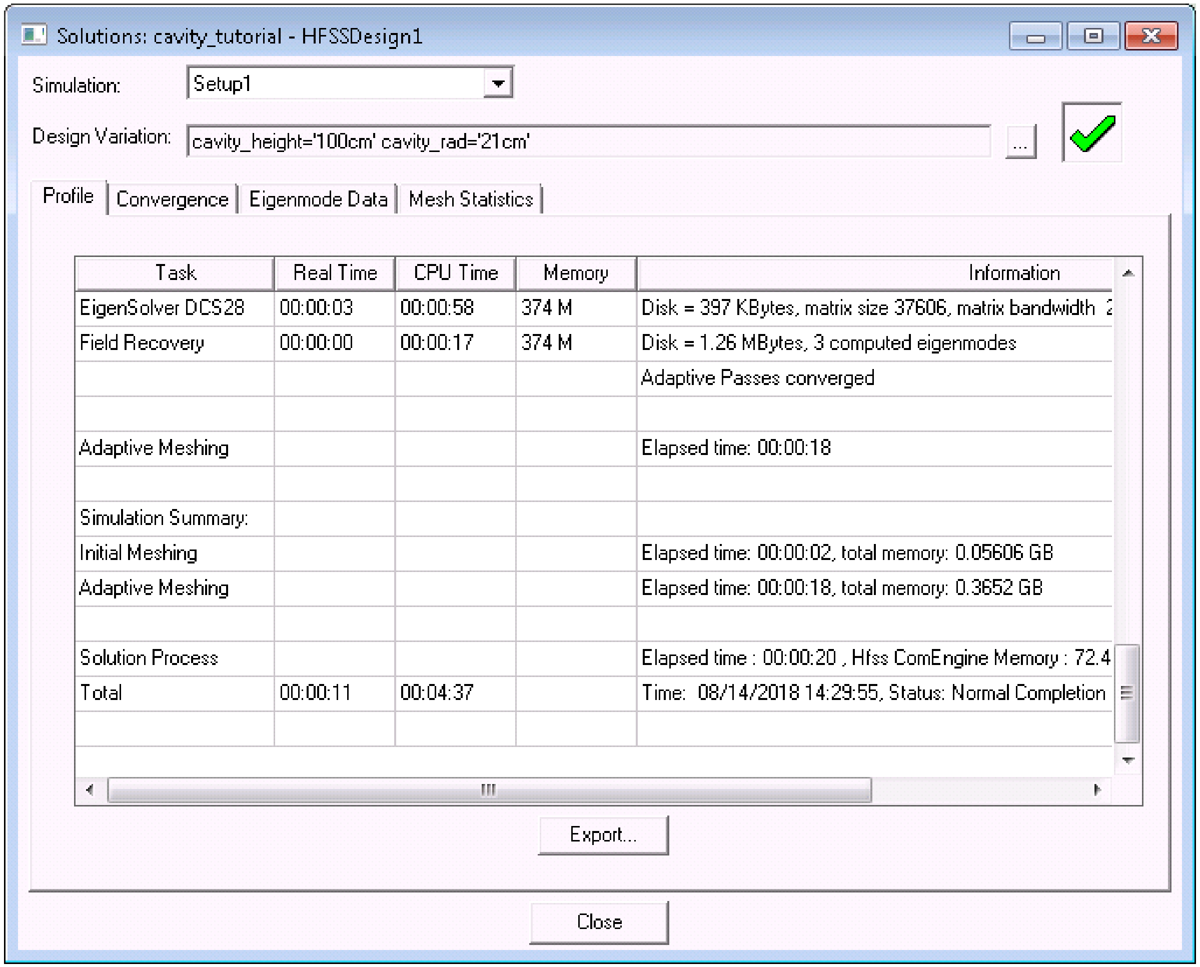
13: View Solution Data

- Select ***Convergence*** tab to view adaptive pass information



13: View Solution Data

- Select ***Profile*** tab to view run log file (20 sec runtime)



14: View E-Field Phase Animation

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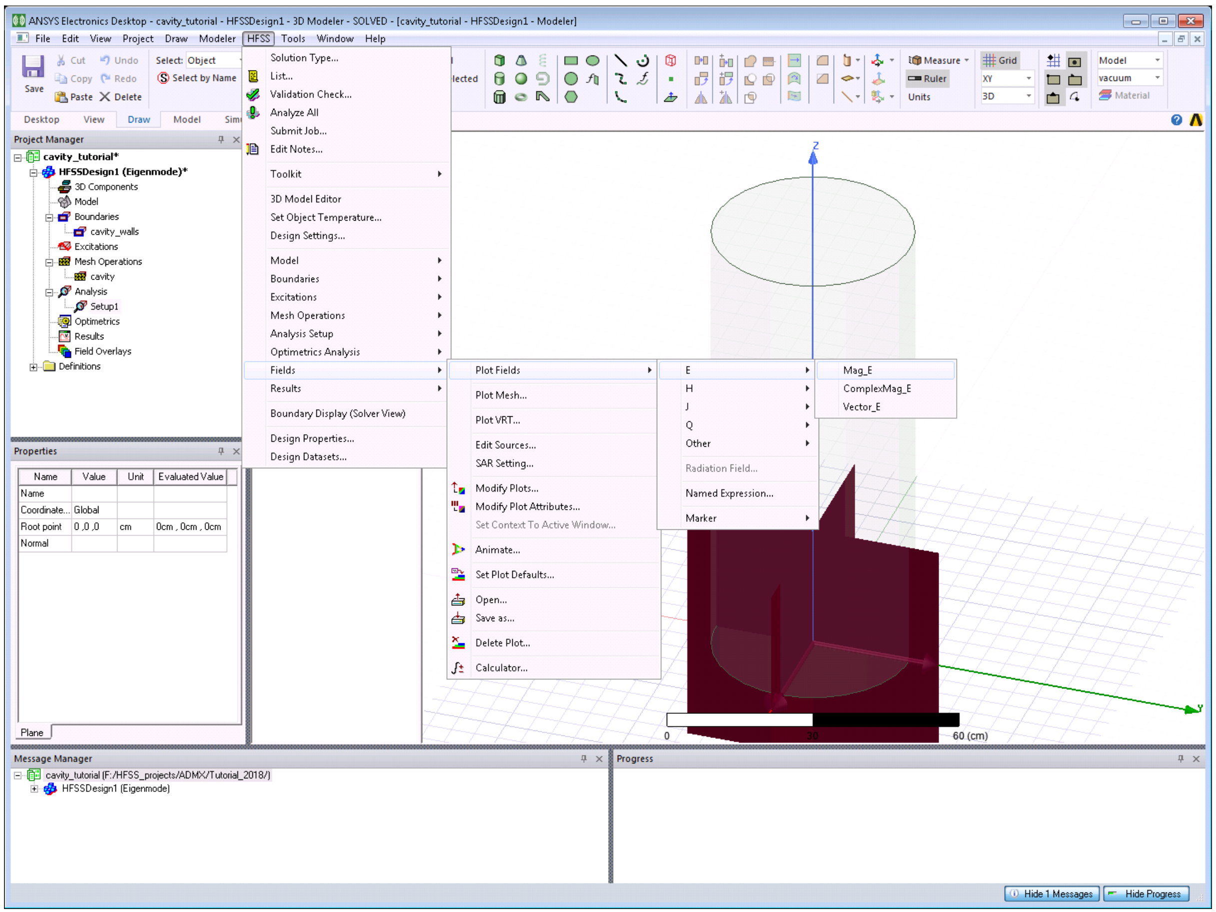
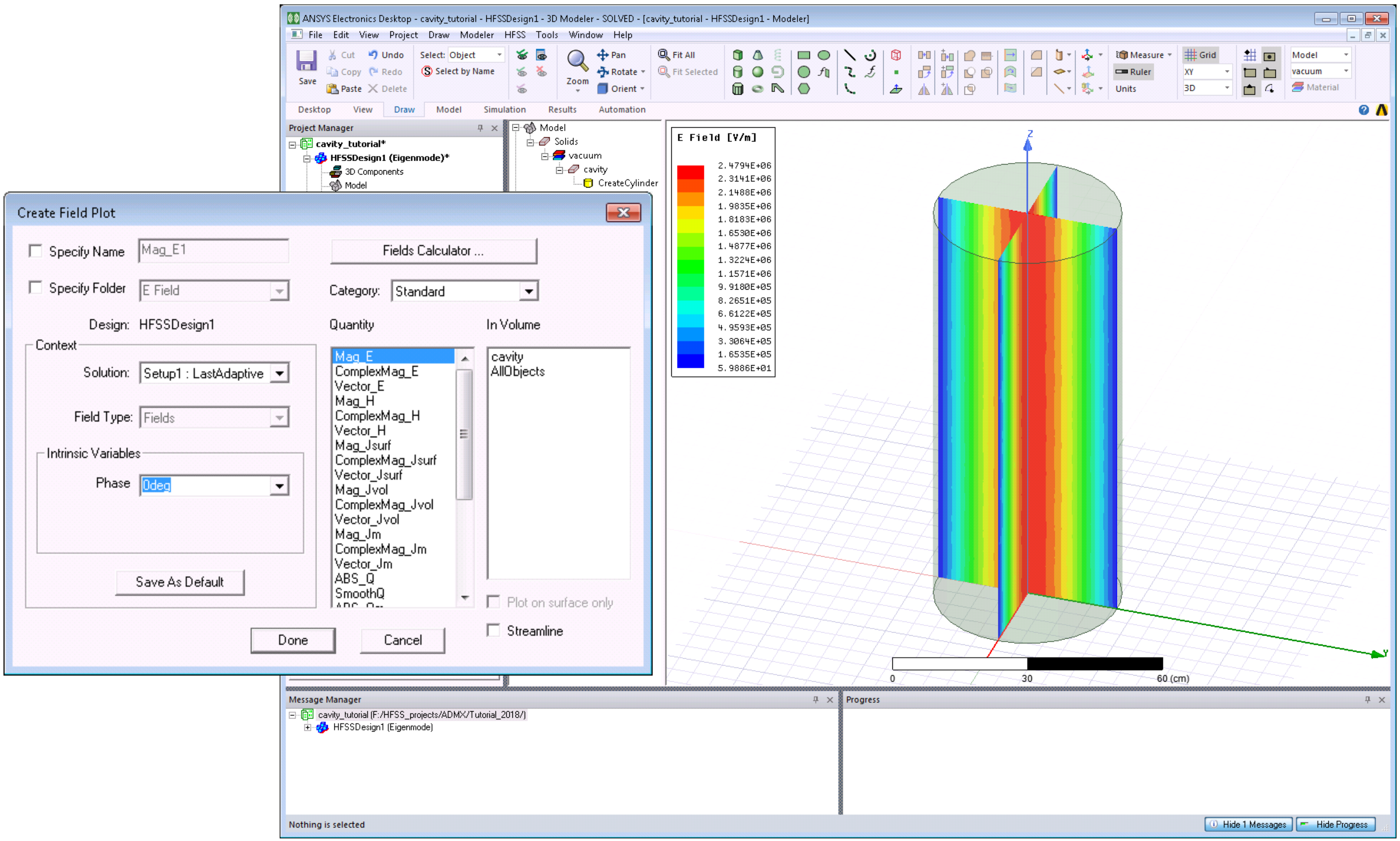
- Select XZ and YZ planes in 3D modeler tree and select ***HFSS > Fields > Plot Fields > E > Mag_E***



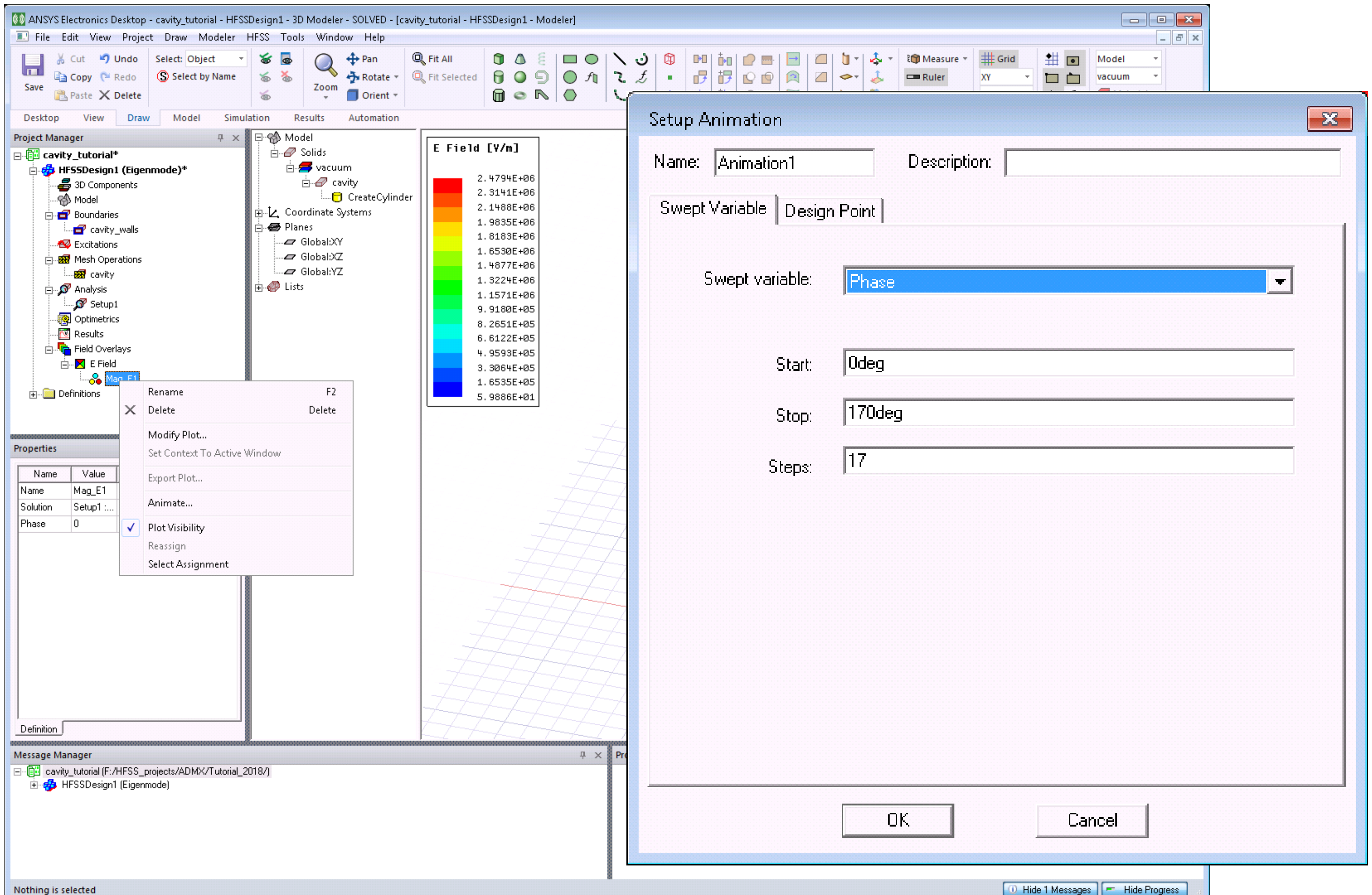
14: View E-Field Phase Animation

- Select Done to create plot of electric field magnitude



14: View E-Field Phase Animation

- Right-click on Mag_E1 plot to animate phasor field



15: View E-Field Vector Animation

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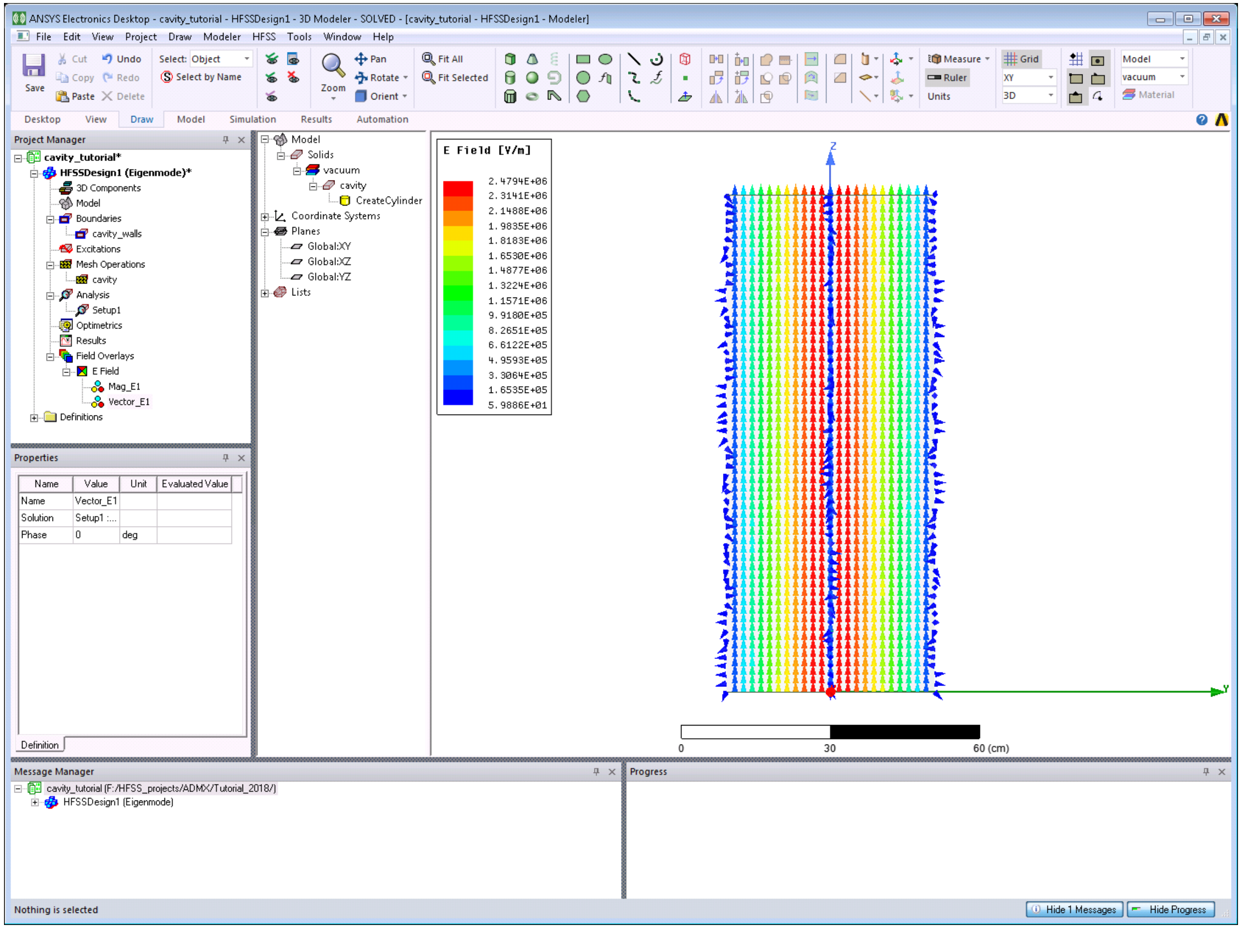
- Select XZ and YZ planes in 3D modeler tree and select ***HFSS > Fields > Plot Fields > E > Vector_E***



How to Activate Mode of Interest for Field Plots and Calculations

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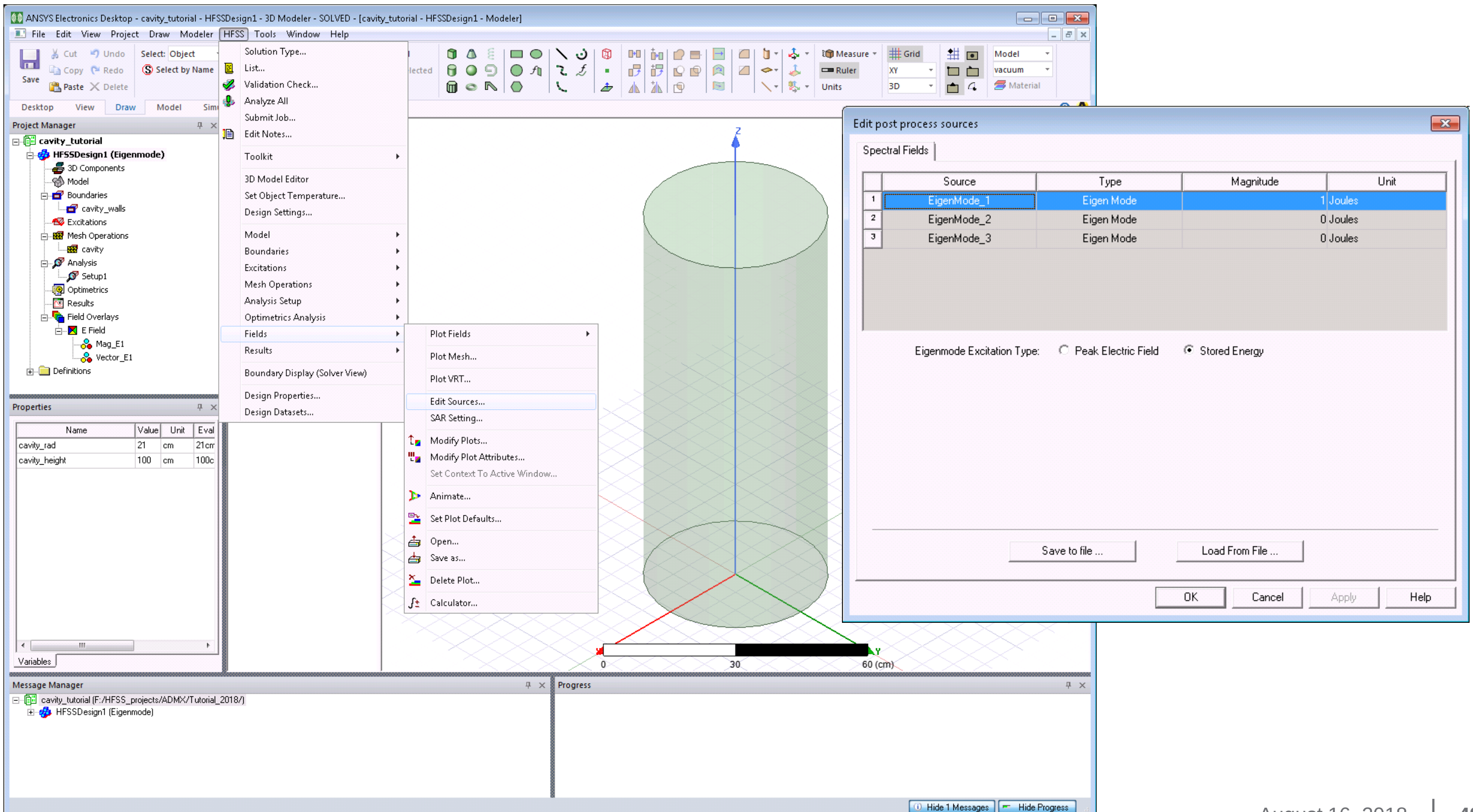
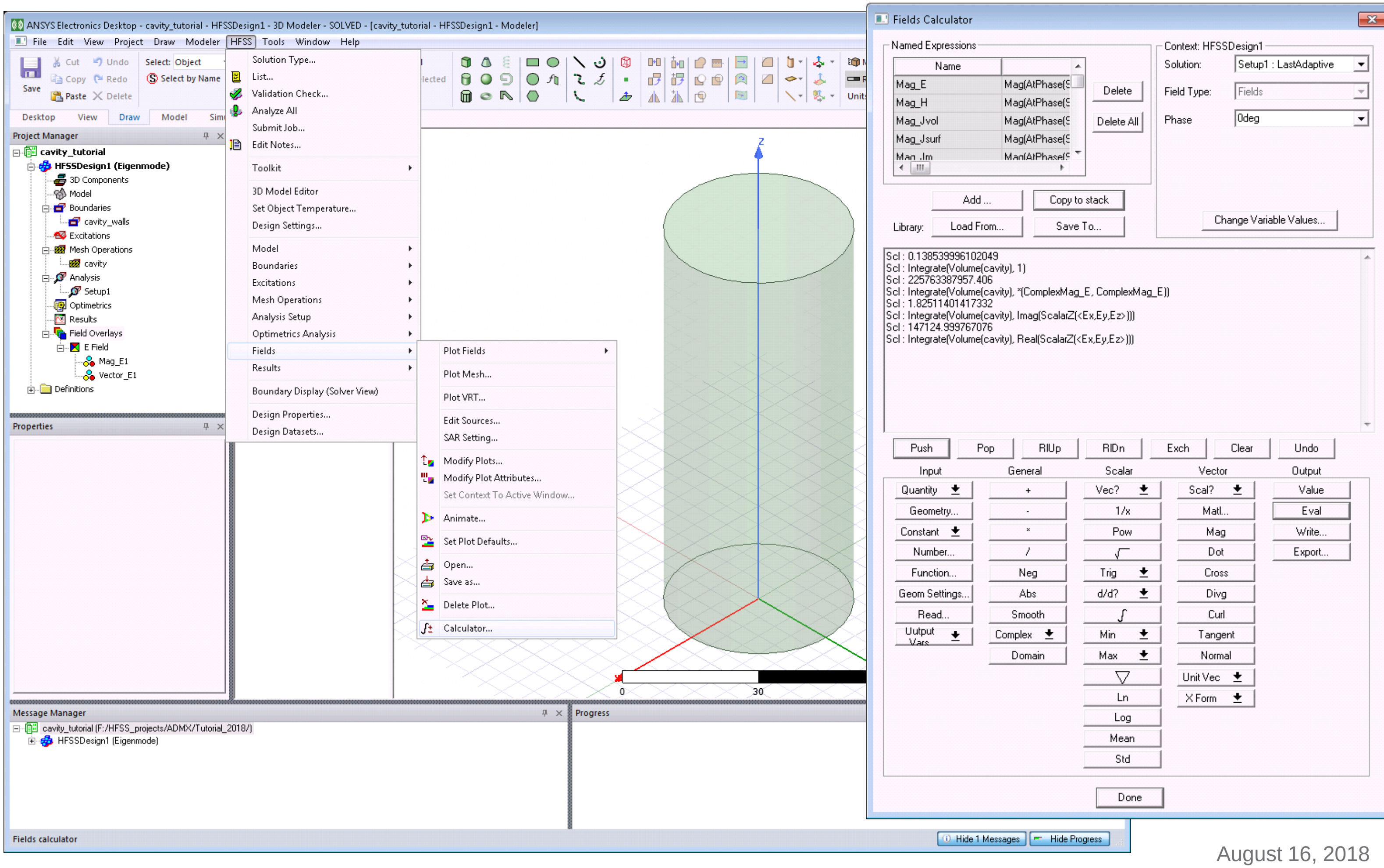
- Select ***HFSS > Fields > Edit Sources***



16: Calculate Form Factor

- Open field calculator using ***HFSS > Fields > Calculator***



16: Calculate Form Factor Assuming Uniform Z-directed Magnetic Field

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- Must use integration by parts
- Step 1: Calculate integral of real(E_z)
  - Quantity > E
  - Scal? > ScalarZ
  - Complex > Real
  - Geometry > Volume > cavity
  - Integrate, Eval
- Step 2: Calculate integral of imag(E_z)
  - Quantity > E
  - Scal? > ScalarZ
  - Complex > Imag
  - Geometry > Volume > cavity
  - Integrate, Eval
- Step 3: Calculate integral of $|E|^2$
  - Copy ComplexMag_E to stack
  - Push
  - Multiply (*)
  - Geometry > Volume > cavity
  - Integrate, Eval
- Step 4: Calculate cavity volume
  - Number -> 1
  - Geometry > Volume > cavity
  - Integrate, Eval
- Form factor = $(147125^2+1.8251^2)$ / (0.13854*225763387957) = 0.692

$$C_E = \frac{\left| \int dV_c \vec{E}_c \cdot \vec{\hat{z}} \right|^2}{V \int dV_c \mid E_c \mid^2} \qquad C_{mnp} \equiv \frac{\left| \int d^3x \, \mathbf{B_0} \cdot \mathbf{E_{mnp}}(\mathbf{x}) \right|^2}{B_0^2 V \int d^3x \, \varepsilon(\mathbf{x}) |\mathbf{E_{mnp}}(\mathbf{x})|^2}$$

Can save operations as Named Expression which can be evaluated in single step

Cavity Simulation Results

- Good agreement between simulated and analytical results

Quantity	Calculation	Simulation	% Difference
Frequency	546.42 MHz	546.42 MHz	0.00%
Unloaded Q-factor	61,391	61,378	0.02%
Form Factor	0.692	0.692	0.00%

$$Q_u = \frac{|\omega|}{2\omega_i}$$