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Cut-off frequency Prediction for MMW Coaxial Interconnects

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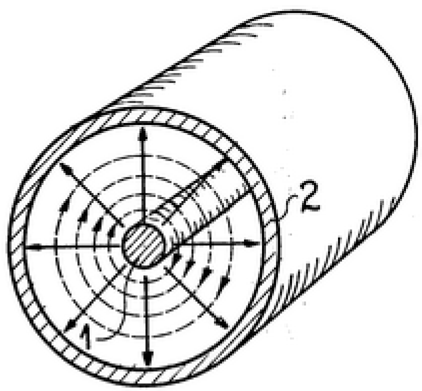
Motivation

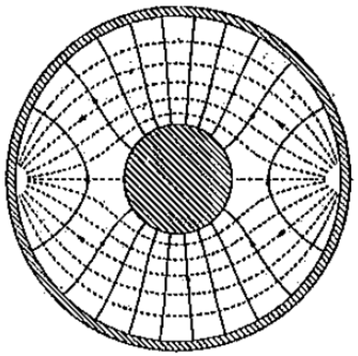
- Knowing the maximum operating frequency of a cable assembly is critical for engineers working at millimeter wave frequencies (e.g. MMW 5G)
- This maximum, or cut-off frequency is considered to be when higher order modes (e.g. the TE_{11} mode) can propagate, robbing signal from the fundamental TEM mode
- Minimizing signal attenuation through the entire frequency range is desired
- The TE_{11} mode frequency and attenuation are both influenced by coax diameter (or size)

Higher order modes in coax

TEM = fundamental mode for coax

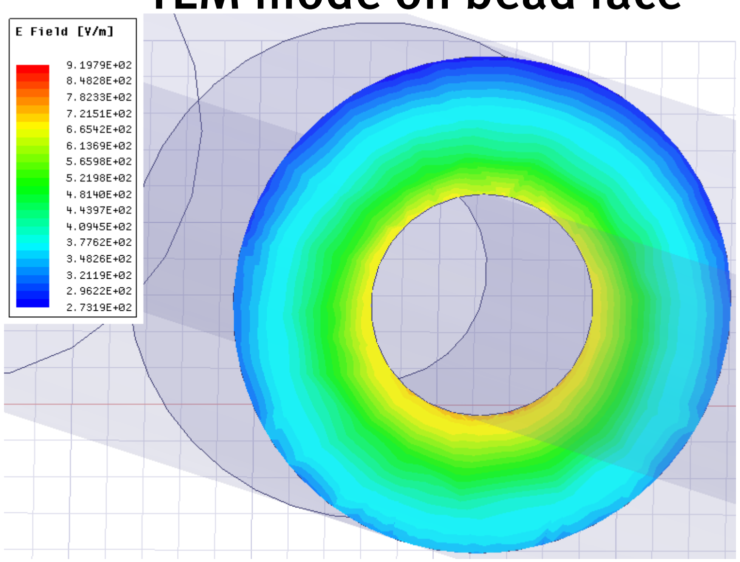


TE_{11} = first higher order mode encountered in coax



Excited by asymmetries in cross section

TEM mode on bead face



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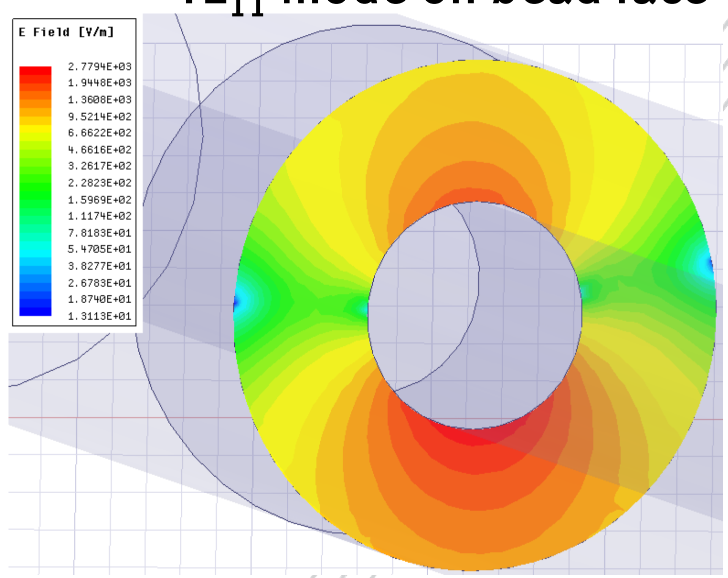
TE_{11} mode on bead face



Cut-off frequency for 50Ω air interfaces

Approximate solution:

$$f_c \approx \frac{190.85}{(d+D)\sqrt{\varepsilon_r}} \text{ (GHz)}$$

d and *D* are inner and outer diameters (mm)

ε_r is the effective dielectric constant of the section

Airline OD (mm)	f_c (TE_{11}) cut-off (GHz)	Rated max frequency (GHz)	Derating for support beads
7.0	19.40	18	7%
3.5	38.80	33	15%
2.92	46.51	40	14%
2.4	56.58	50	12%
1.85	73.40	65	11%
1.0	135.80	110	19%

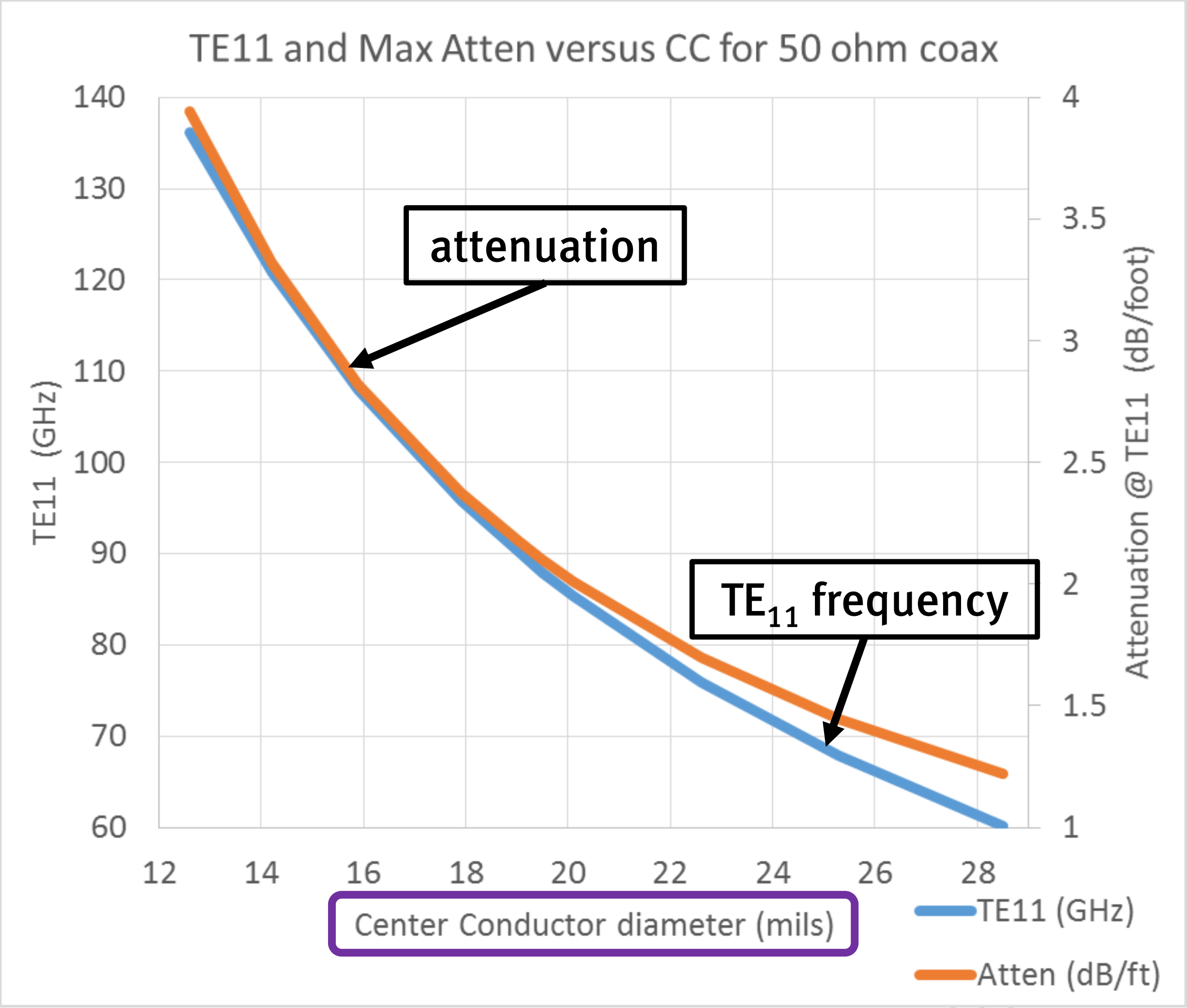
Exact solution using characteristic Bessel equation (first root):

$$J_1'(k_c b)Y_1'(k_c a) - J_1'(k_c a)Y_1'(k_c b) = 0$$

where; a = Inner radius, b = Outer radius

$$k_c = 2\pi\sqrt{\varepsilon_r}\frac{f_c}{c_0}$$

Cut-off frequency and attenuation of coax



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Note: simulation given microporous PTFE dielectric

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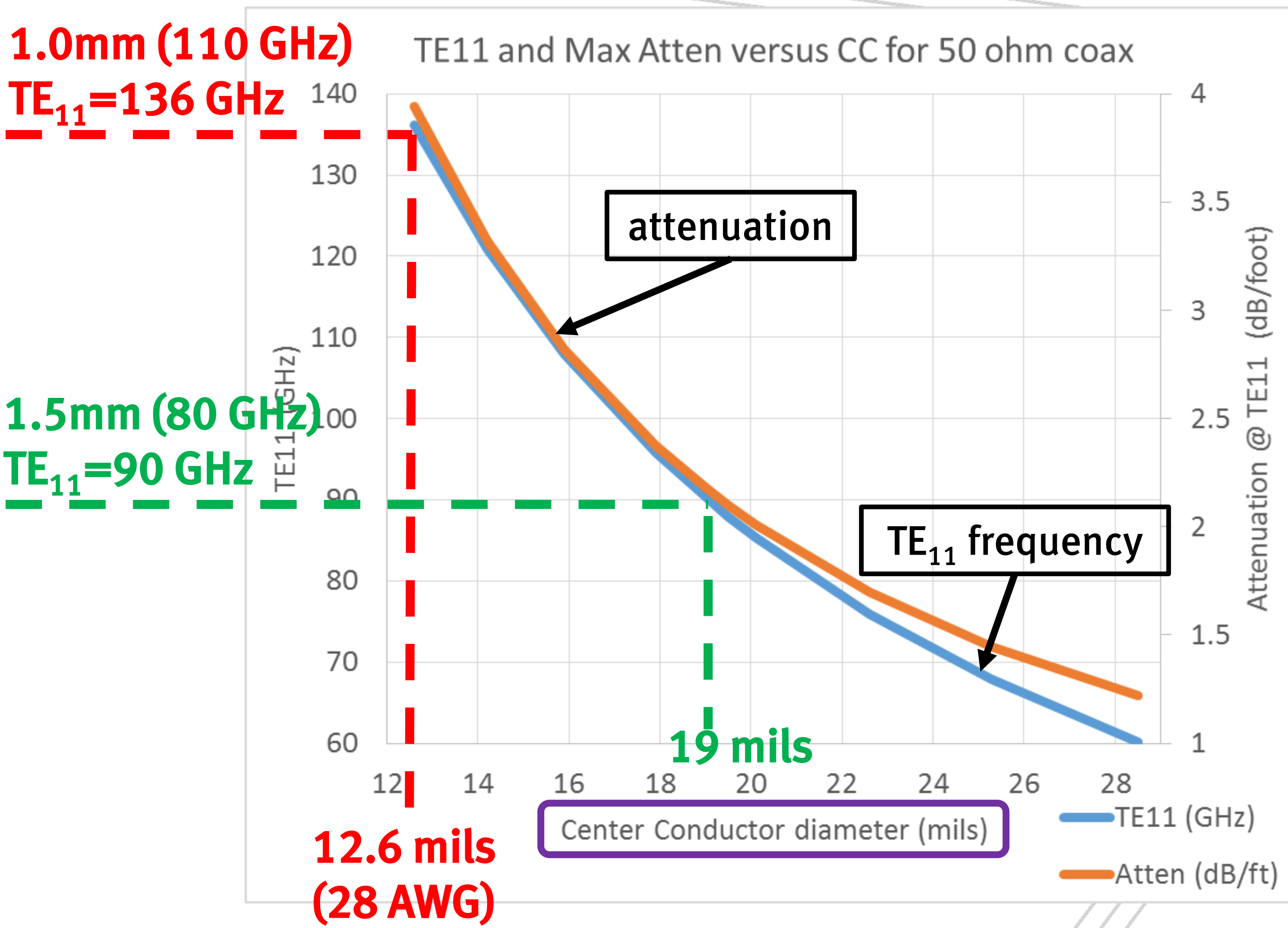
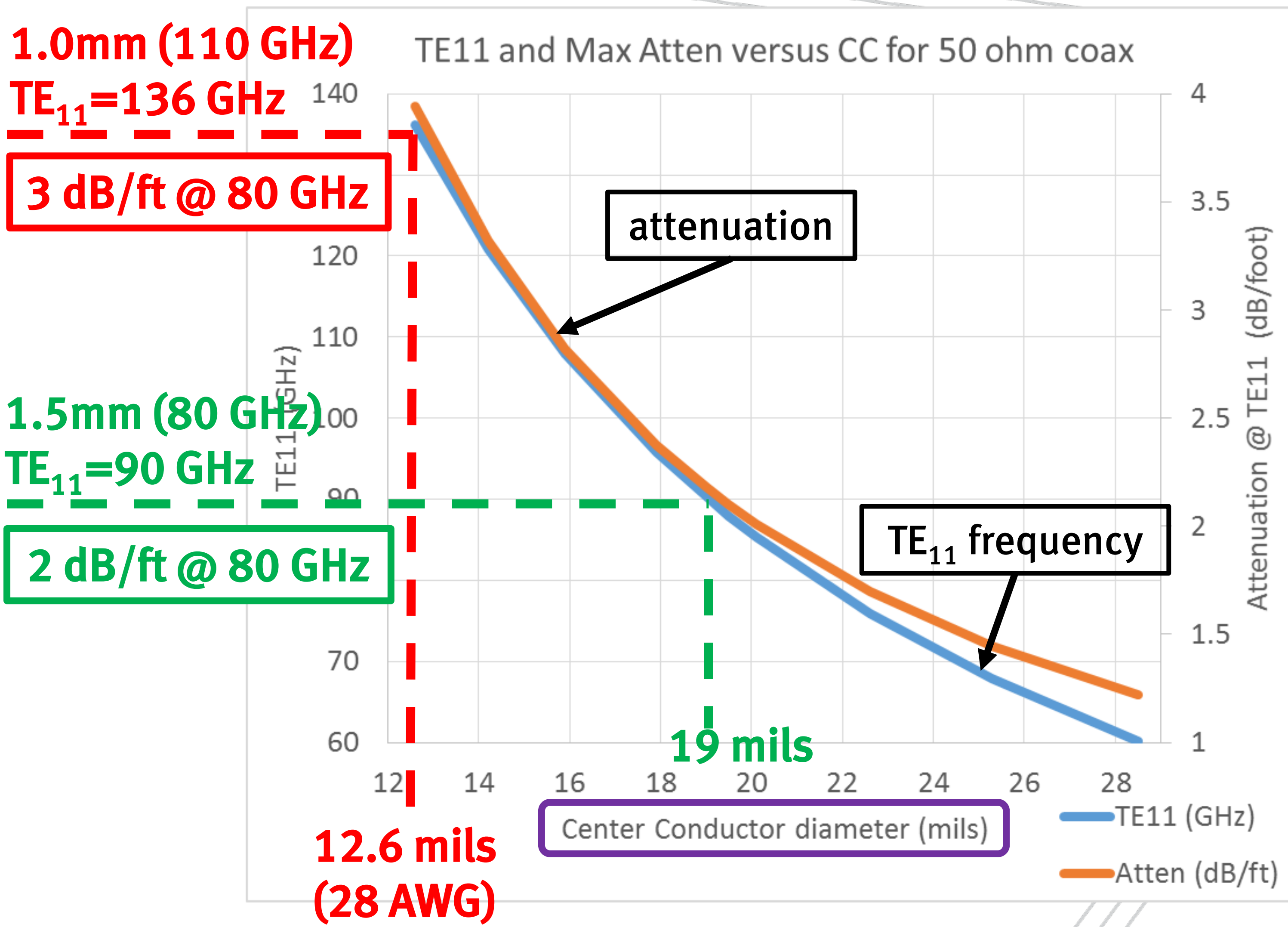
Cut-off frequency and attenuation of coax



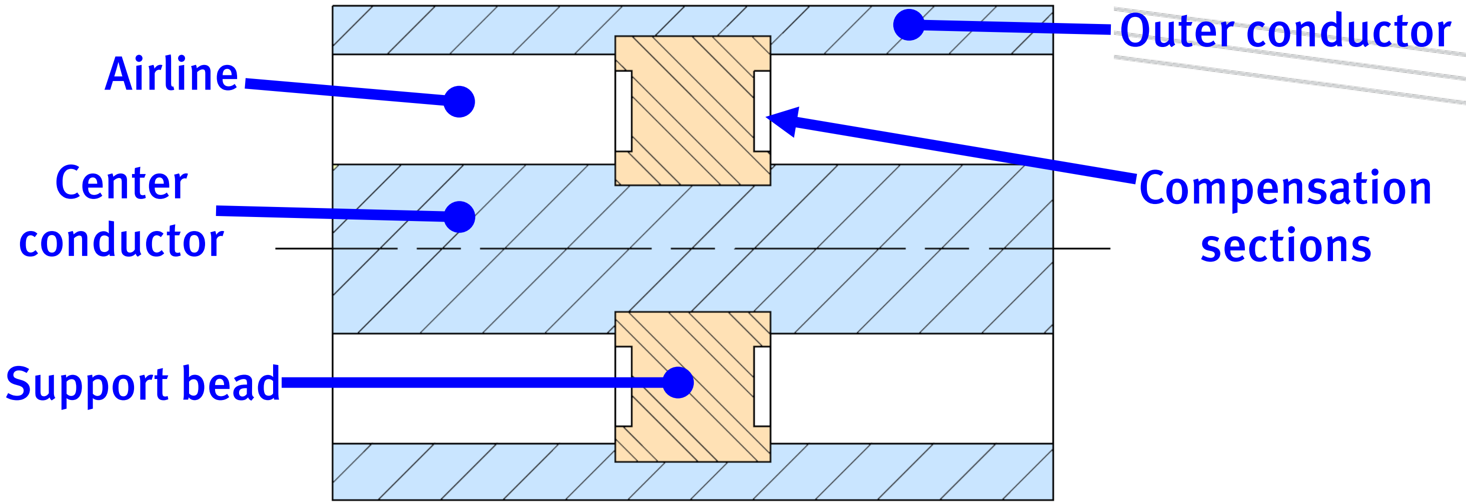
Note: simulation given microporous PTFE dielectric

Cut-off frequency and attenuation of coax



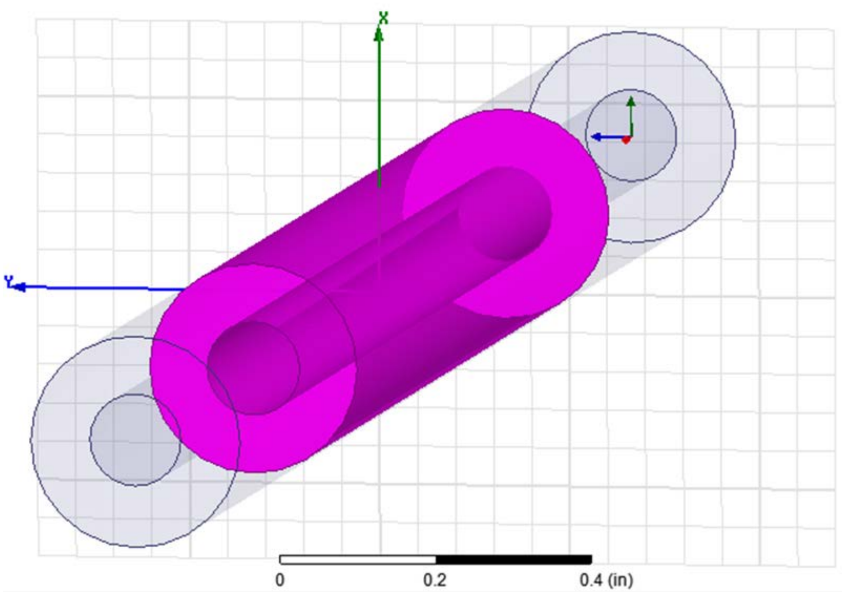
Note: simulation given microporous PTFE dielectric

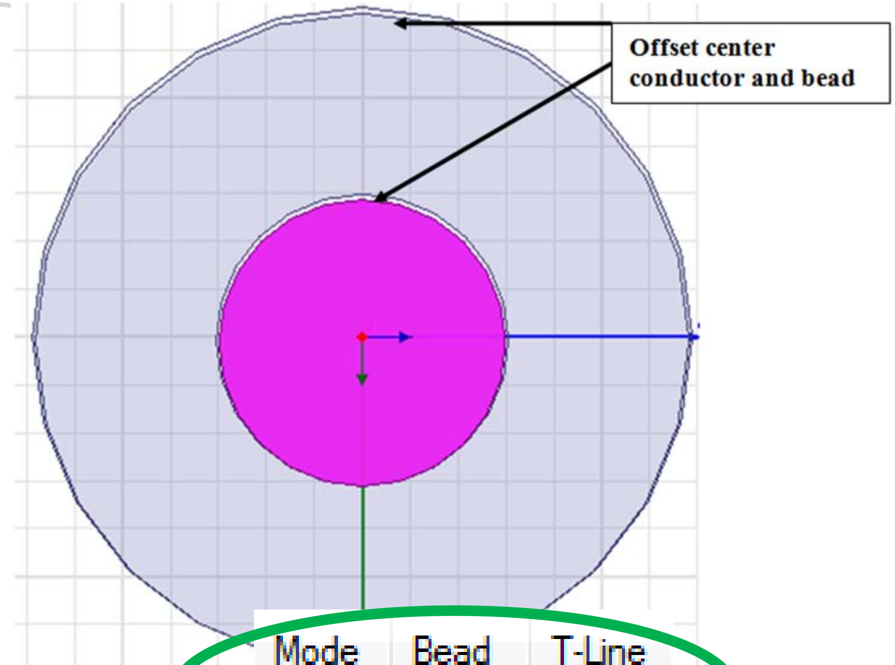
Support beads for connectors



- Bead supports CC radially and longitudinally and has the same nominal impedance as airline
- TE_{11} mode frequency in bead section is lower than in airline
- Effective cut-off frequency of bead will end up somewhere between TE_{11} of bead and airline
  - Resonance occurs when impedance of TE waves are complex conjugates at boundaries

Example: PTFE beads in 7mm airline





Mode	Bead	T-Line
TE11	13.8	19.4
TE21	27.0	38.0
TE31	39.4	55.4
TM01	53.3	75.0
TE01	55.1	77.6
TM11	55.1	77.6
TE12	57.4	80.7
TM21	60.2	84.6
TE22	63.7	89.6

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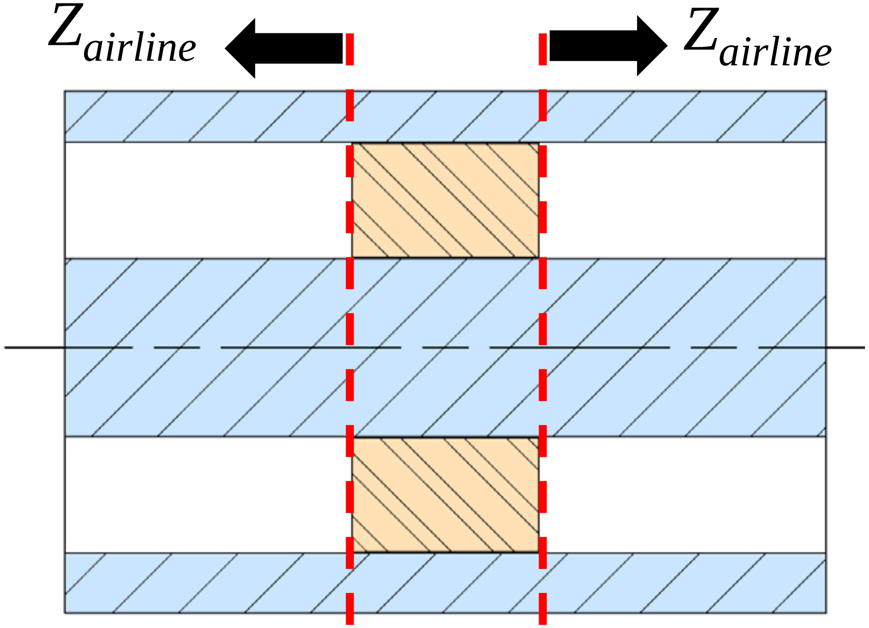
Support bead in airline



$$Z_{airline} = j\eta_0 \frac{f}{f_{ca}} \frac{1}{\sqrt{1-\left(\frac{f}{f_{ca}}\right)^2}}$$

for $f < f_{ca}$

$$\gamma_{airline} = 2\pi \frac{f_{ca}}{c_0} \sqrt{1-\left(\frac{f}{f_{ca}}\right)^2}$$

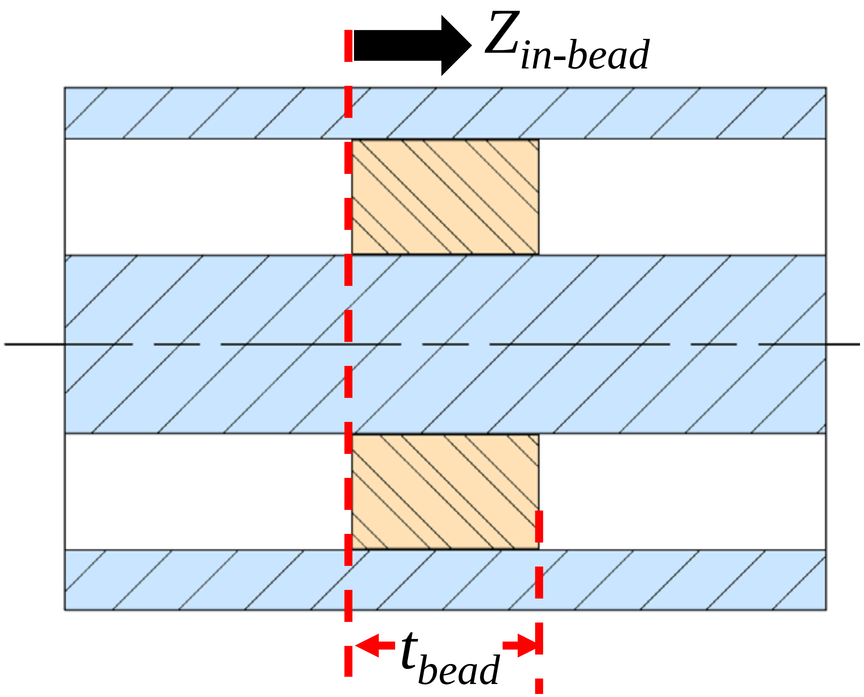
where; $\eta_0 = 376.7$ ohms

$f_{ca} = TE_{11}$ frequency of airline

= 19.4 GHz for 7mm line

Calculate transmission line parameters in terms of TE wave impedance and propagation constant

Support bead in airline



$$Z_{in-bead} = Z_{bead}\frac{Z_{airline} + Z_{bead}\tanh(\gamma_{bead}t_{bead})}{Z_{bead} + Z_{airline}\tanh(\gamma_{bead}t_{bead})}$$

$$\text{where; } Z_{bead} = \eta_{bead}\frac{1}{\sqrt{1-\left(\frac{f_{cb}}{f}\right)^2}}$$

$$\gamma_{bead} = j2\pi\sqrt{\varepsilon_{rb}}\frac{f}{c_0}\sqrt{1-\left(\frac{f_{cb}}{f}\right)^2}$$

$$\eta_{bead} = \frac{376.7}{\sqrt{\varepsilon_{rb}}}$$

t_{bead} = Length of bead

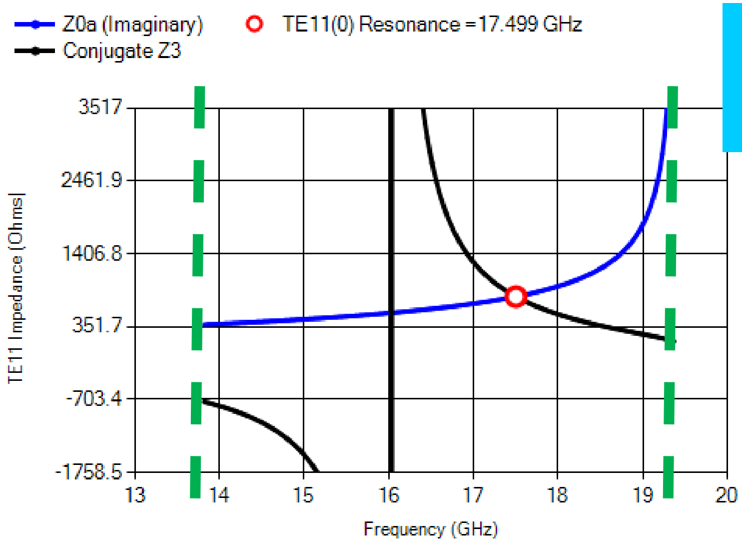
$f_{cb} = TE_{11}$ frequency of bead

= 13.8 GHz for PTFE bead

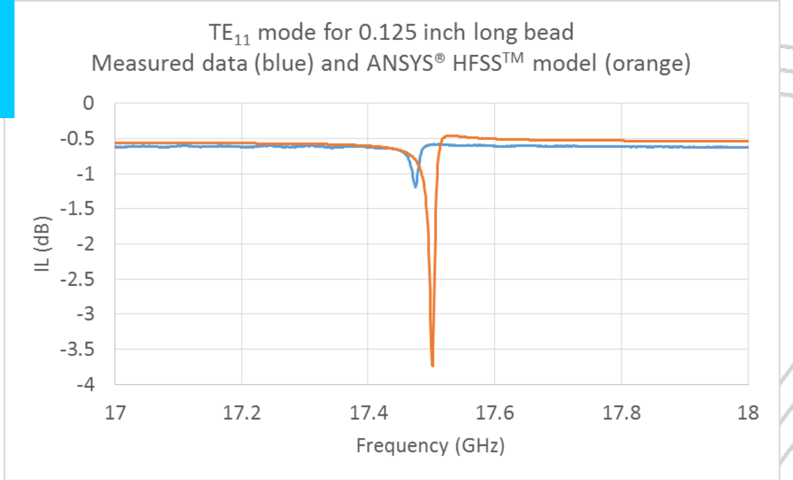
Resonance conditions occur when:

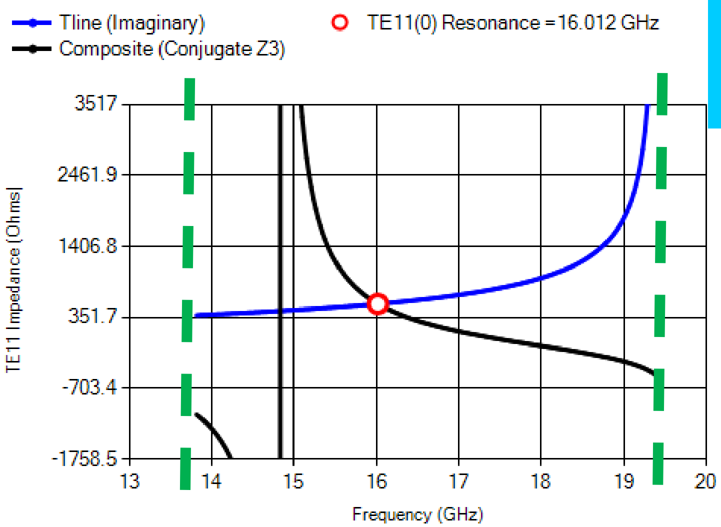
$$Z_{in-bead} = Z^*_{airline}$$

PTFE bead with 7mm airline experiment

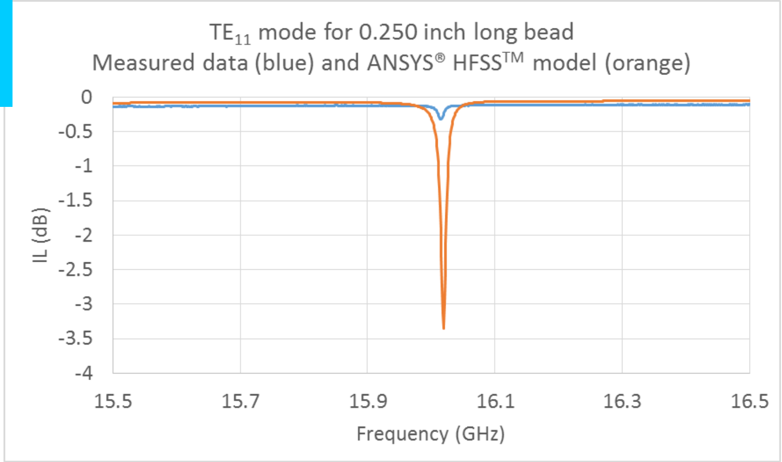


0.125 inch long bead





0.250 inch long bead



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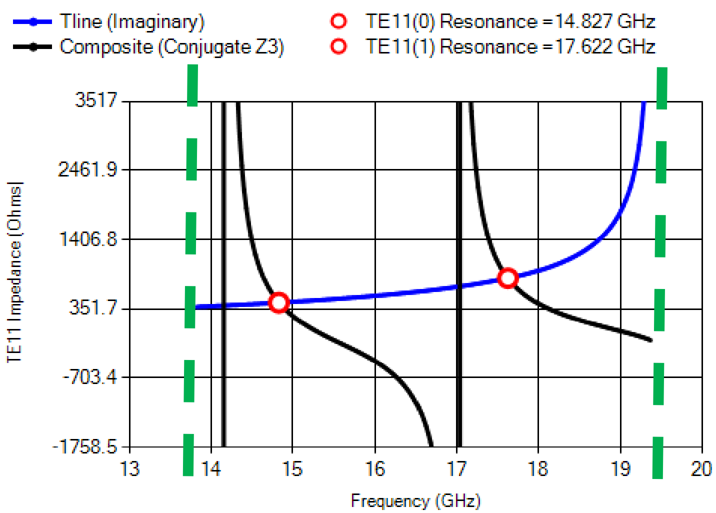
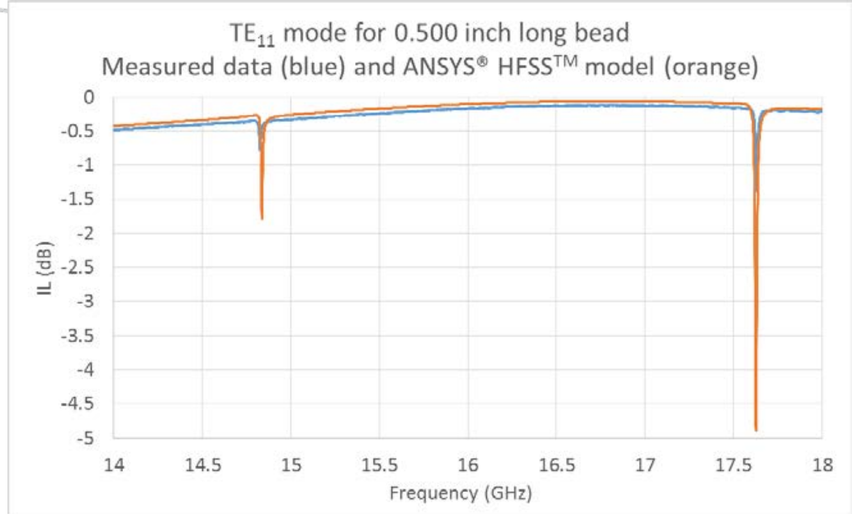
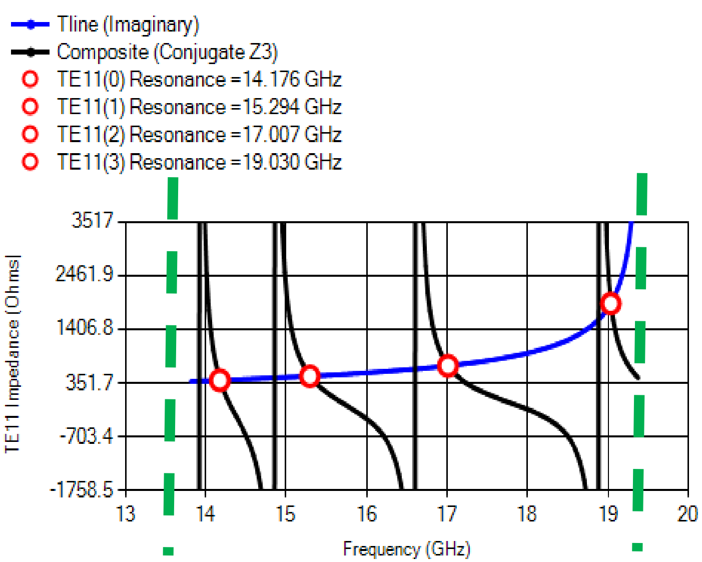
PTFE bead with 7mm airline experiment

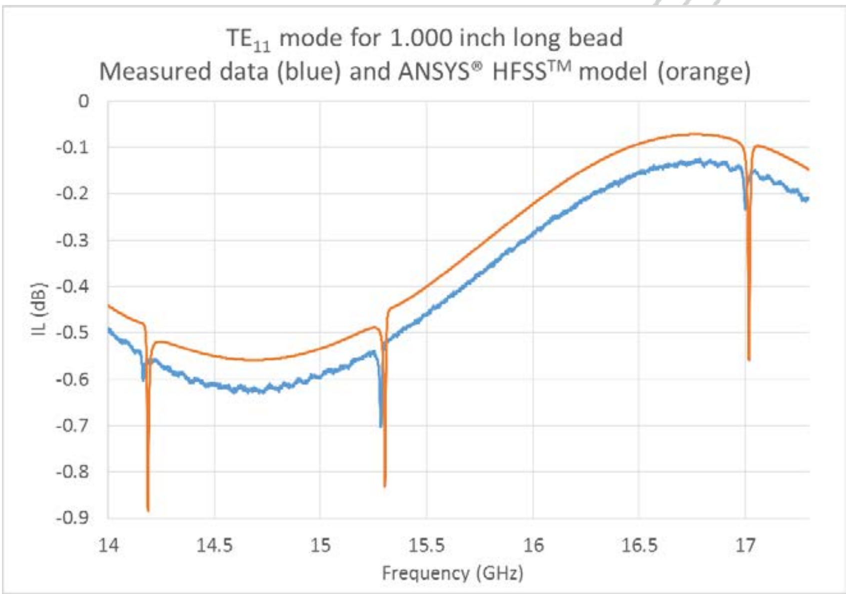


0.5 inch long bead





1.0 inch long bead



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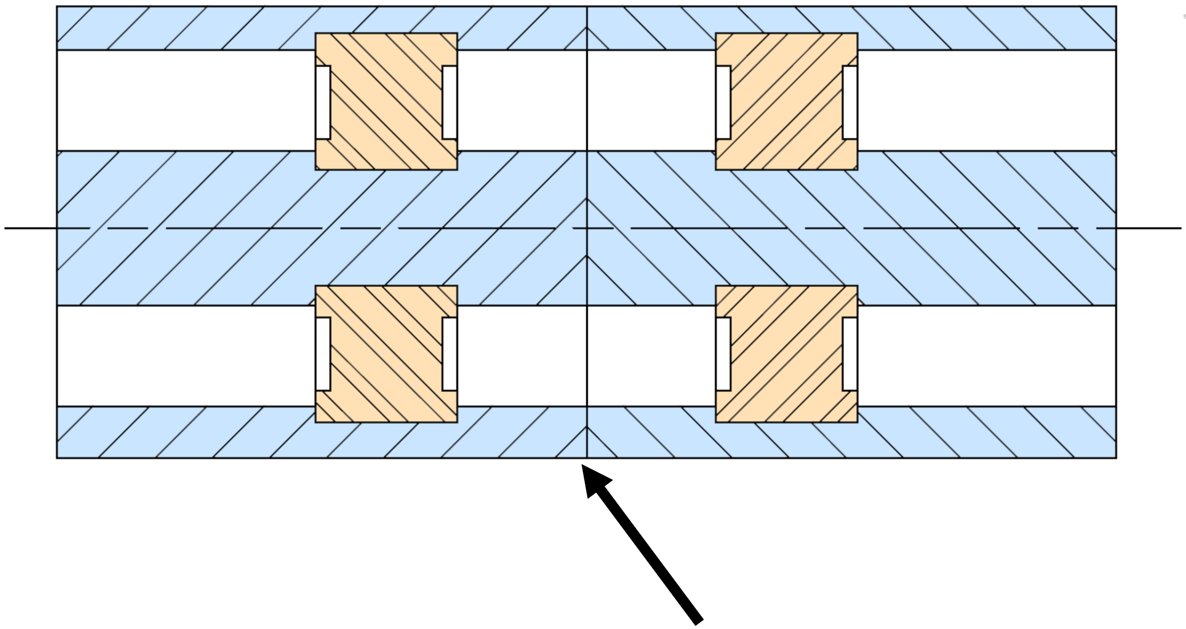
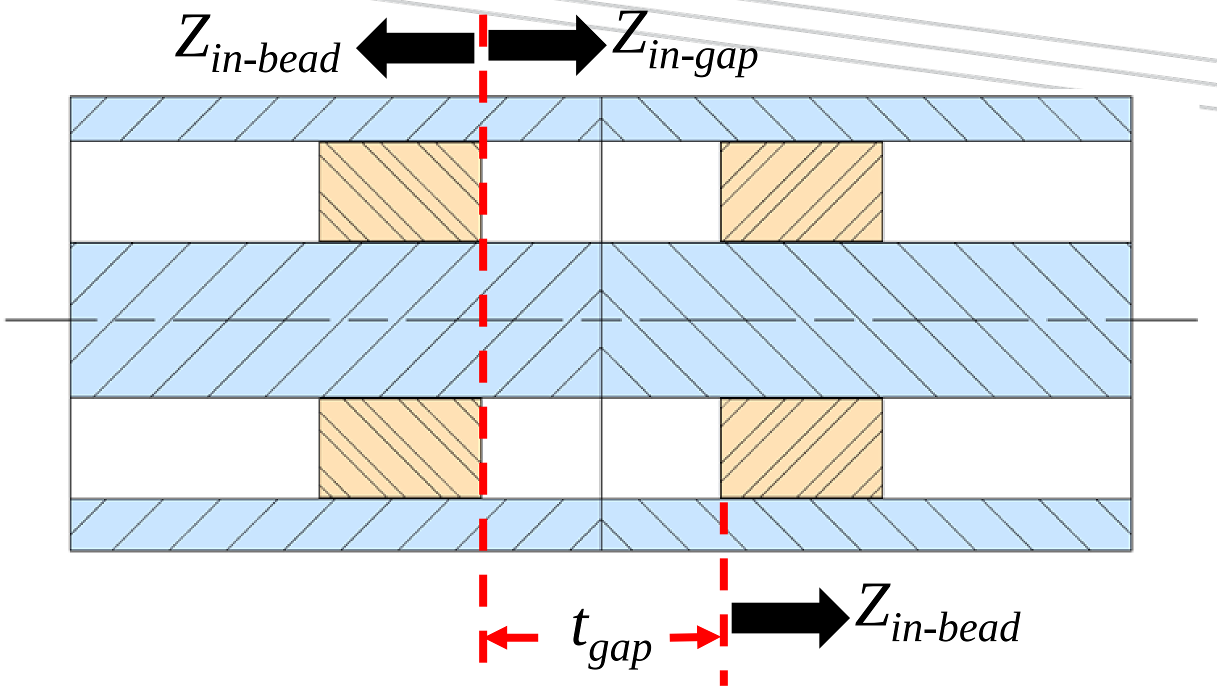
Dual beads within an airline



Interface between
two connectors

Dual beads within an airline



$$Z_{in-gap} = Z_{gap} \frac{Z_{in-bead} + Z_{gap} \tanh\left(\gamma_{gap} t_{gap}\right)}{Z_{gap} + Z_{in-bead} \tanh\left(\gamma_{gap} t_{gap}\right)}$$

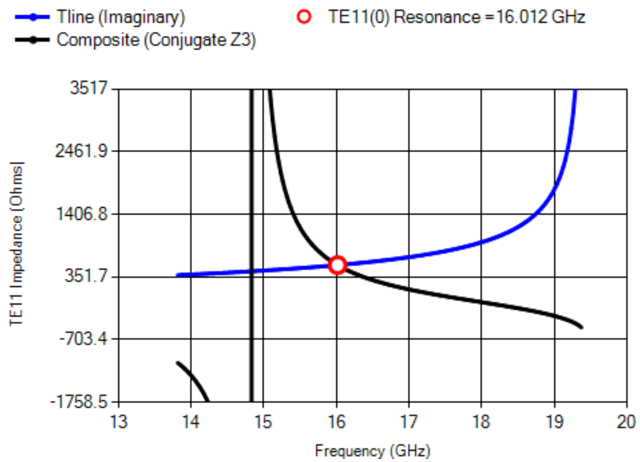
where; $Z_{gap} = Z_{airline}$; $\gamma_{gap} = \gamma_{airline}$

Resonance occurs when:

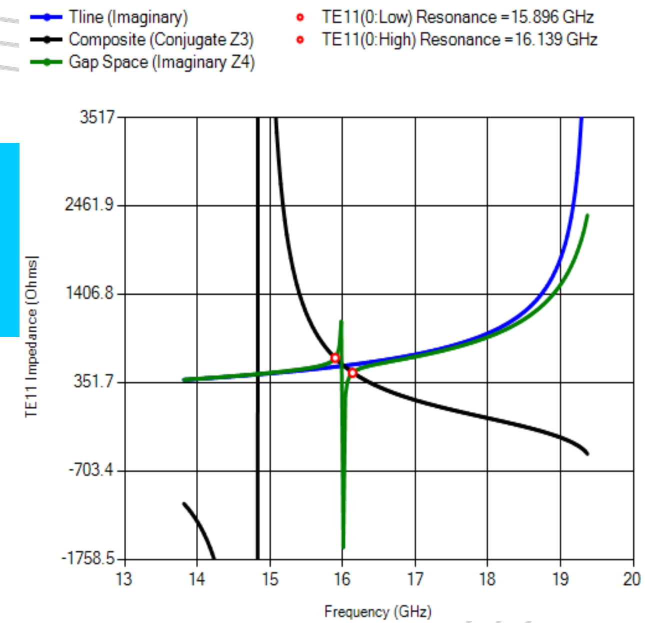
$$Z_{in-gap} = Z_{in-bead}^{*}$$

Dual PTFE beads within 7mm airline

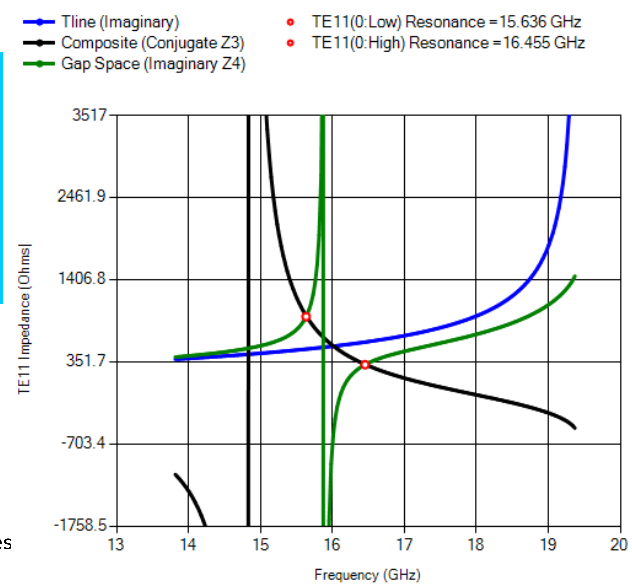
0.250 inch long single bead



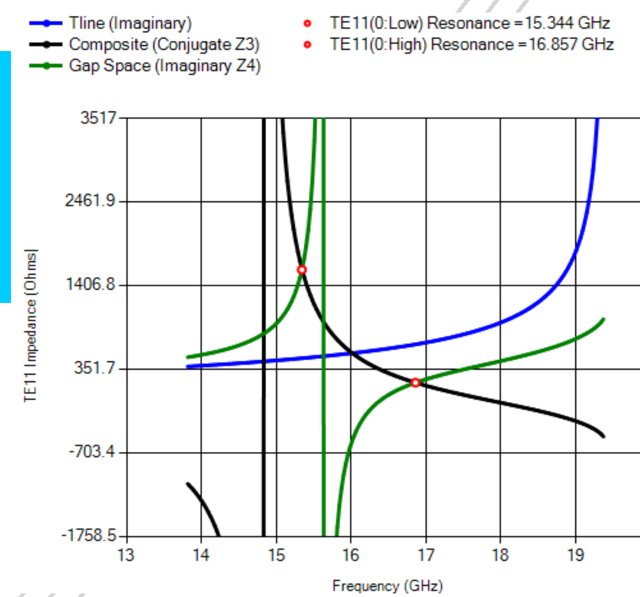
(2x) 0.250 beads, 0.5 inch apart



(2x) 0.250 beads, 0.250 inch apart



(2x) 0.250 beads, 0.125 inch apart



Conclusions:

- Important to understand TE_{11} mode resonant conditions in order to determine the max operating frequency of coax assembly
  - Use transmission line calculation approach
    - Using TE wave impedance and prop const.
  - Simulate using ANSYS® HFSS™ software
    - Introduce slight asymmetries in geometry
  - Measure the assembly to validate the lowest TE_{11} resonant frequency