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# Cut-off frequency Prediction for MMW Coaxial Interconnects

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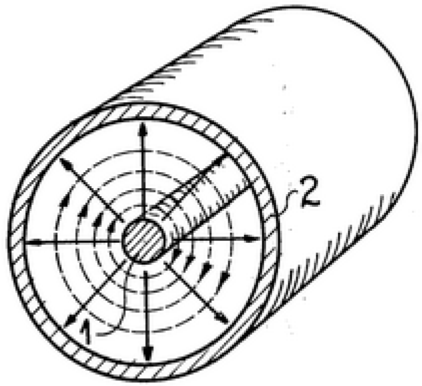
# Motivation

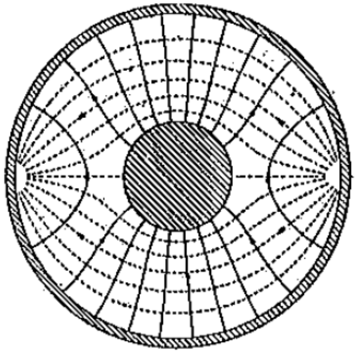
- Knowing the maximum operating frequency of a cable assembly is critical for engineers working at millimeter wave frequencies (e.g. MMW 5G)
- This maximum, or cut-off frequency is considered to be when higher order modes (e.g. the $TE_{11}$ mode) can propagate, robbing signal from the fundamental TEM 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

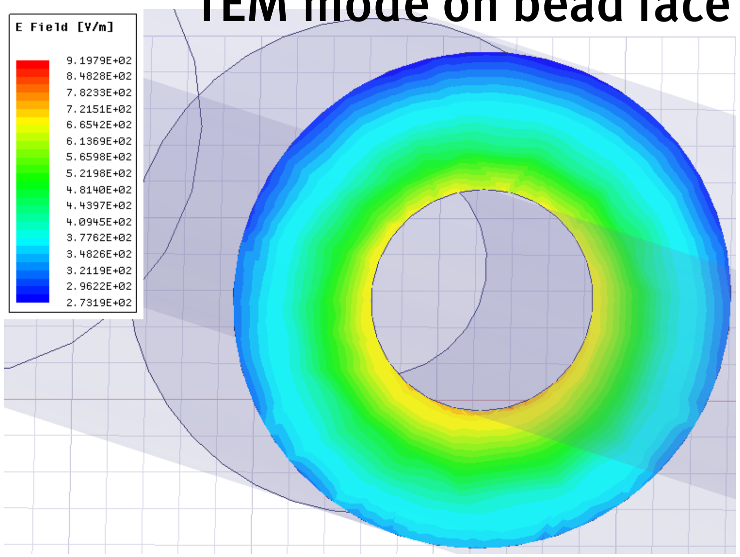
TEM = fundamental mode for coax



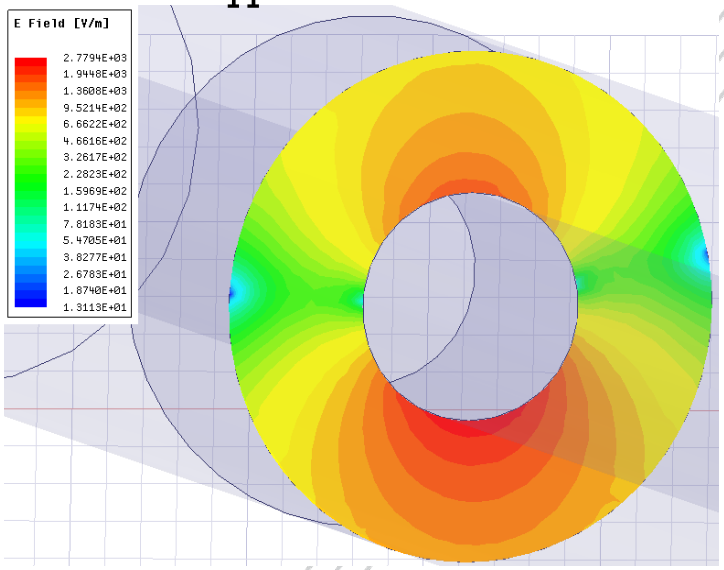

$TE_{11}$ = first higher order mode encountered in coax



TEM mode on bead face




$TE_{11}$ mode on bead face

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# Cutoff frequency for 50Ω airlines

| Airline OD (mm) | TE11 cutoff (GHz) | Rated max frequency (GHz) | Derating for connectors |
|---|---|---|---|
| 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% |

**Approximate solution:**

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

*d* and *D* are inner and outer diameters (mm)
$\varepsilon_r$ is the effective dielectric constant of the section

**Exact solution using characteristic Bessel equation:**

$$J_1'(k_c b)\,N_1'(k_c a) - J_1'(k_c a)\,N_1'(k_c b) = 0$$

where; $a$ = Inner radius, $b$ = Outer radius

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

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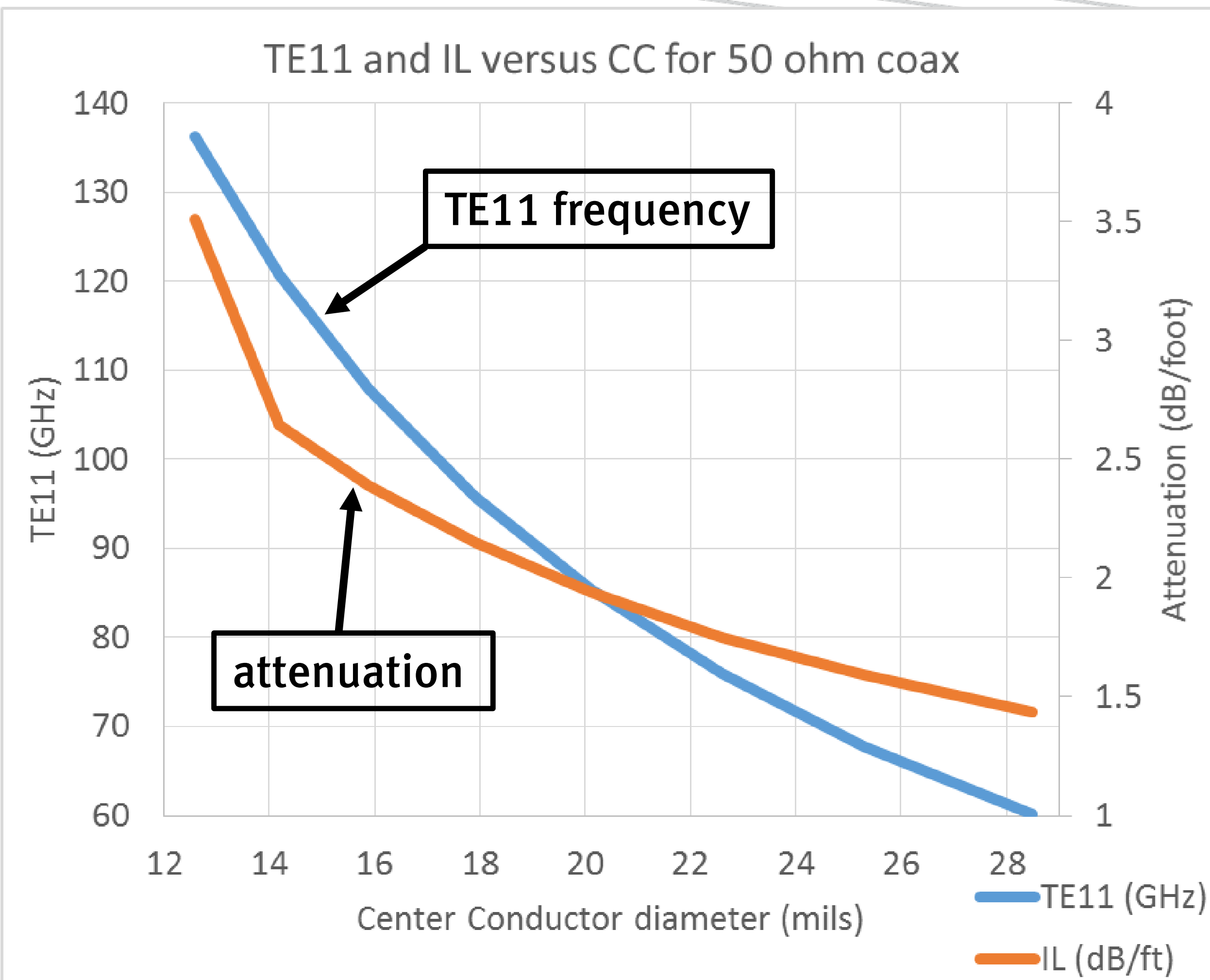
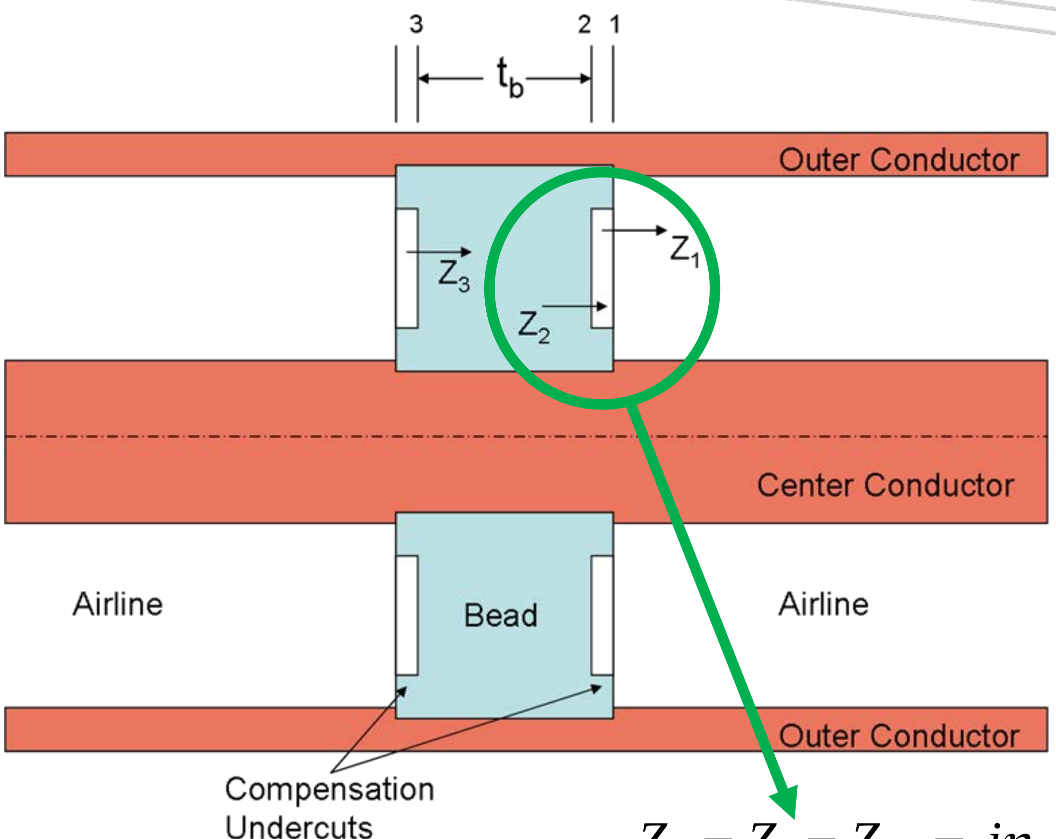
# Cutoff frequency versus attenuation




**Note: simulation given microporous PTFE dielectric**

# Calculate effective $TE_{11}$ modes beads




Gilmore, The General Radio Experimenter, 1966

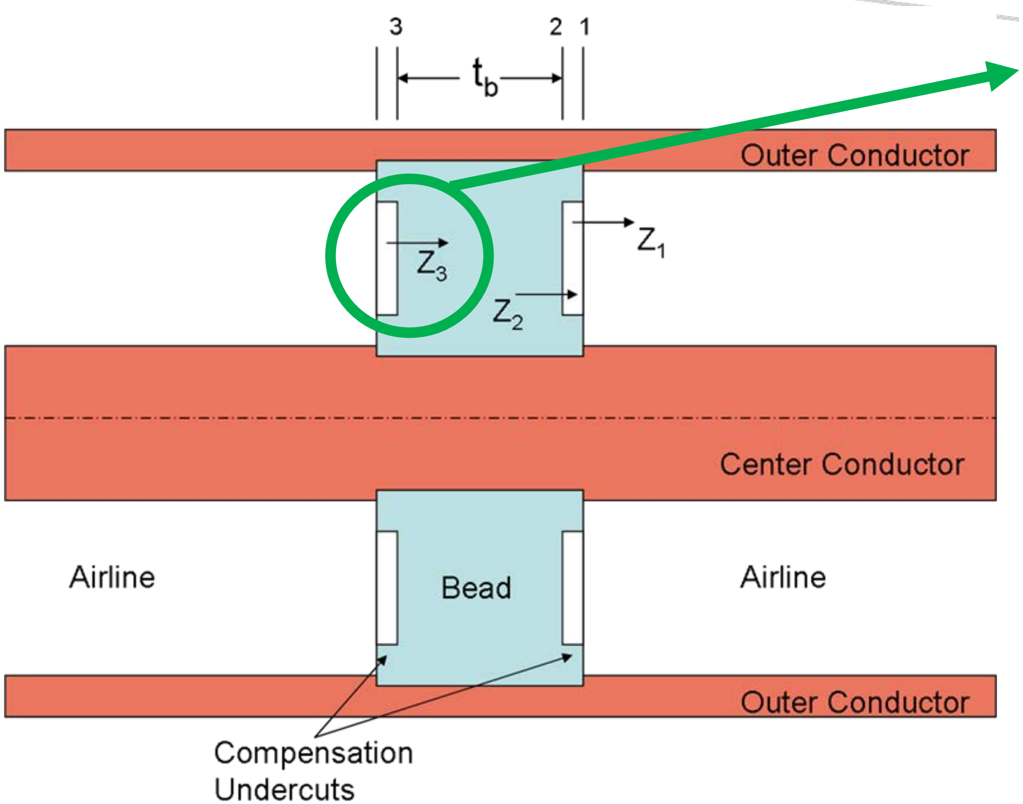
*Perform transmission line calculations in terms of TE wave impedance and propagation constant*

$$Z_2 = Z_1 = Z_{0a} = j\eta_0 \frac{f}{f_{ca}} \frac{1}{\sqrt{1-\left(\frac{f}{f_{ca}}\right)^2}} \qquad \text{for } f < f_{ca}$$

where; $\eta_0 = 376.7$ ohms

$f_{ca}$ = TE11 frequency of the infinite airline section

# Calculate effective $TE_{11}$ modes beads




$$Z_3 = Z_{0b}\frac{Z_{0a} + Z_{ob}\tanh(\gamma_b t_b)}{Z_{0b} + Z_{oa}\tanh(\gamma_b t_b)}$$

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

$$\gamma_b = jk_b\sqrt{1-\left(\frac{f_{cb}}{f}\right)^2}$$

$$\eta_b = \frac{376.7}{\sqrt{\varepsilon_{rb}}}$$

$$k_b = 2\pi\sqrt{\varepsilon_{rb}}\frac{f}{c_0}$$

$$t_b = \text{ Length of bead section}$$

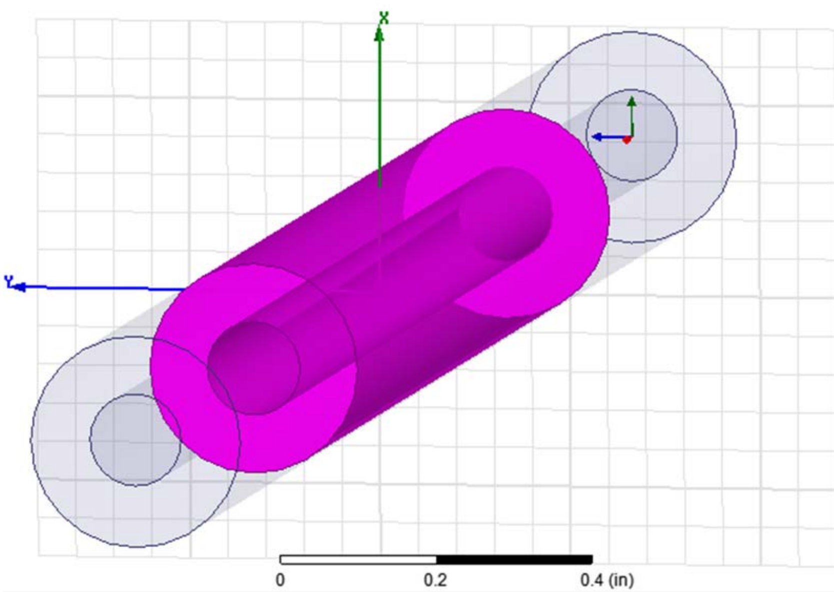
**Resonance conditions occurs when:**

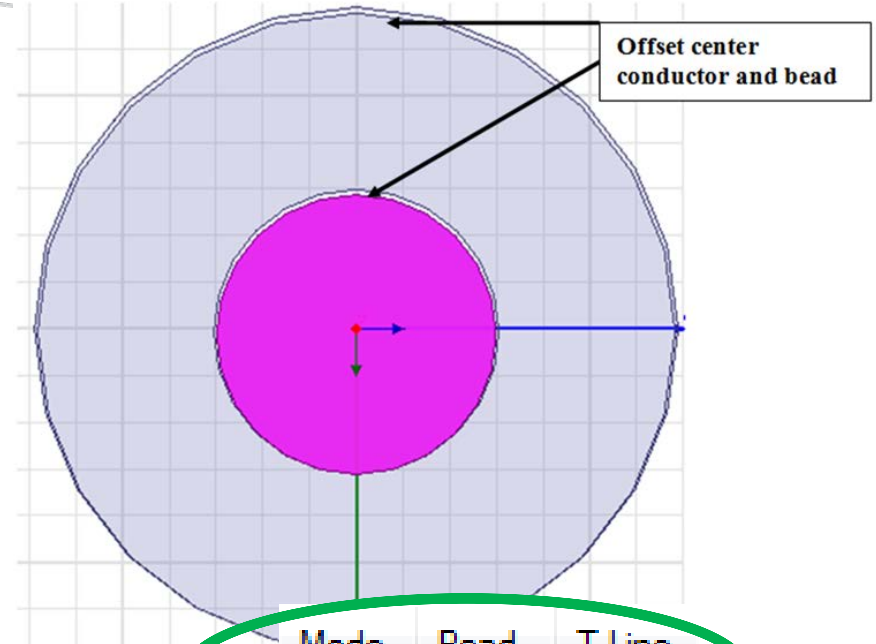
$$Z_3 = Z_{0a}^*$$

# Effective $TE_{11}$ mode in coax support beads

- $TE_{11}$ mode resonance(s) will occur at the frequencies where $Z_3 = Z_{0a}$*
- Multiple resonances can occur for the $TE_{11}$ mode, based on bead length
- The bead is now the determining factor for the maximum operating frequency of the coax assembly
- A simple experiment can be run to test the theory
    - Use various lengths of a PTFE bead inserted into a 7mm airline

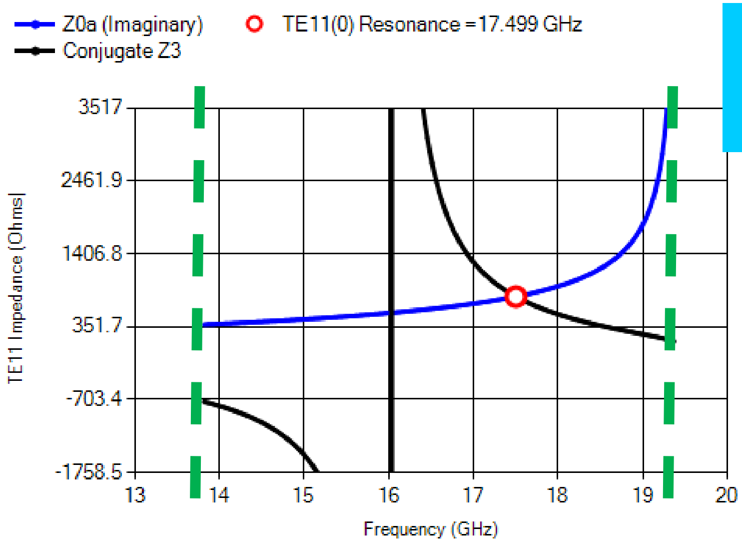
# PTFE bead with 7mm airline experiment



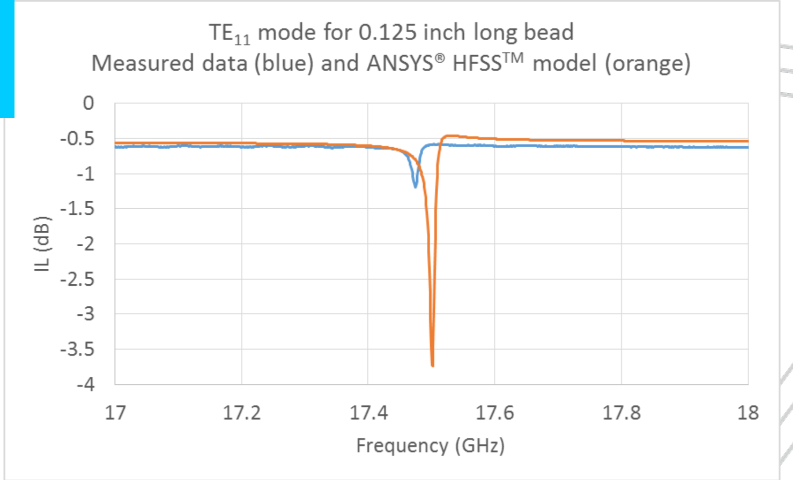



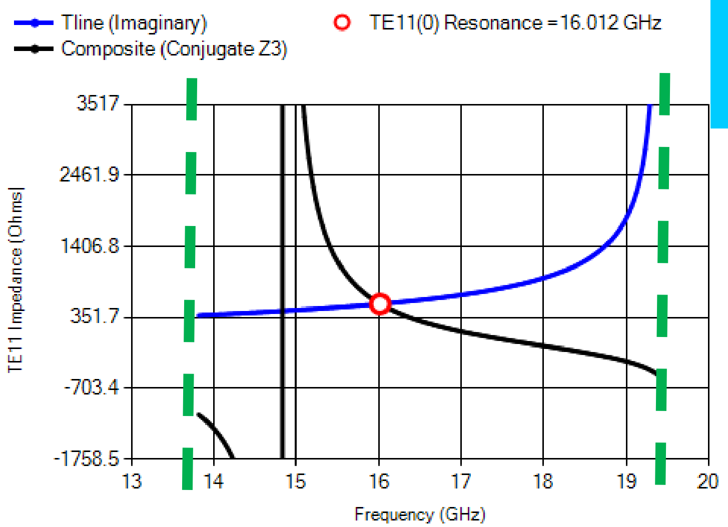

| Mode | Bead | T-Line |
|---|---|---|
| TE11 | 13.8 | 19.4 |
| TE21 | 27.0 | 38.0 |
| TE31 | 39.4 | 55.4 |
| TM01 | 53.3 | 75.0 |
| TE01 | 55.1 | 77.6 |
| TM11 | 55.1 | 77.6 |
| TE12 | 57.4 | 80.7 |
| TM21 | 60.2 | 84.6 |
| TE22 | 63.7 | 89.6 |

# PTFE bead with 7mm airline experiment

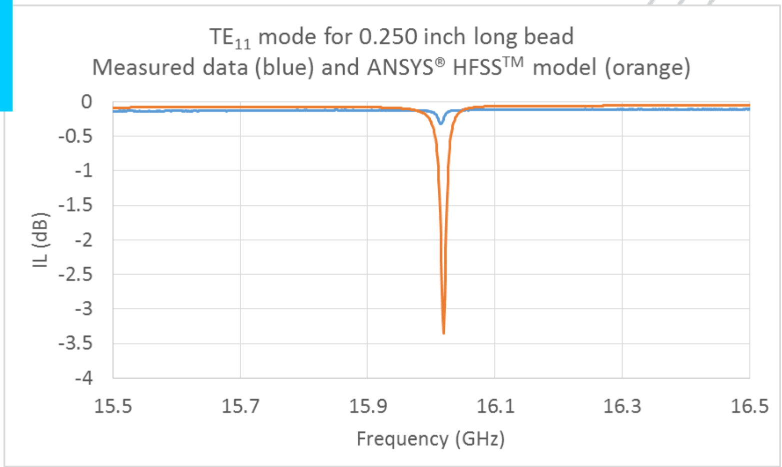



**0.125 inch long bead**




**0.250 inch long bead**

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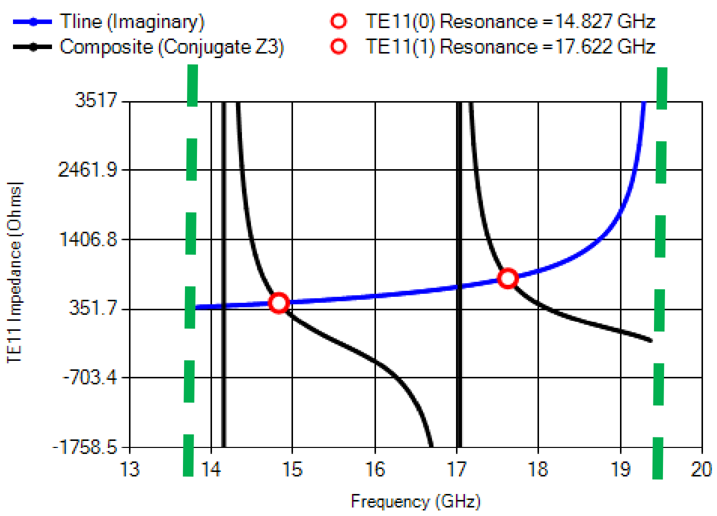
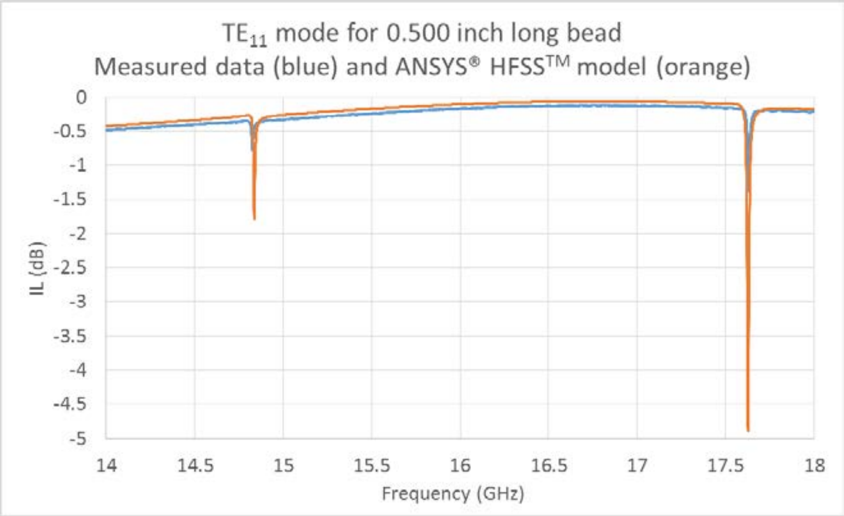
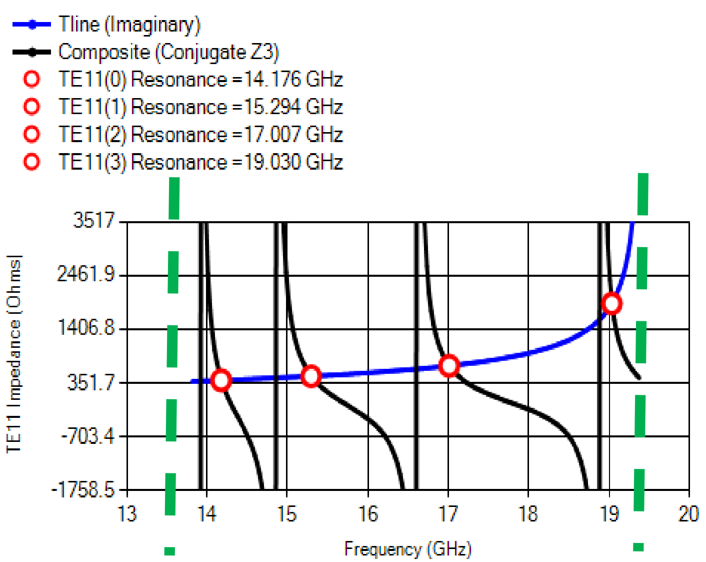
# PTFE bead with 7mm airline experiment

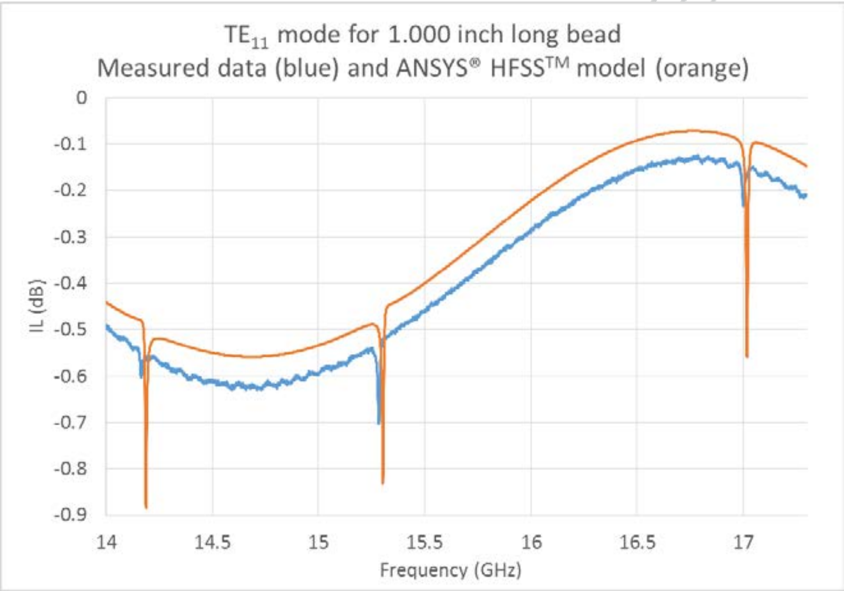



**0.5 inch long bead**




**1.0 inch long bead**

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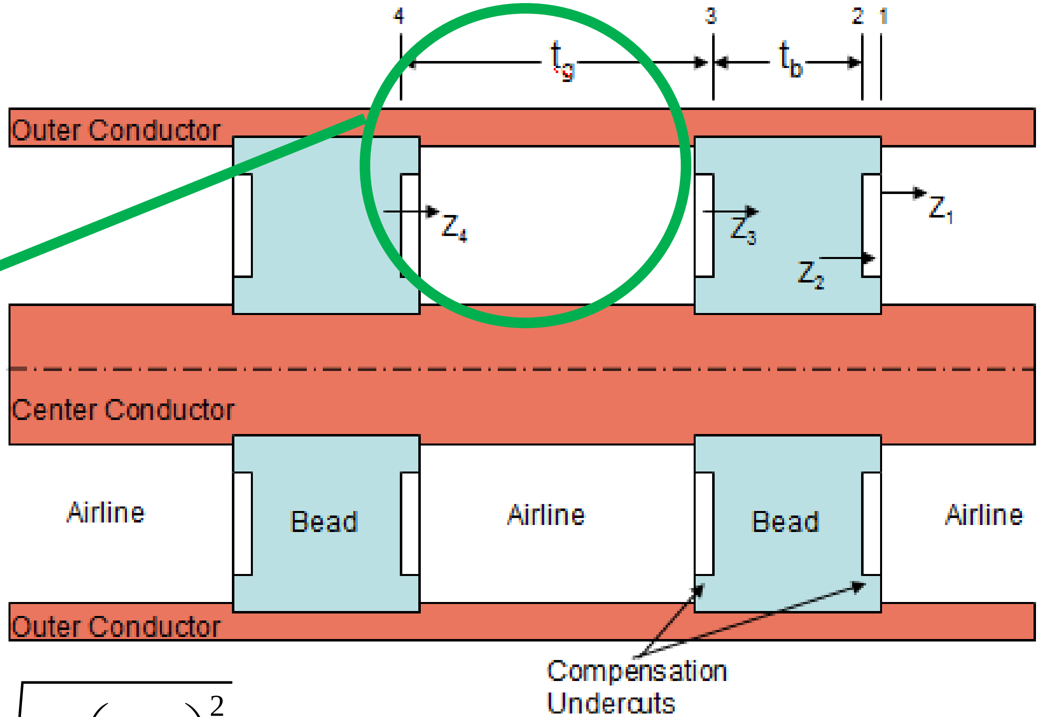
# Dual beads within an airline




$$Z_4 = Z_{0g} \frac{Z_3 + Z_{0g} \tanh\left(\gamma_g t_g\right)}{Z_{0g} + Z_3 \tanh\left(\gamma_g t_g\right)}$$

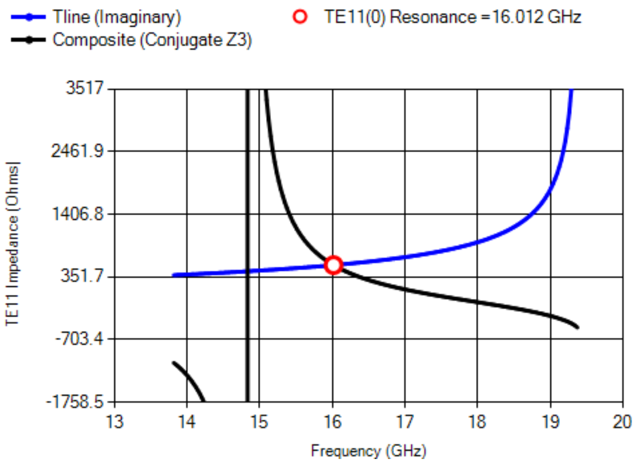
$$\text{where; } Z_{0g} = Z_{0a} \;;\; \gamma_g = \gamma_a = k_a \sqrt{1 - \left(\frac{f}{f_{ca}}\right)^2}$$

**Resonance conditions occurs when:**

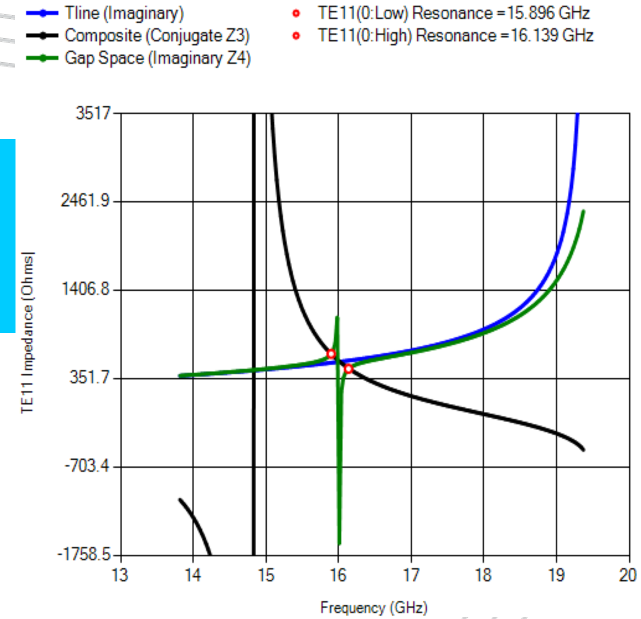
$$Z_4 = Z_3^*$$

# Dual PTFE beads within 7mm airline

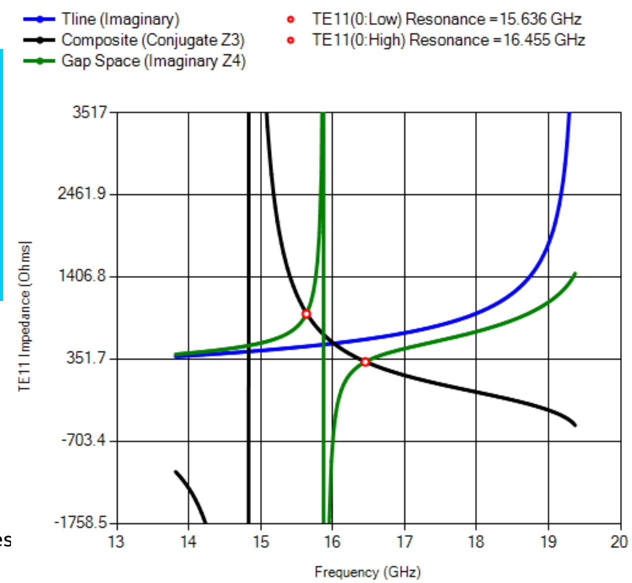
## 0.250 inch long single bead



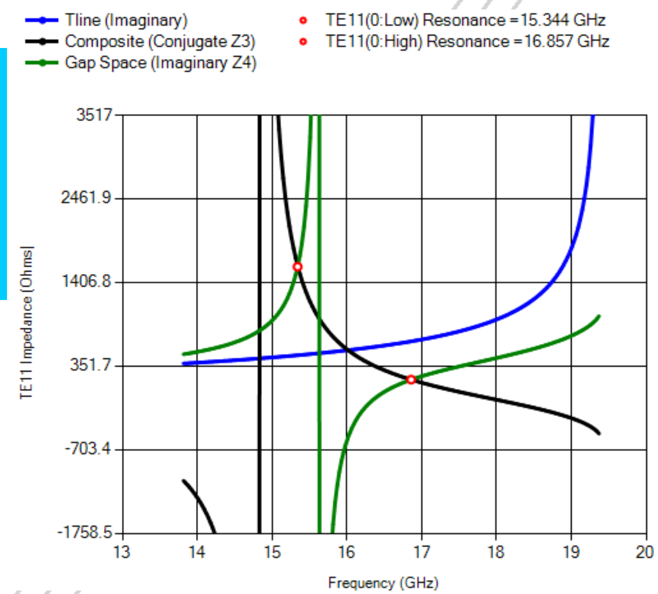

## (2x) 0.250 beads, 0.5 inch apart




## (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 (or equiv.)
    - Introduce slight asymmetries
  - Measure the assembly to validate the lowest $TE_{11}$ resonant frequency