RF Modeling of the Helical Kicker for Project X

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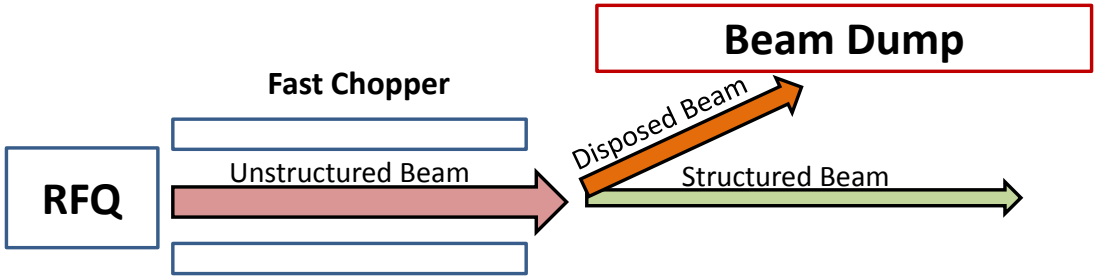
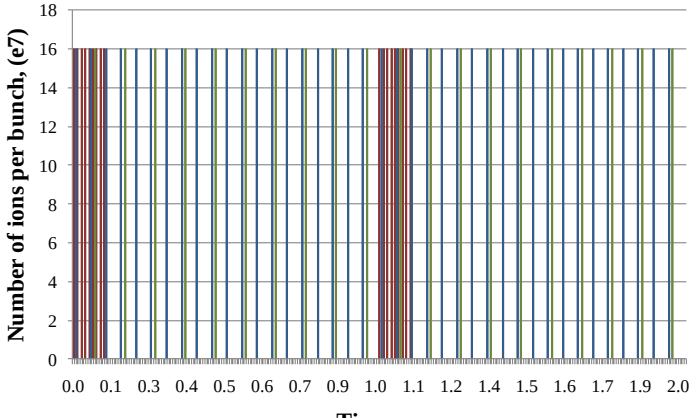
Project X Bunch Structure

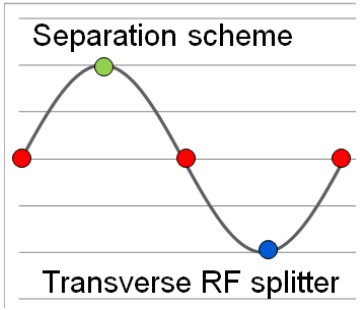
Multiple experimental program necessitates complicated bunch structures

	Train Frequency	Pulse Width (nanoseconds)
Kaon experiments	20-30 MHz	<0.2
Muon conversion experiment	0.5-1.0 MHz	<100
$\mu \rightarrow e\gamma$ & $\mu \rightarrow eee$ experiments	80-300 MHz	<0.2

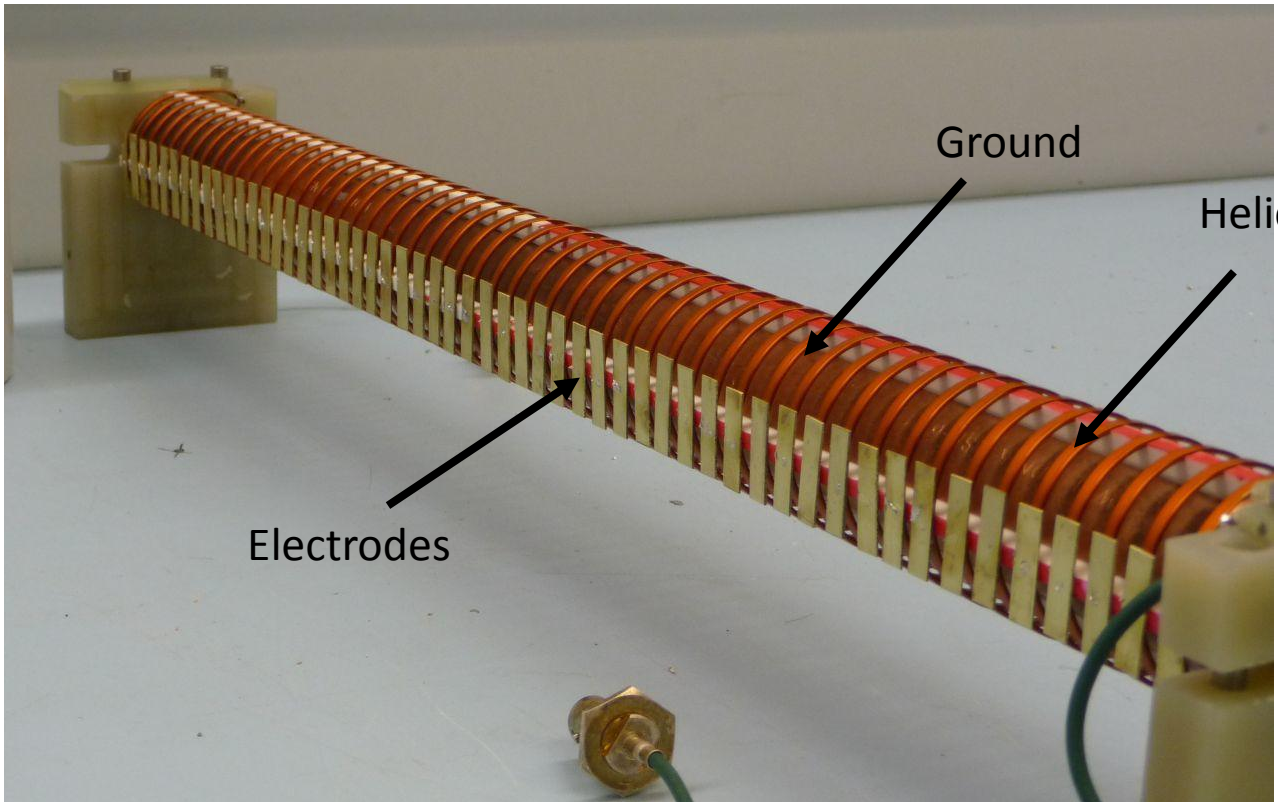




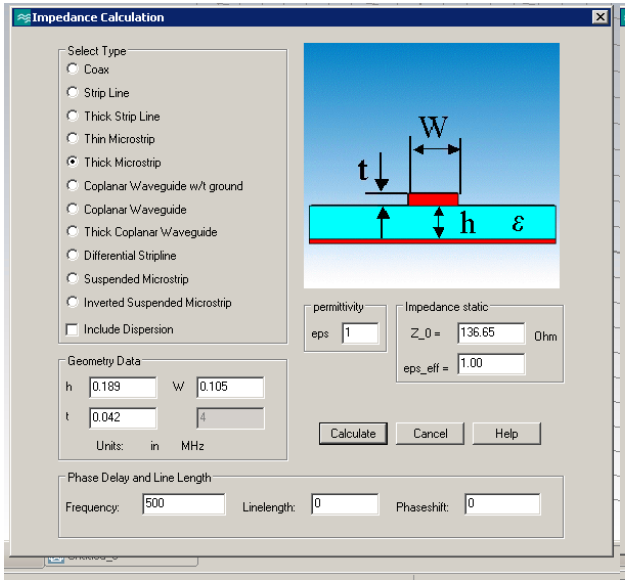
The fast chopper is needed to construct the structured bunch stream



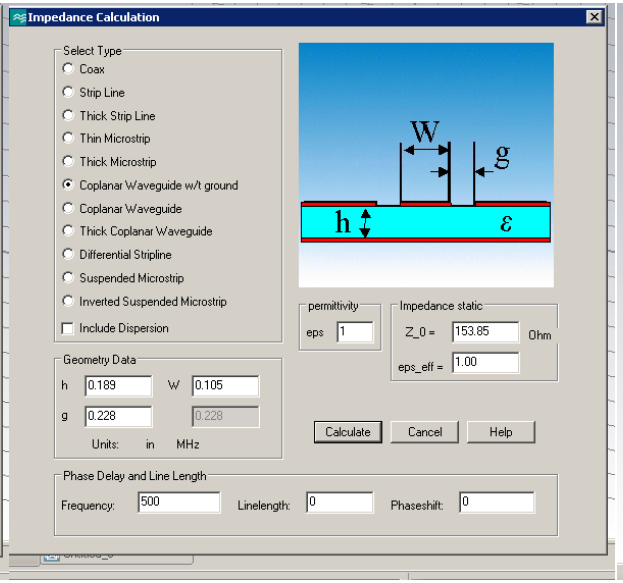
Helical Chopper Prototype



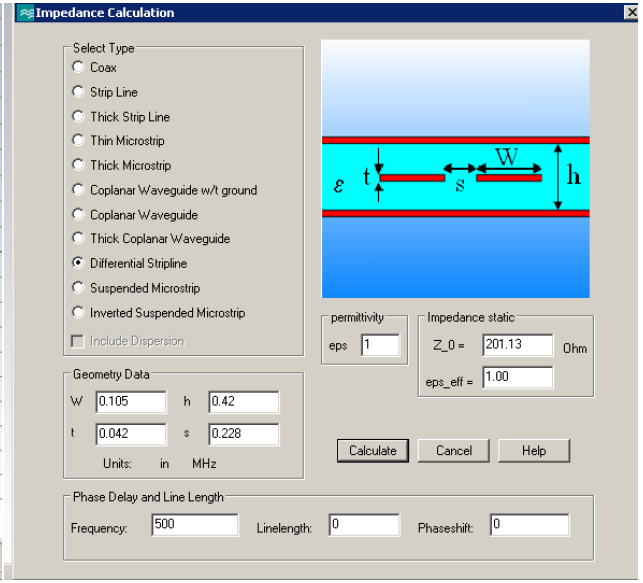
Characteristic Impedance of Comparable Planar Lines



Micorstrip Line
Z_0=137Ω

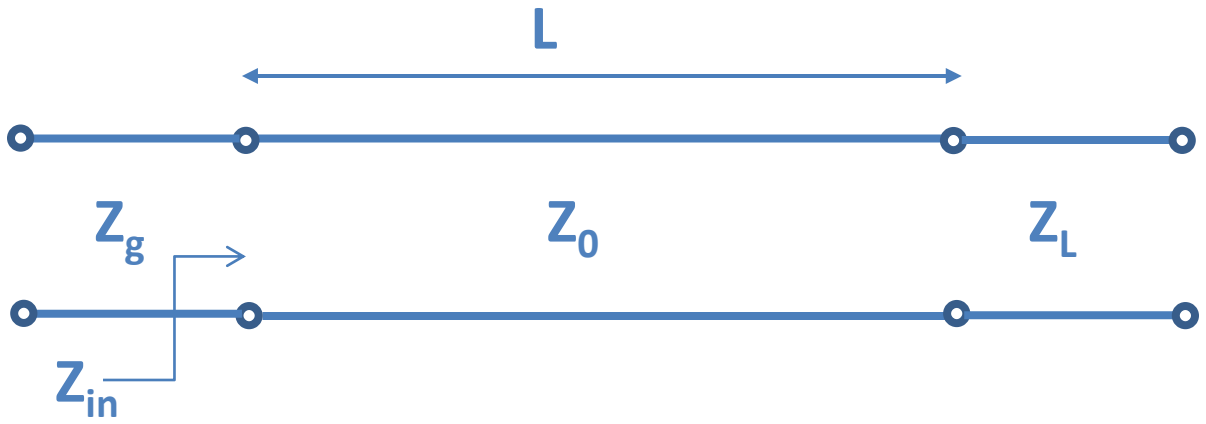


Coplanar WG
Z_0=154Ω



Differential Line
Z_0=201Ω

Ideal Transmission Line Model

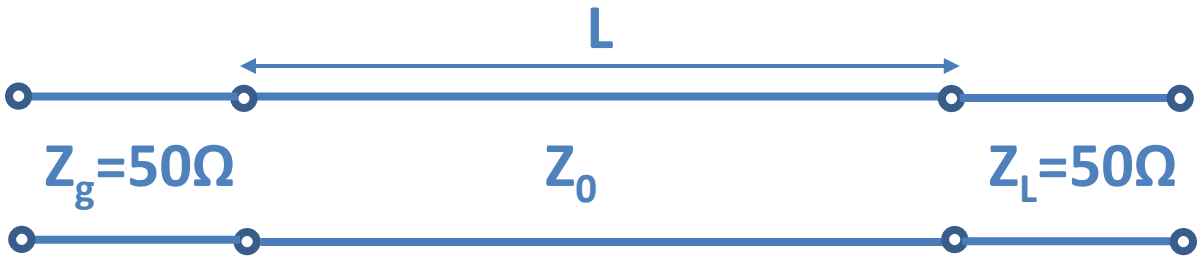


$$Z_{in} = Z_0 \frac{Z_L + jZ_0 \cdot \tan(\beta.L)}{Z_0 + jZ_L \cdot \tan(\beta.L)}$$

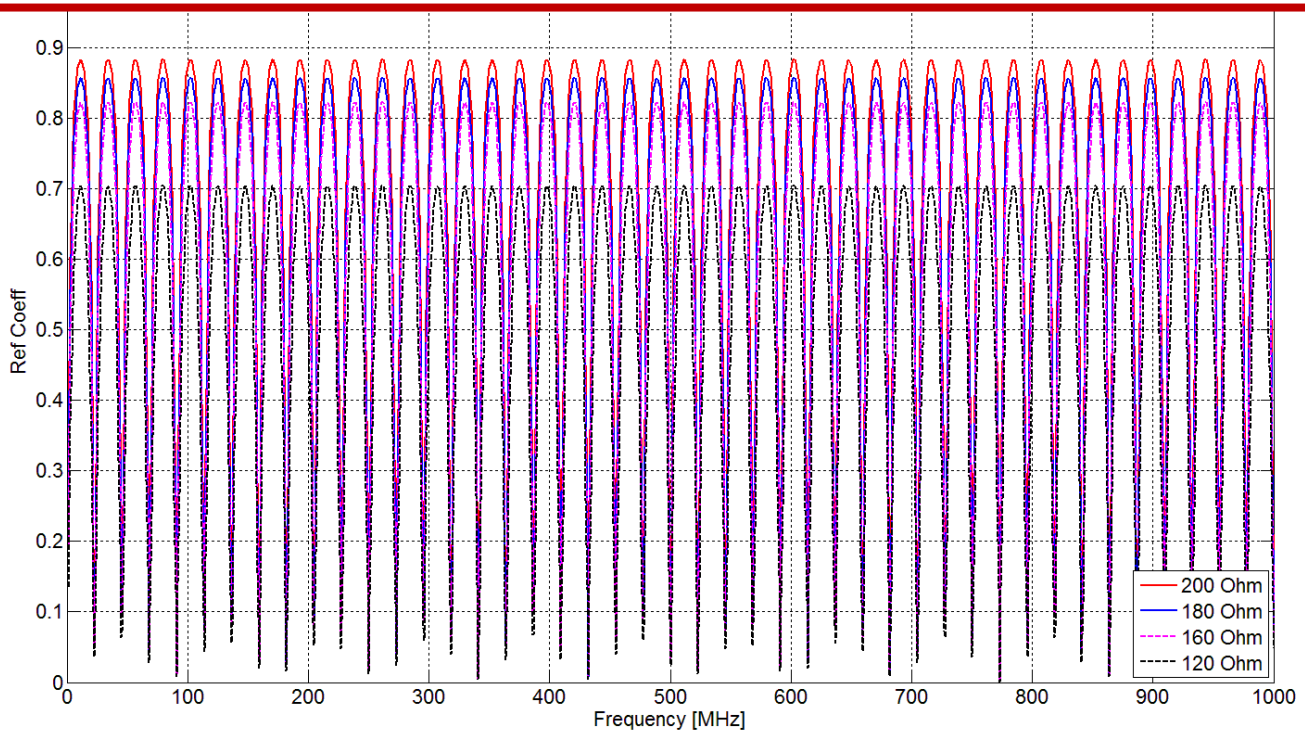
$$\Gamma = \frac{Z_{in} - Z_g}{Z_{in} + Z_g}$$

Assume Z_g=Z_L=50 Ω to mimic the measurement setup and vary Z_0 to have a feeling about what should we expect for the reflection from the helix (if it has uniform characteristic impedance)

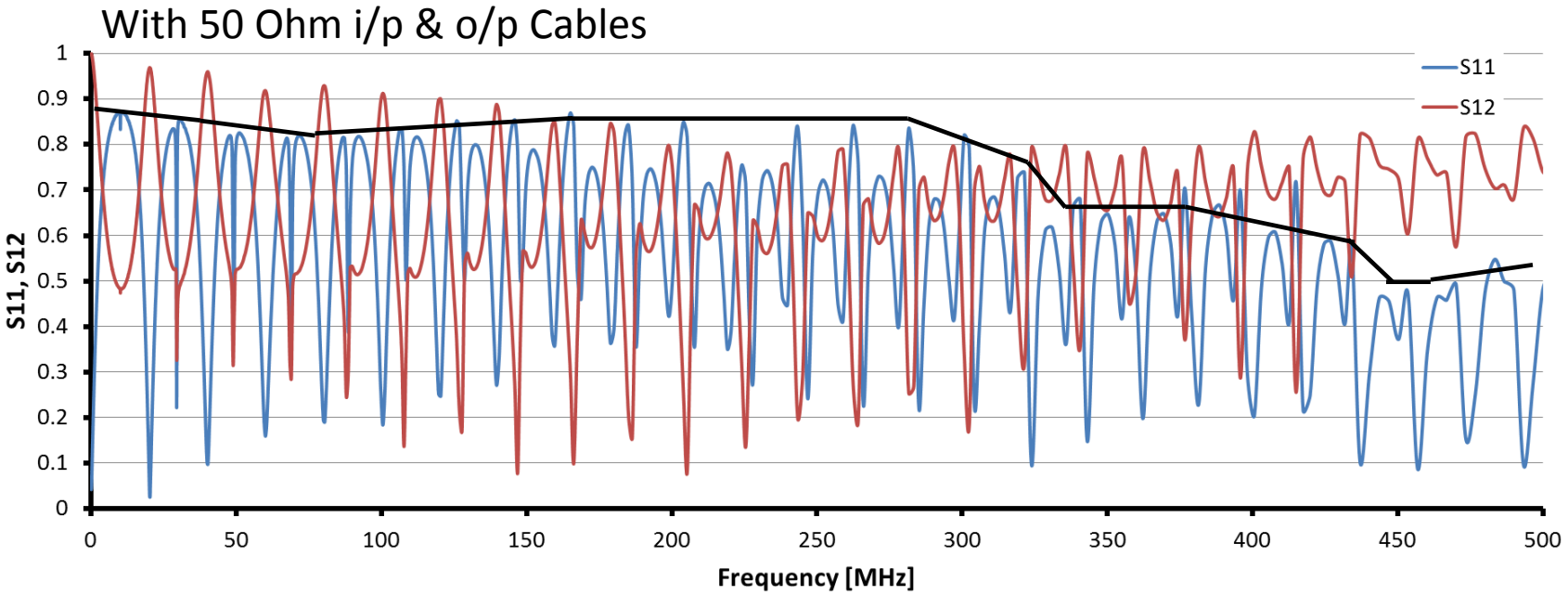
Theoretical Reflection Response for an Ideal Transmission Line



For ideal transmission line with 200 Ω, we expect about 0.88 reflection coeff.

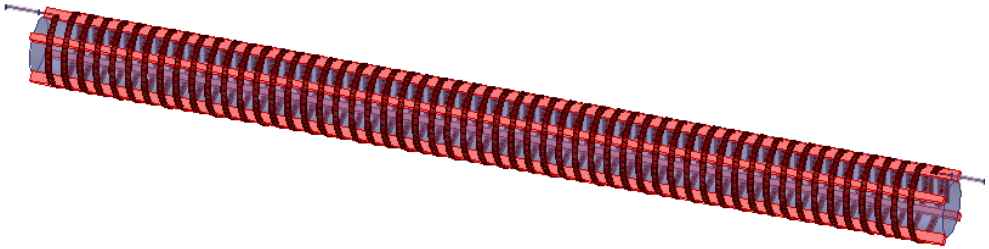


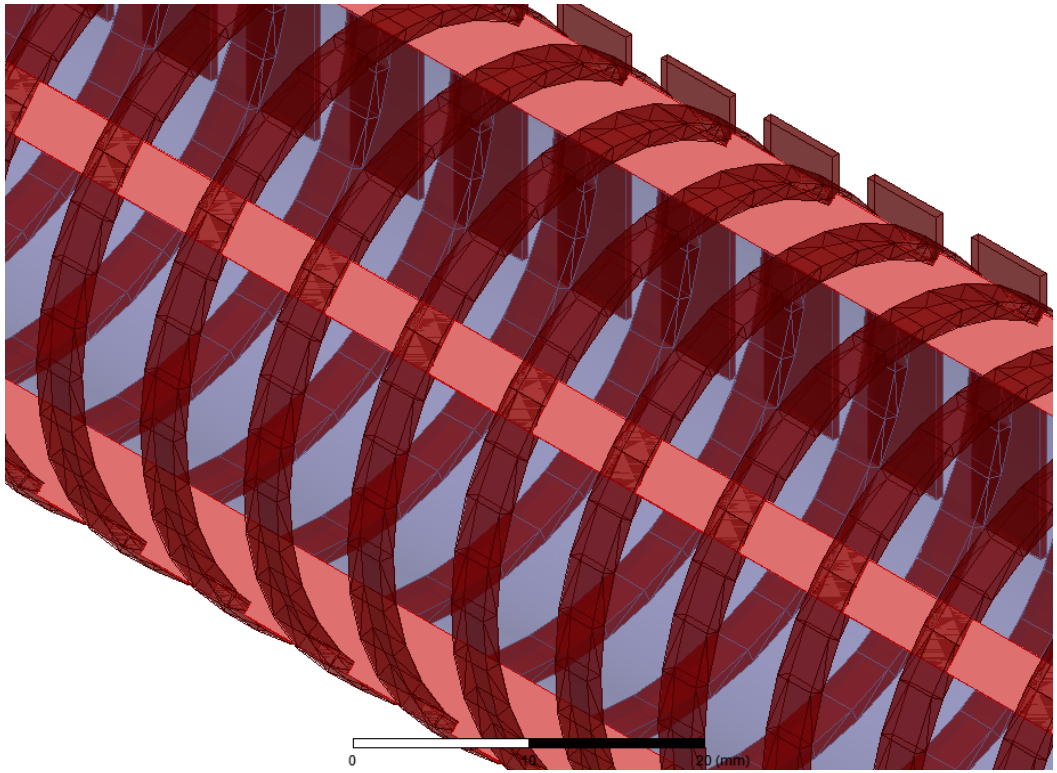
Measurements

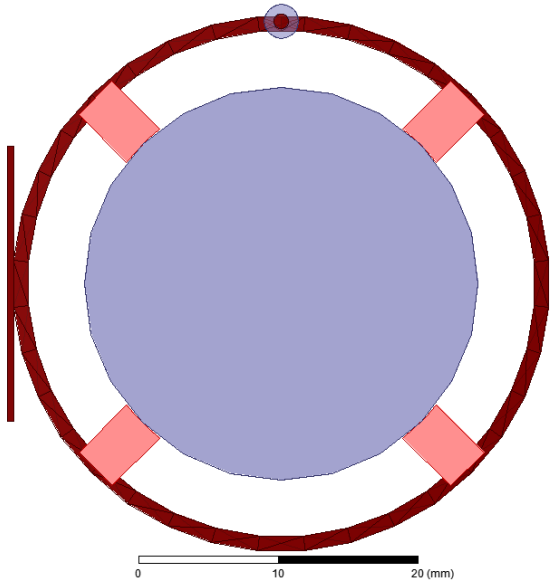


The characteristic impedance of the structure starts by about 200 Ω at 20 MHz but then changes significantly with frequency ⟹ Dispersion

HFSS Model

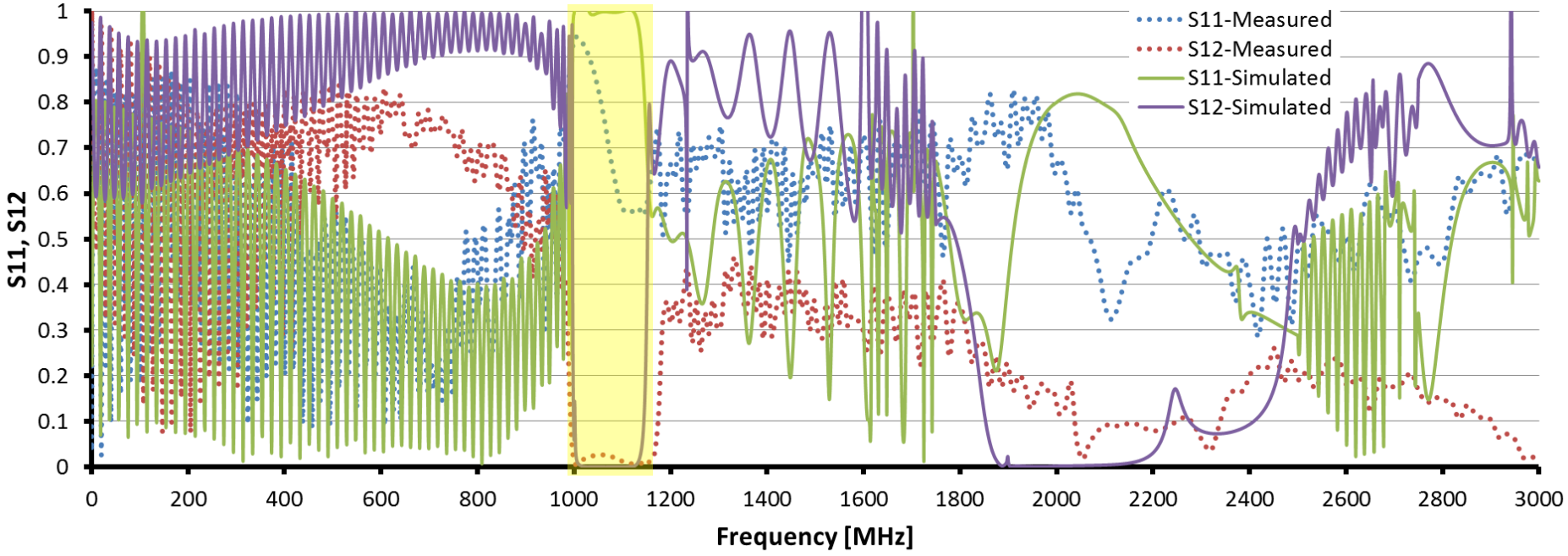




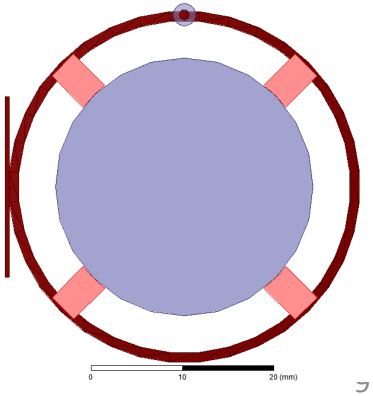


- 55 Turns
- With Electrodes
- Open to Air Except the Mirror Plane
- 50 Ohm Excitation

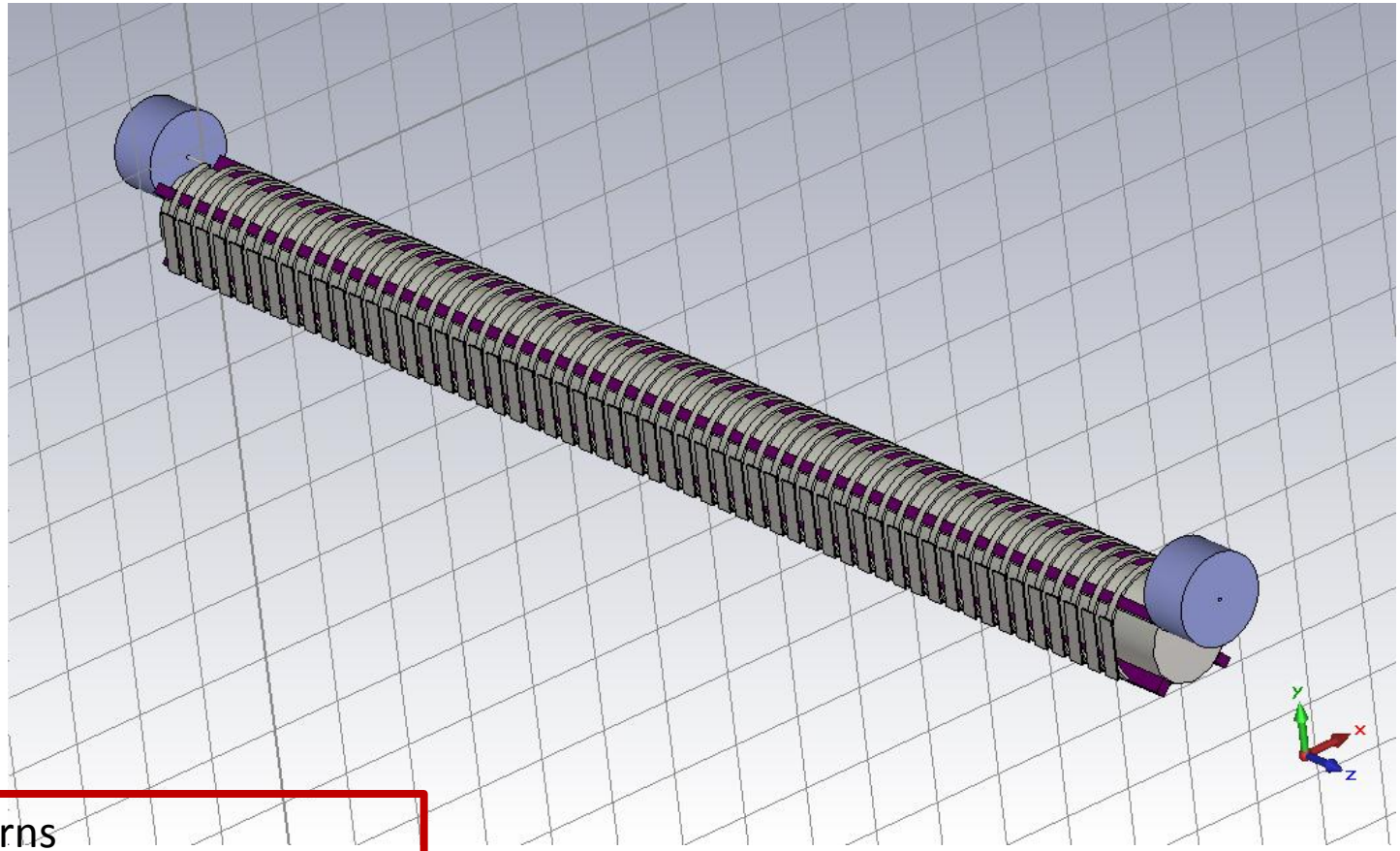
Simulated versus Measured S-Parameters



- Periodicity of the dielectric supports causes the stop bands at 1 GHz, 2 GHz
- Simulated frequency response agrees with the measured one in terms of these stop bands of the periodic structure



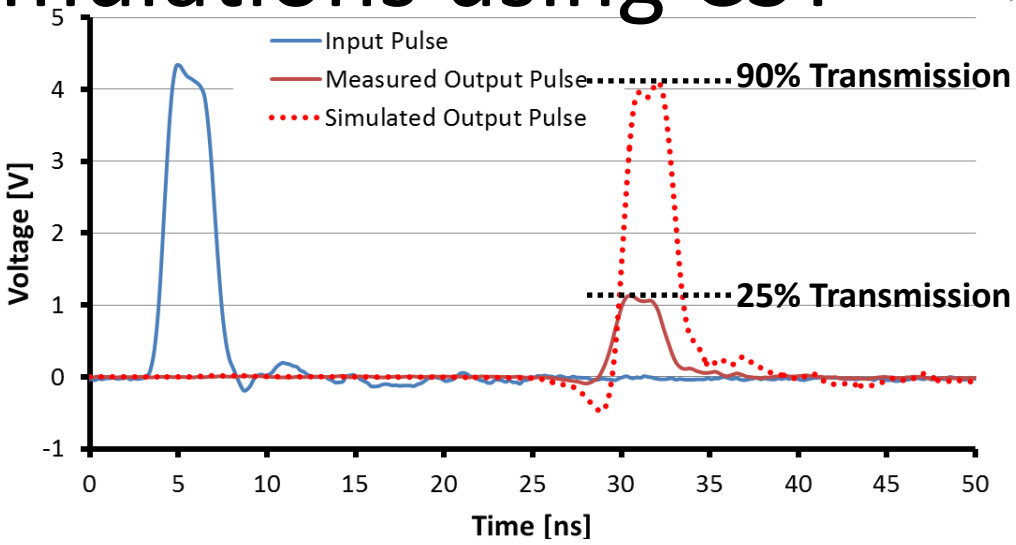
CST Model



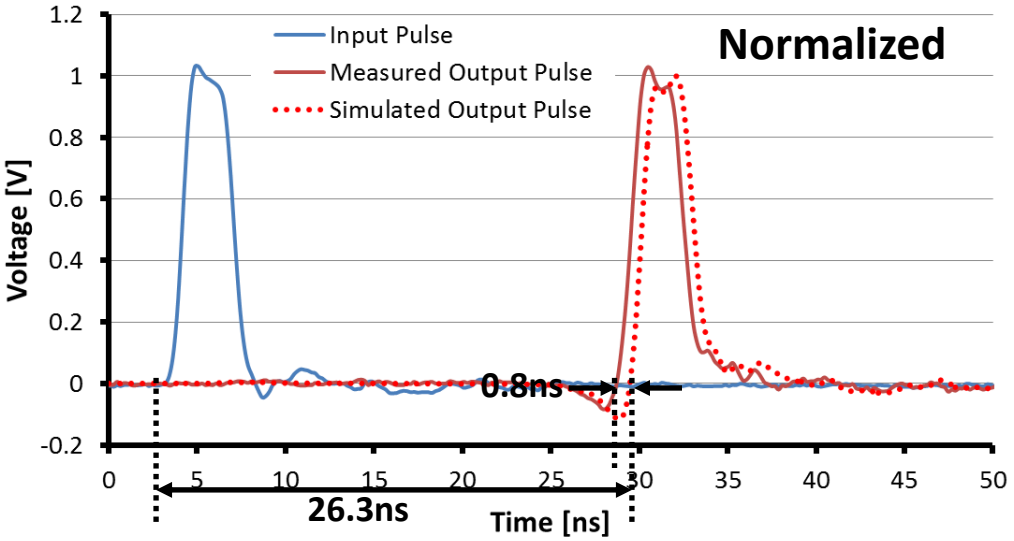
- 55 Turns
- With Electrodes
- Open to Air Except the Mirror Plane
- 200 Ohm Excitation

Time Domain Simulations using CST

- Dimensions corresponds to the latest measured prototype
- Structure simulated open to air
- Actual pulse with 1ns rise\fall time was used as excitation



- Simulated pulse delay for **0.333”** pitch is 26.3 ns
- Need to account for 1” input/output coaxials ~2”/3e8=0.17 ns
- Delay in the helical structure is 26.1 ns



- About 0.8 ns difference between the simulated and measured transmission pulses
- Simulation shows better transmission of the pulse through the structure
- Due to the different excitations used in simulation and measurements

Adjusting the Delay

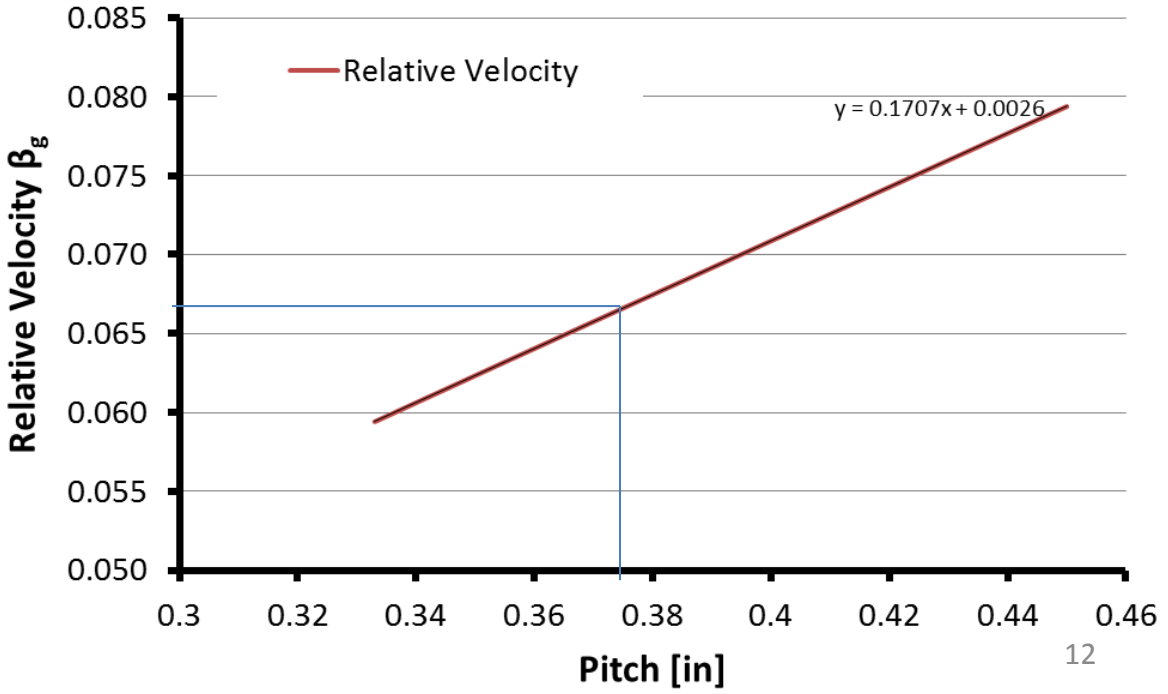
E=2.1 Mev -- Gamma=E/940.85[MeV]+1, Gamma=1.002232, Targeted β_g 0.0667

hs=0.189” L=N*P v=L/Delay β_g=v/c

	L, Delay	β_g
P=0.333”	465.2 mm, 26.1 ns	0.05941
P=0.370”	516.89 mm, 26.2 ns	0.06576
P=0.450”	628.77mm, 26.4ns	0.07939

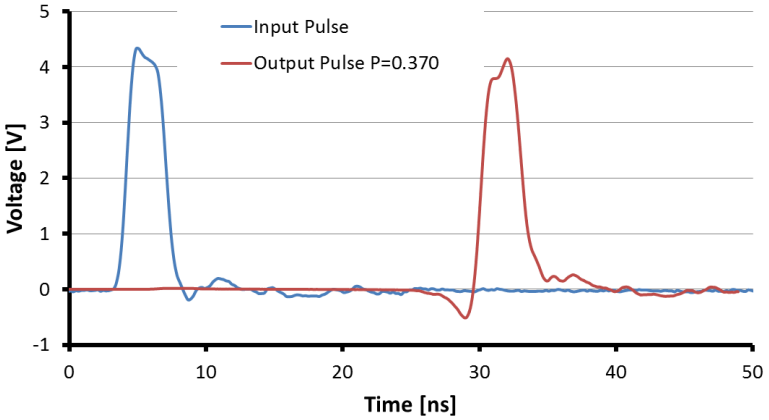
$P = (\beta_g\text{-}0.0026)/0.1707$
P=0.376”

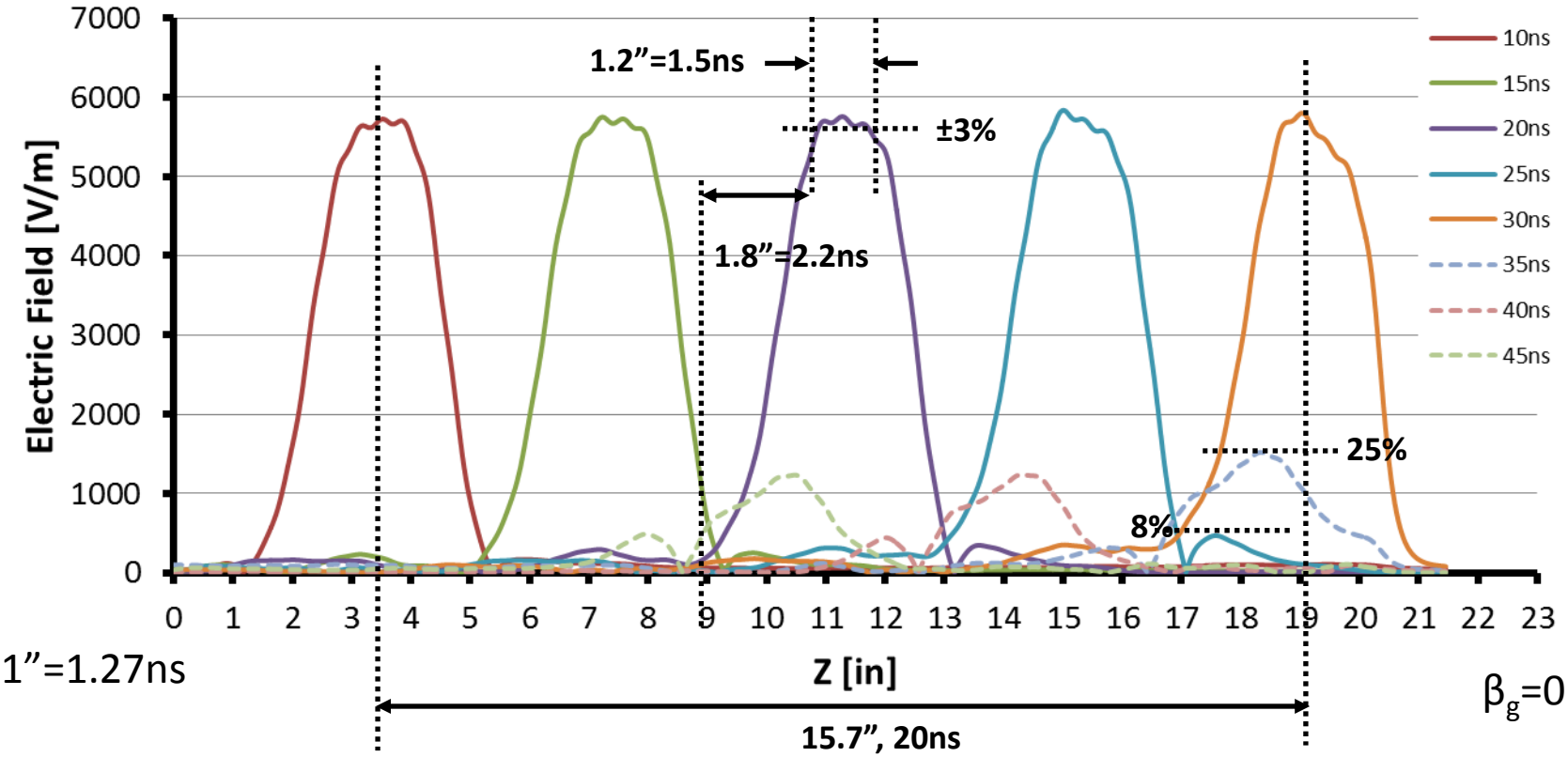
- To get the targeted value of the delay, the pitch need to be changed



Field on Beam Axis

- Field on beam axis for P=0.37”
- Actual input pulse with 2ns hold time and 1ns rise/fall time
- 200 Ω input/output excitation to the structure

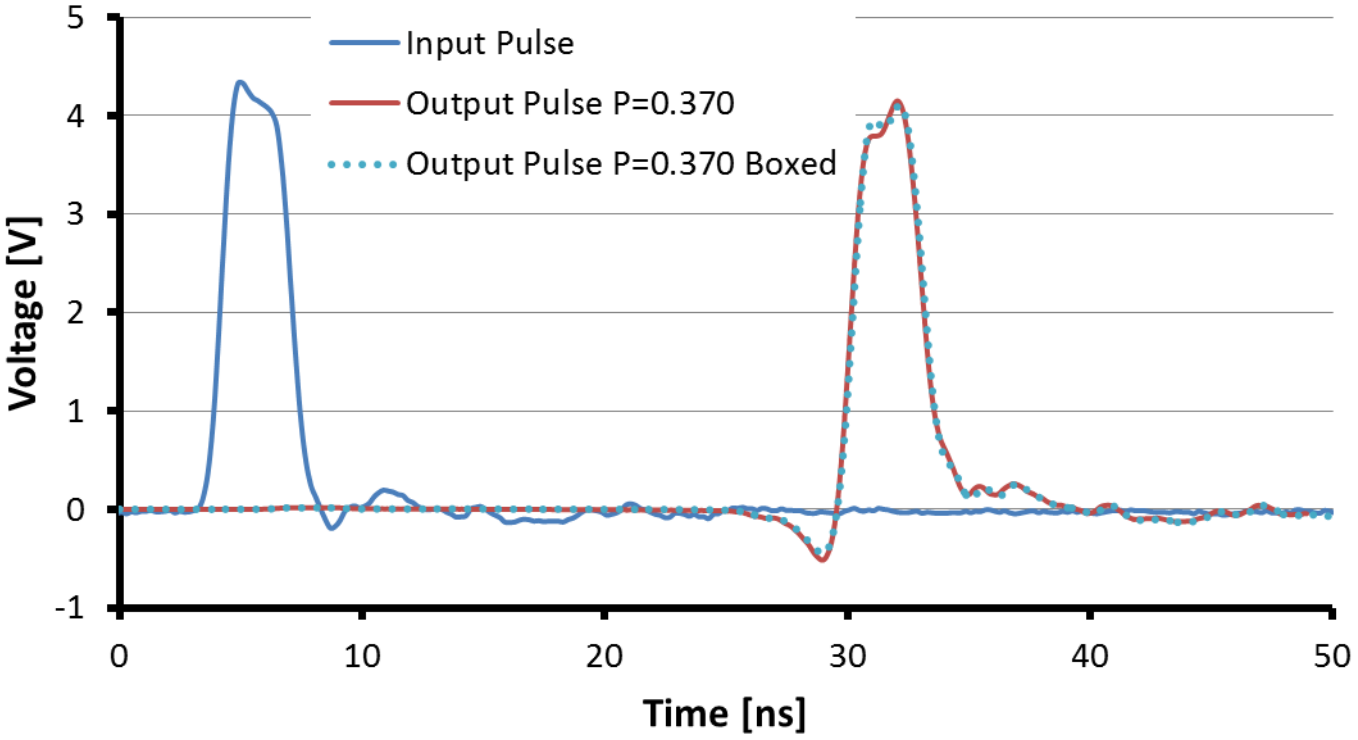




β_g=0.06648

Open vs Boxed Structure

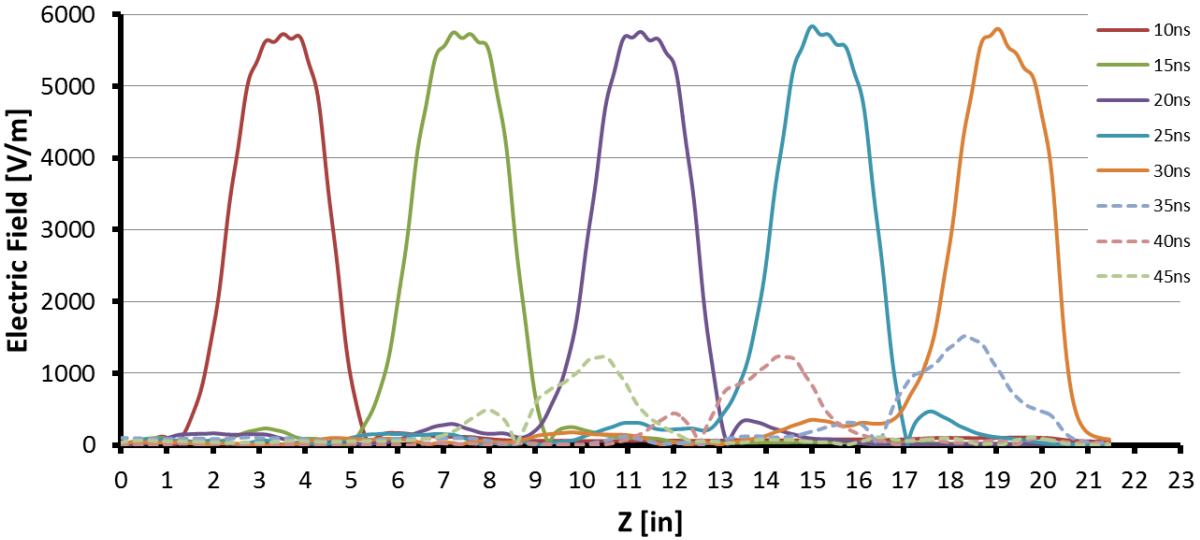
- Used a box according to the drawing 2251



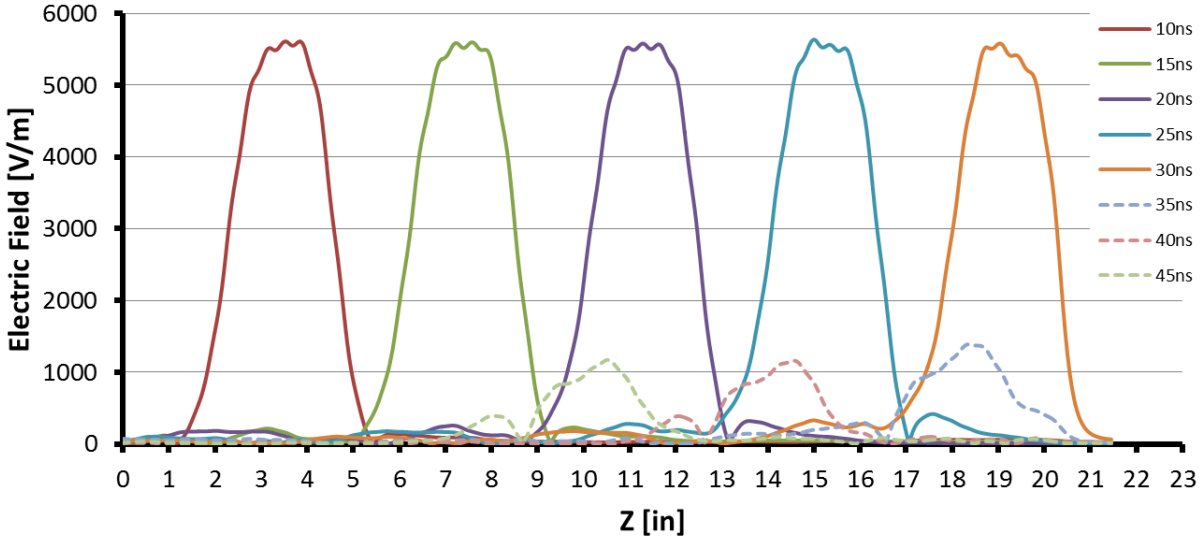
Delay didn't change upon boxing the structure

Open vs. Boxed Structure

Open

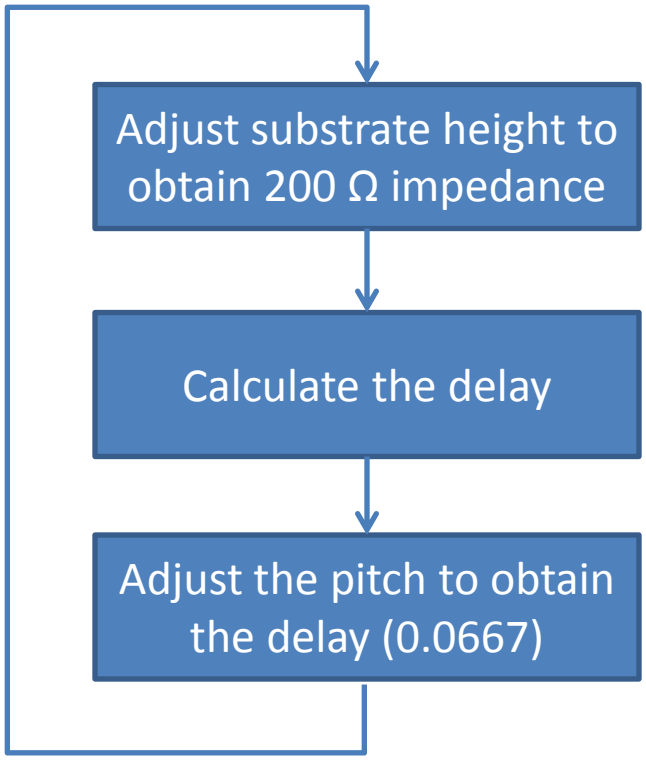


Boxed



Dispersion looks a little bit better after boxing the structure

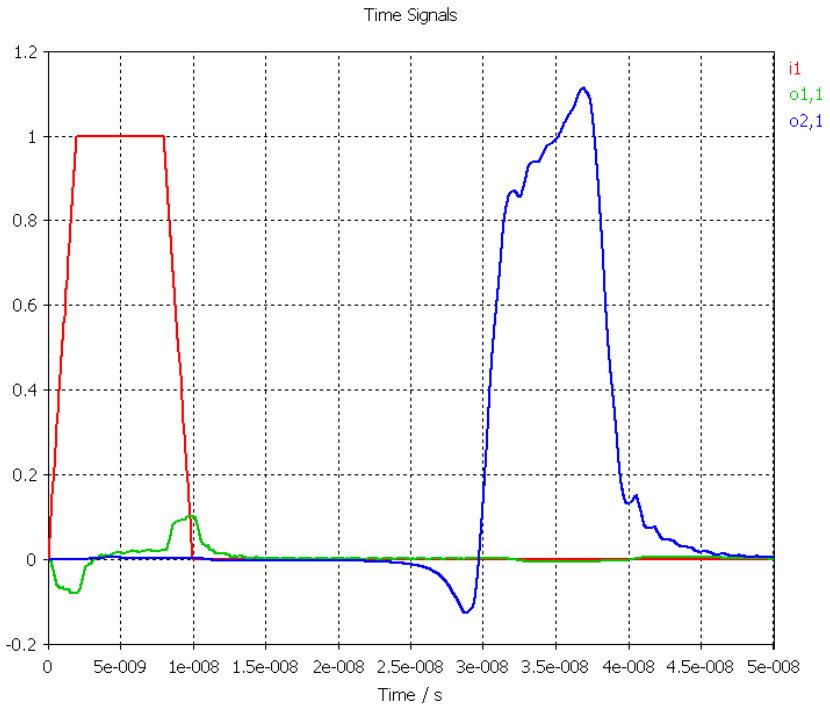
Adjusting the impedance and delay

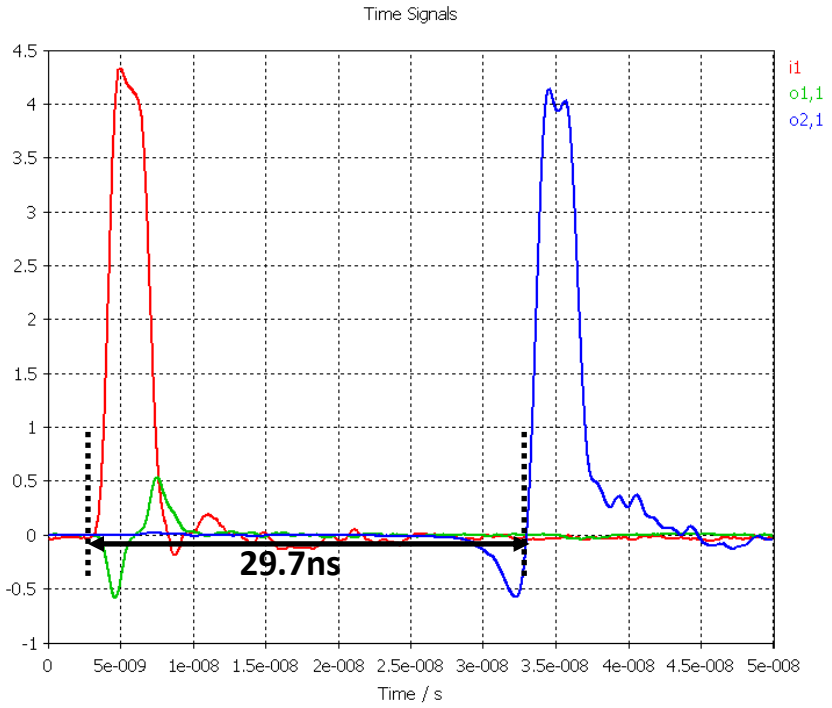


Getting both the impedance and the delay required few design iterations changing the substrate height and pitch

Final Design

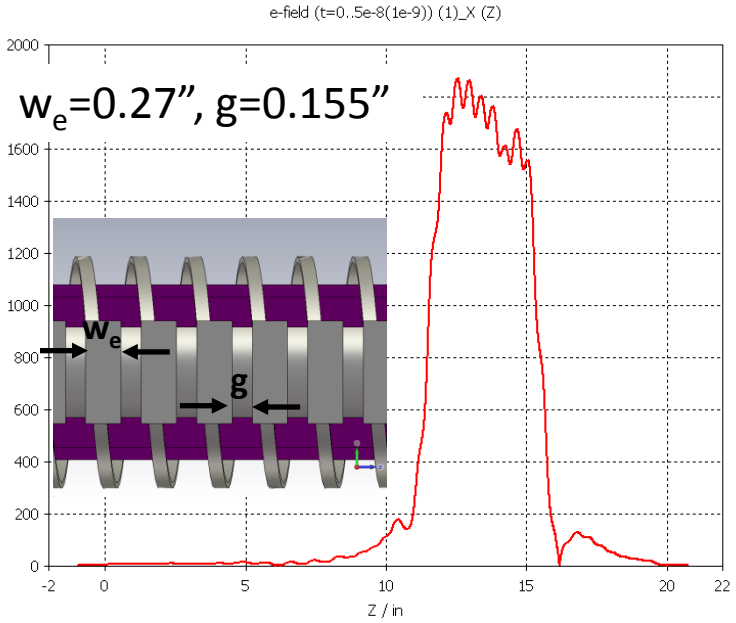
- Substrate height (metal to metal in different to the sketch) hs=0.285”, h=hs+t/2=0.306
- Pitch=0.425”
- Everything else is the same

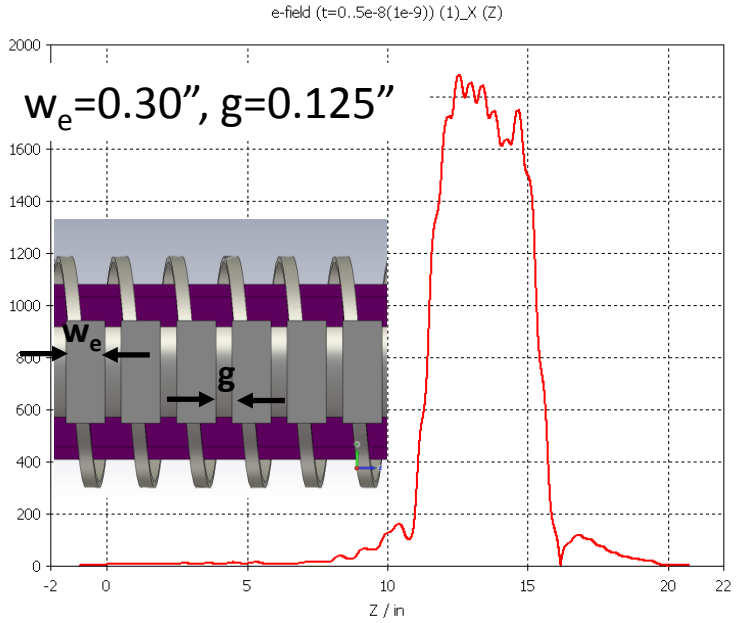


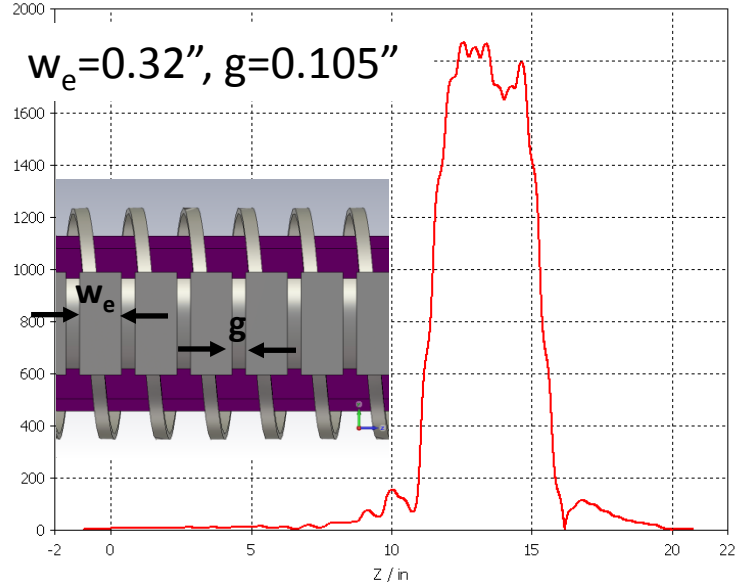


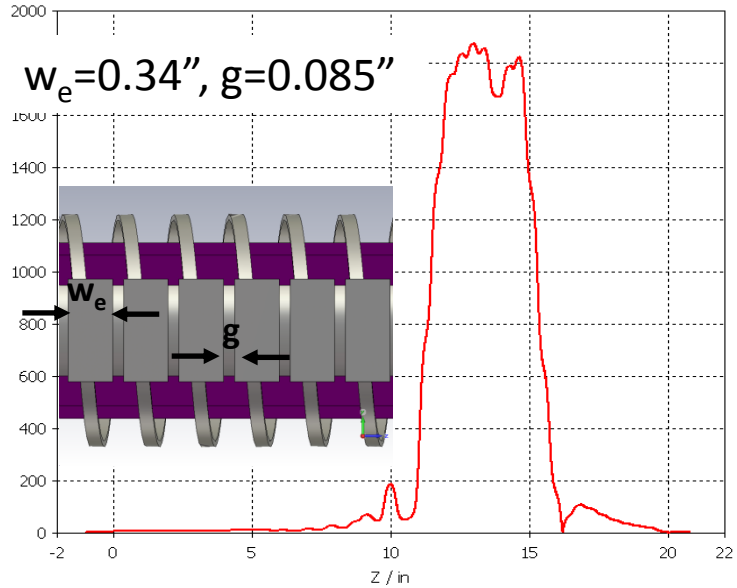
β_g 0.0666

Effect of Changing Electrode Size

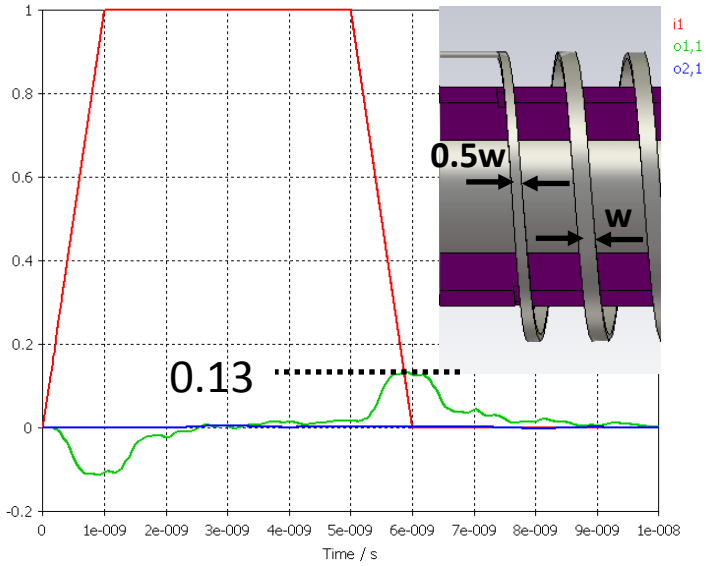


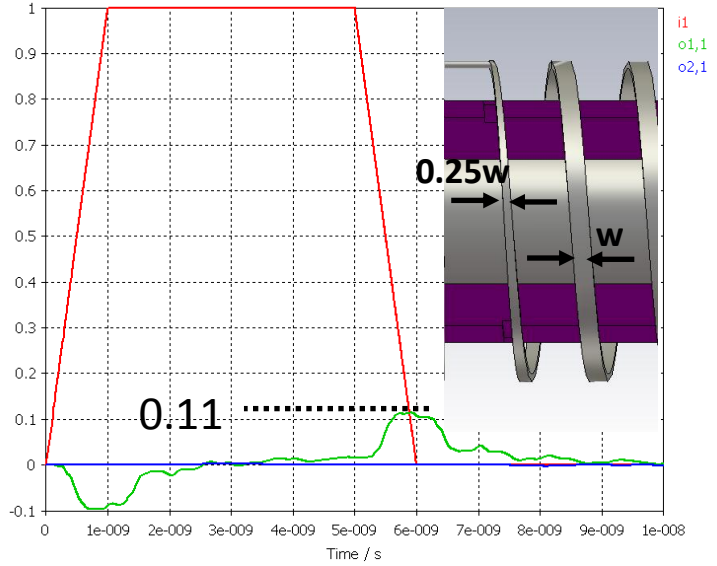




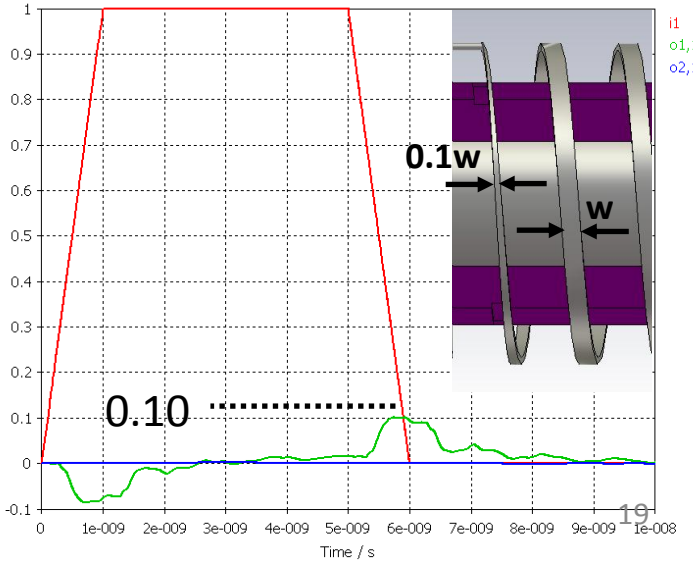


Effect of Flaring the Wire Ends

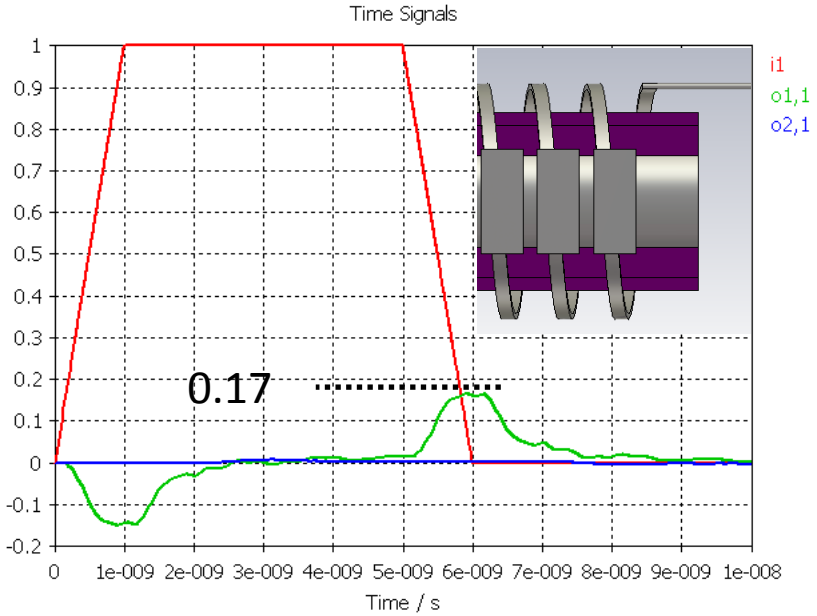


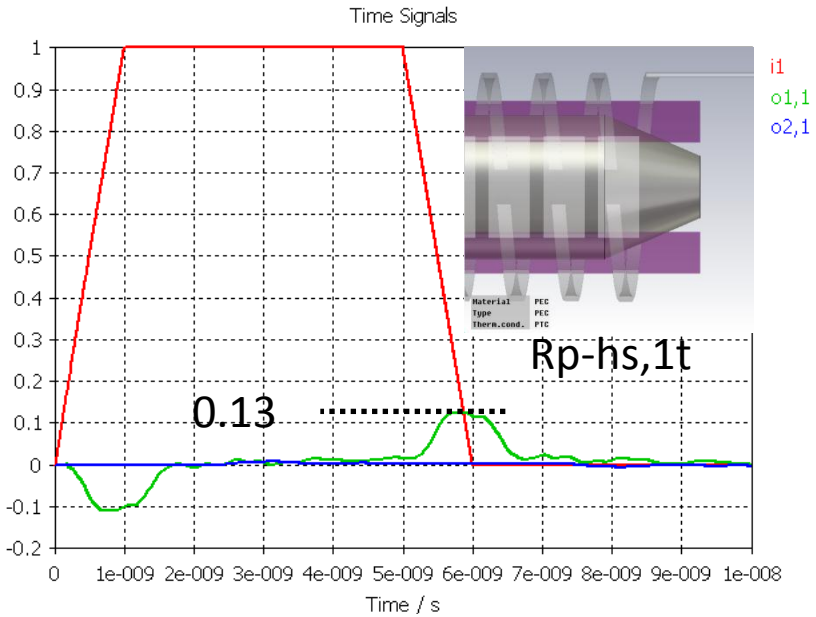


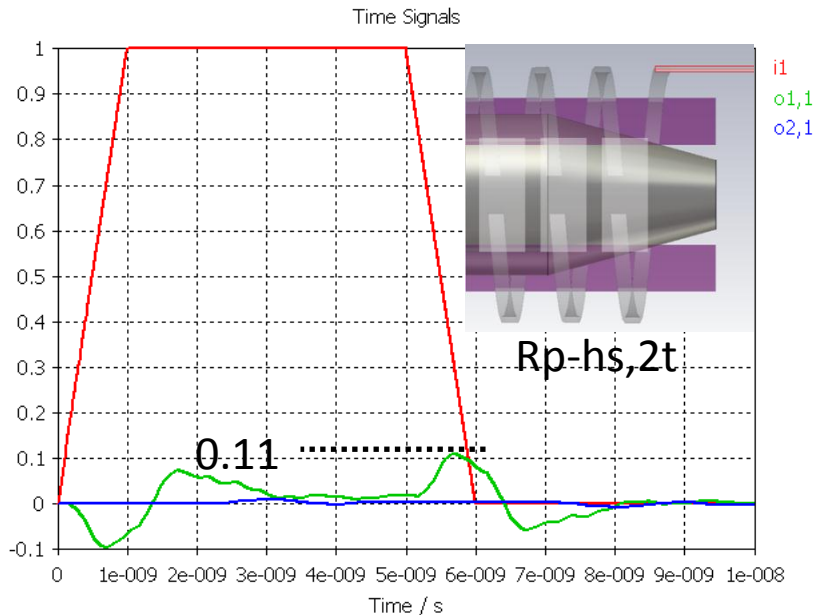
The wire would need to get too thin, which is unrealistic to implement

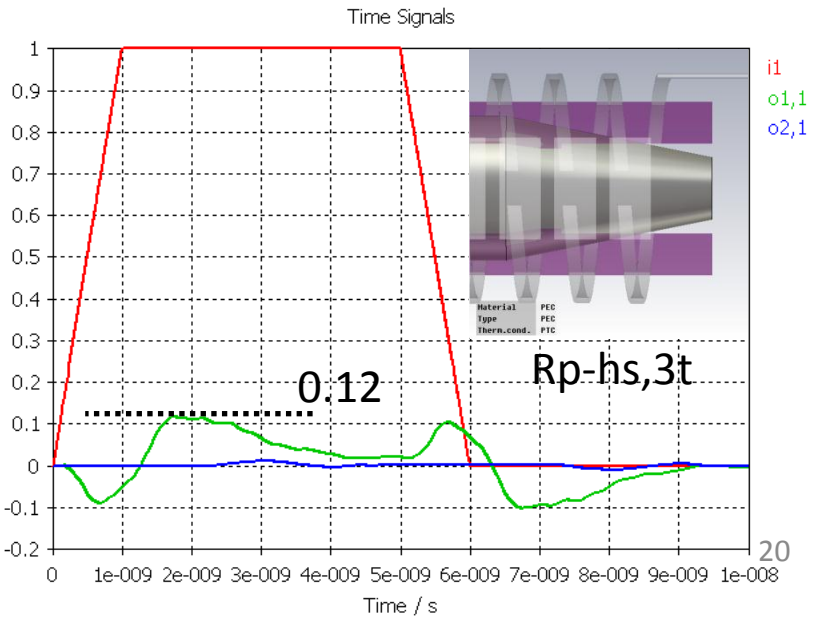


Tapering Ground Tube

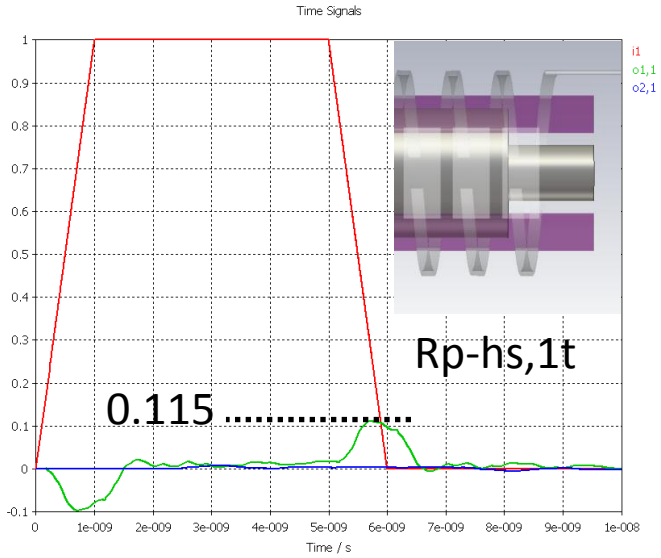


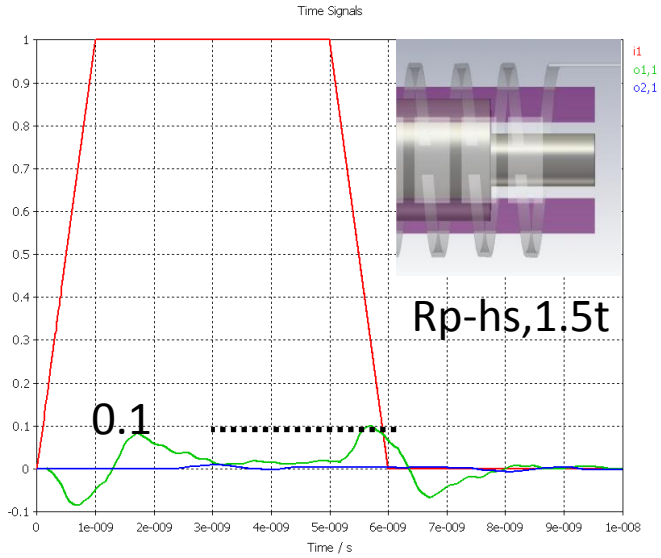


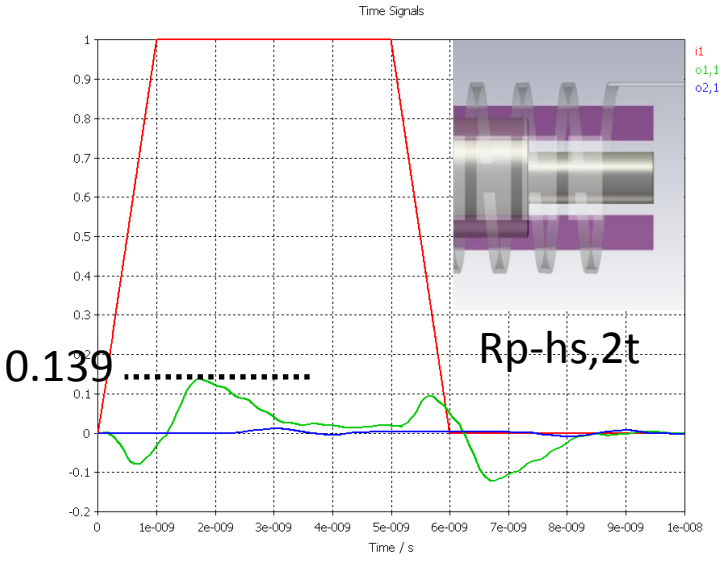




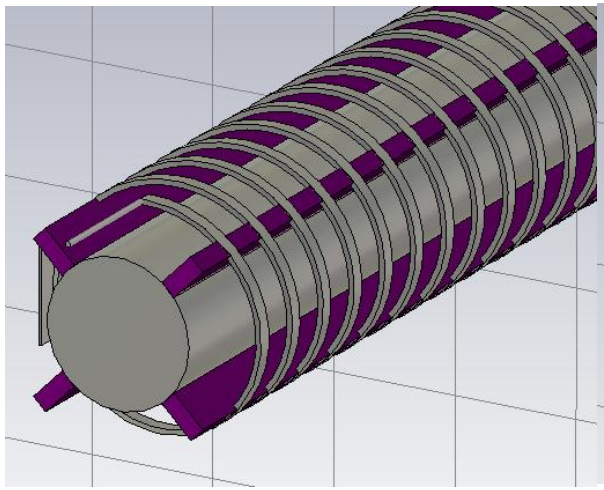
Stepped Ground Tube

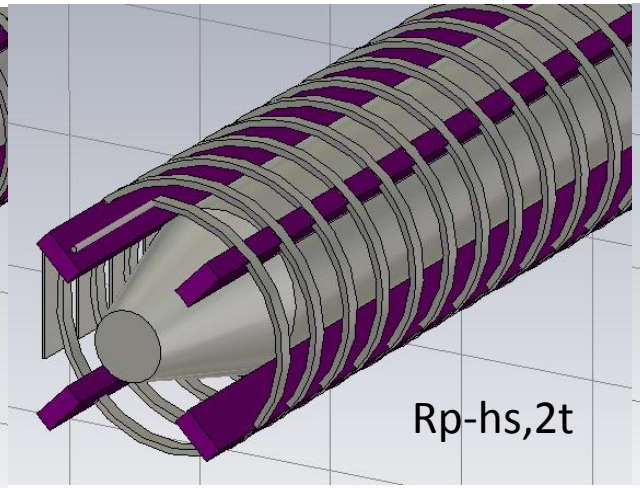


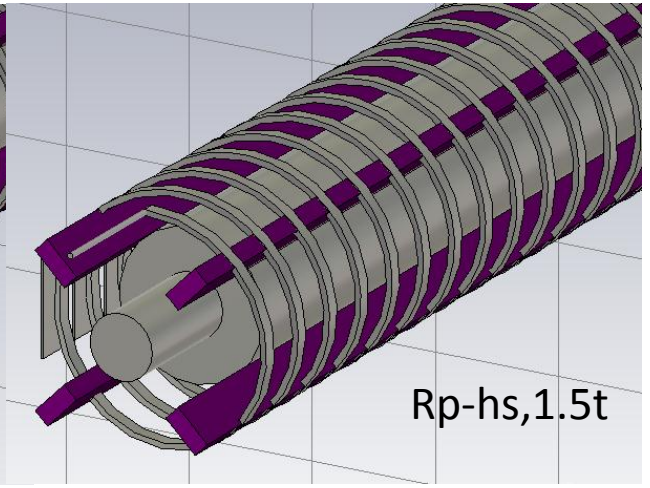


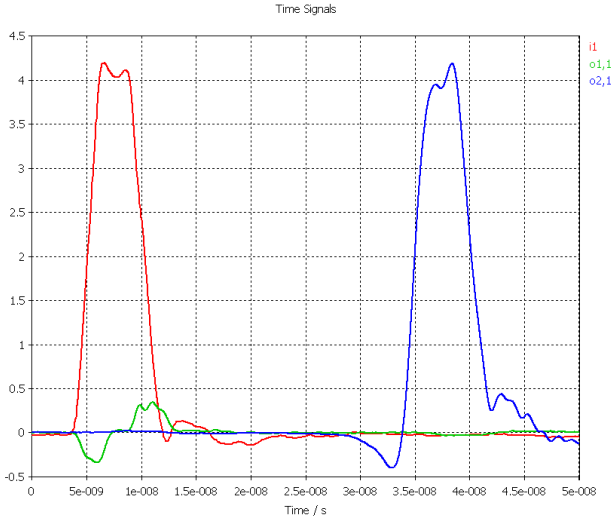


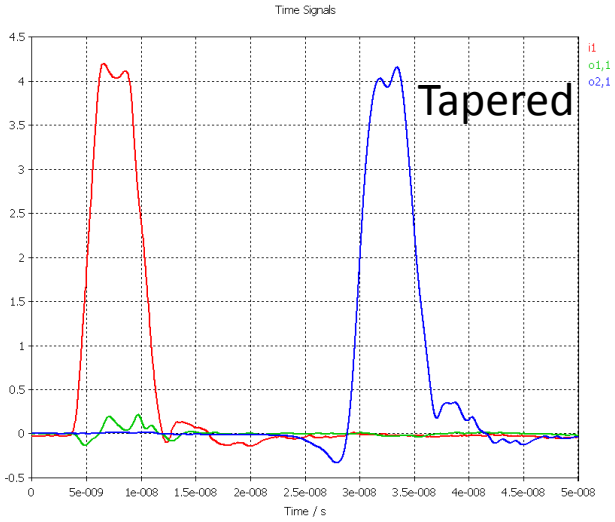
Design with End Effects Compensation

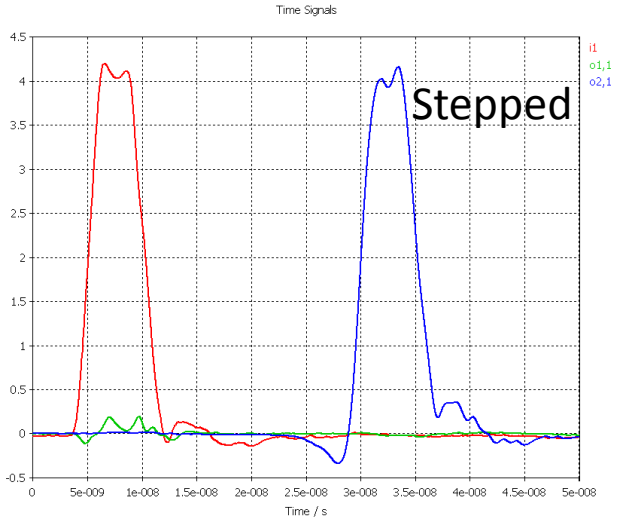












Conclusion

- The helical kicker has been thoroughly modeled
- Pitch of 0.425” is recommended to match the beam velocity with dielectric support of height 0.285” to get the 200 Ω impedance
- Boxing the structure with the current dimensions on drawing 2251 has negligible effects on the structure performance
- End effects could be compensated by flaring(or stepping) the ground for a couple of turns at the ends