Helical transmission line test stand for non-relativistic BPM calibration

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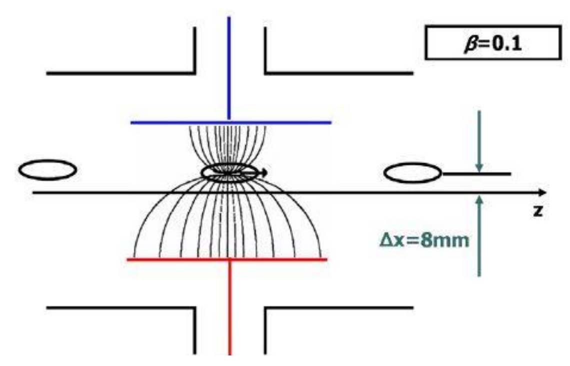
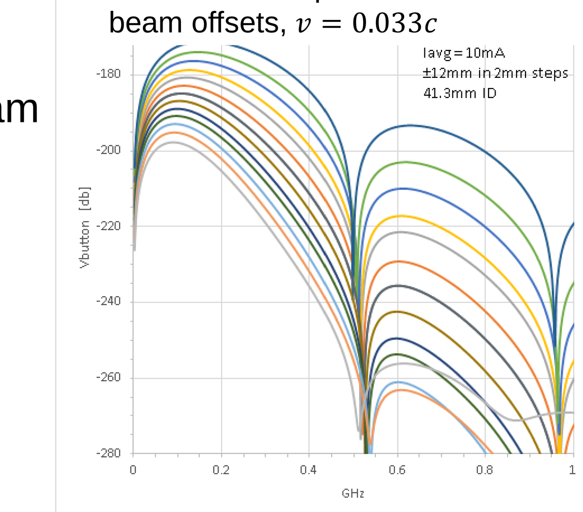
Corrections for capacitative pick-ups for non-relativistic effects

- Non-relativistic beams are not pancaked longitudinally.
  - Standard analysis does not account for non-relativistic effects to simplify results.
  - The different field extents affect the measurements
- Corrections for non-relativistic effects
  - Analytic: $I_{beam}(\omega) = I_{wall}(\omega) \cdot I_0\left(\frac{\omega R}{\beta\gamma c}\right)$
  - Simulation: simulate response of device to non-relativistic beams
- Want benchtop test stand for measuring effects
  - Test stand must replicate field profile and velocity of beam
- Helical transmission lines can be used
  - They propagate pulses at low phase velocities
  - Need to understand impedance and dispersion for use in test stand

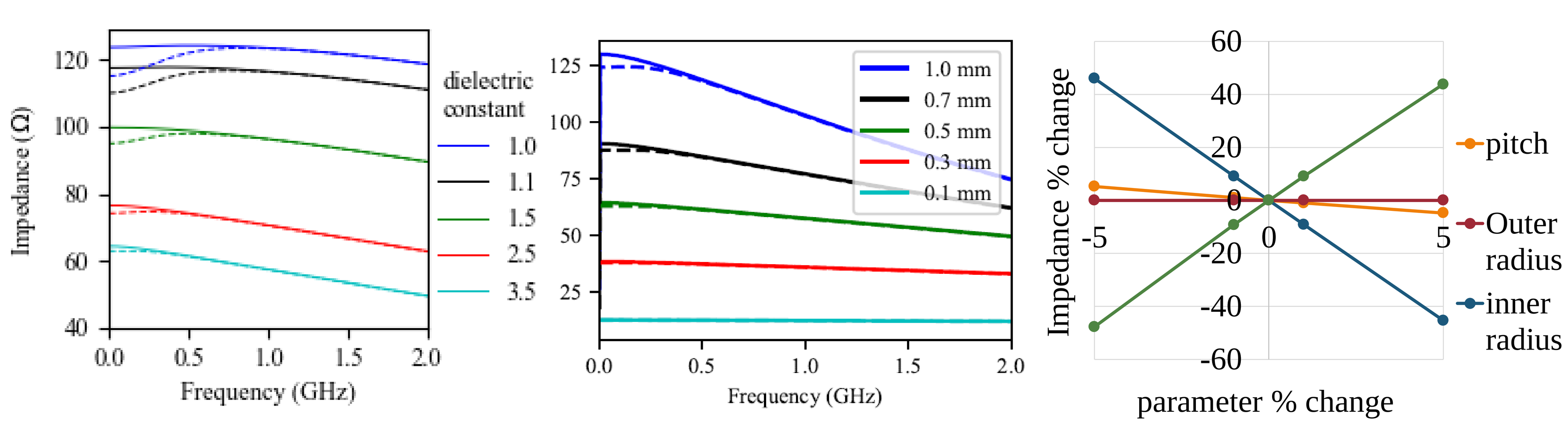


BPM button response for different beam offsets, $v = 0.033c$



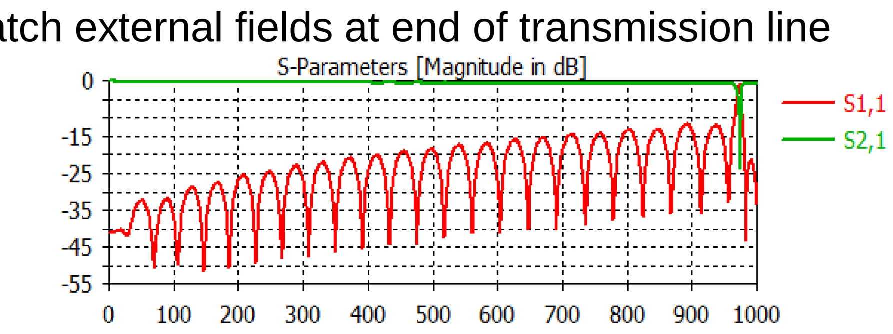
Impedance - theory

- Impedance calculated from fields found using the sheath helix approximation
- Impedance calculated in two regions
  - Z_inner: between helix and inner conductor, solid line
  - Z_outer: between helix and outer pipe, dashed line
  - Z_inner ~ Z_outer except at low frequency
- Low frequency limit $Z \propto \epsilon_r^{-0.5}$
- Smaller separation reduces variation in impedance
- Other changes to the geometry are minimal compared to the separation
  - Require constant separation, helix and inner conductor radii can vary

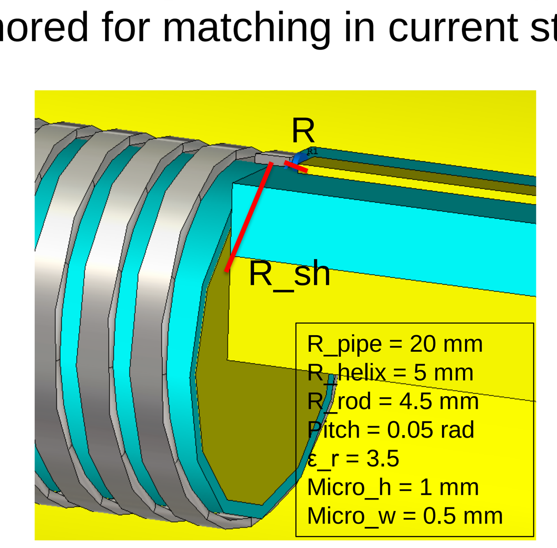


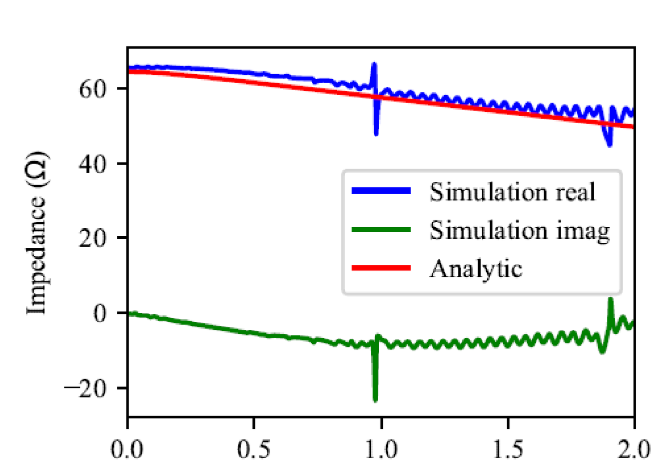
Impedance - simulation

- Impedance measured with frequency domain simulations
- Input and output matched with microstrip line
  - Set microstrip impedance to low frequency helix impedance
  - Attach ground to inner conductor of helix and the microstrip to the helix
  - Resistor between pipe and helix to match external fields at end of transmission line
  - S_{11} < -15 dB, S_{21} > -2 dB up to 2 GHz
  - Resonances due to system length



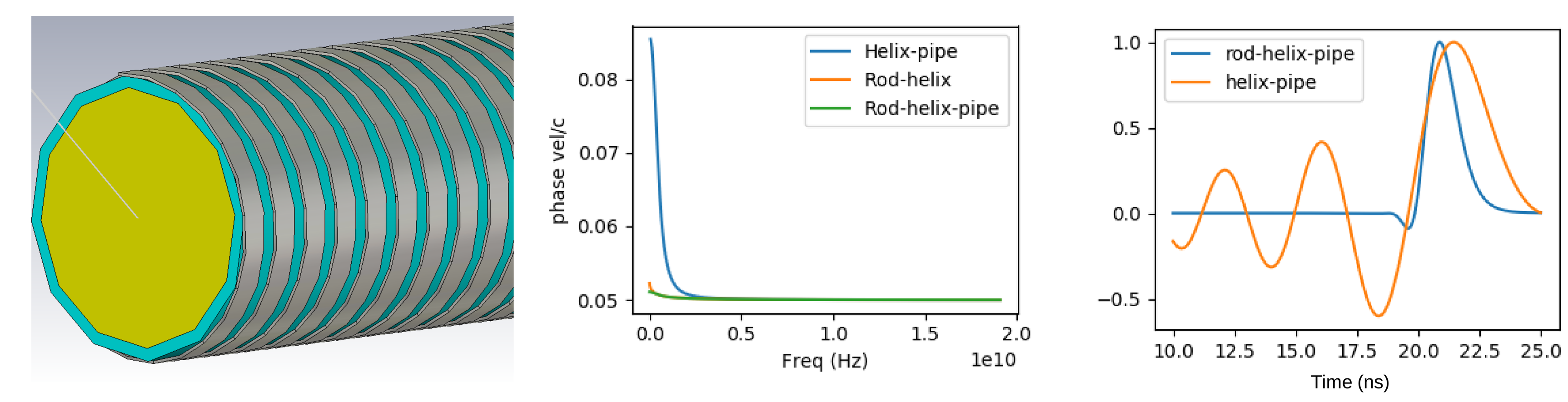
- Determine impedance from S_{11}
  - Resistive L-network between helix and microstrip to damp out resonances
    - $Z_{helix} = \left(R_{sh}^{-1} + \left[Z_{micro}\frac{1-S_{11}}{1+S_{11}} + R\right]^{-1}\right)^{-1}$, R_{sh} is shunt resistor, R is series resistor
  - Real part of impedance agrees within 3% up to 2 GHz
  - Simulation gives reactance not predicted by theory. Reactance is small enough to be ignored for matching in current studies



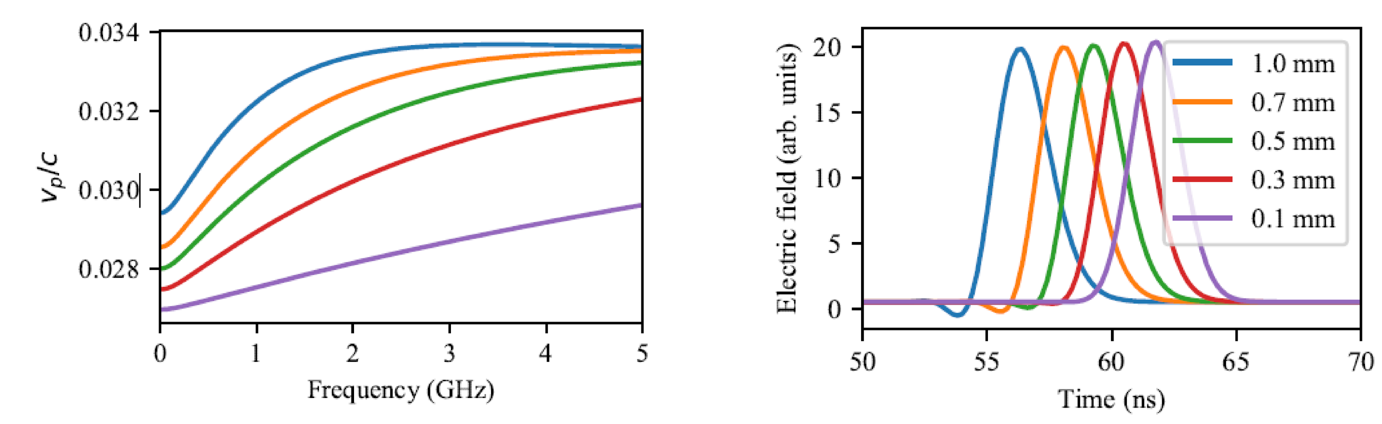


Dispersion reduction - theory

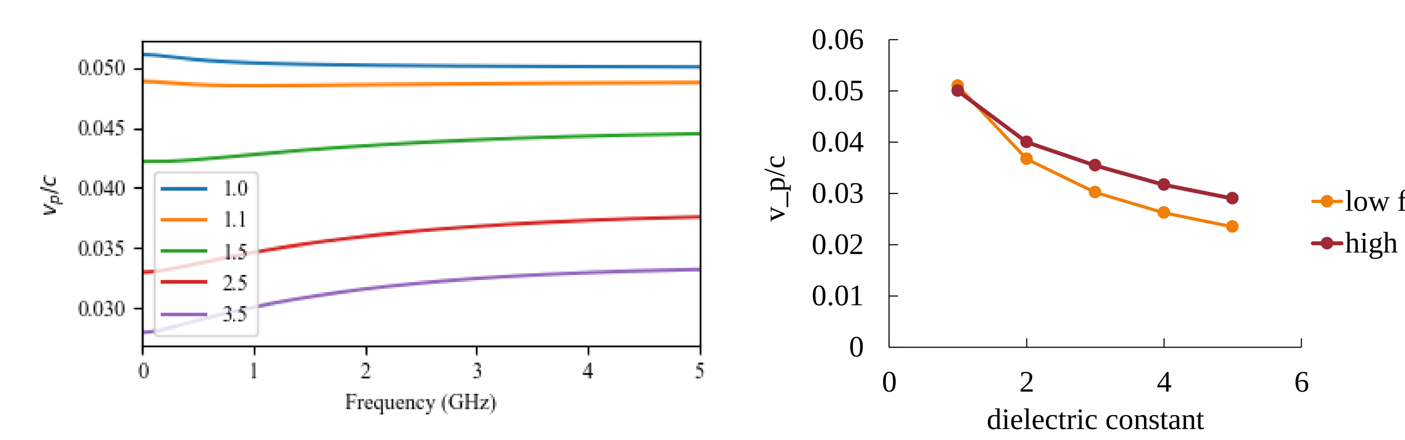
- Previous geometry – helix in a pipe
  - Significant dispersion caused pulses to quickly deform
  - No reasonable method found to correct pulses
- Improved geometry – add inner conductor
  - Reduces phase velocity at low frequency, does not change high frequency limit



- Varying separation between helix and inner conductor
  - Smaller separations reduce the variation of the phase velocity with frequency
  - Results in slower deformation

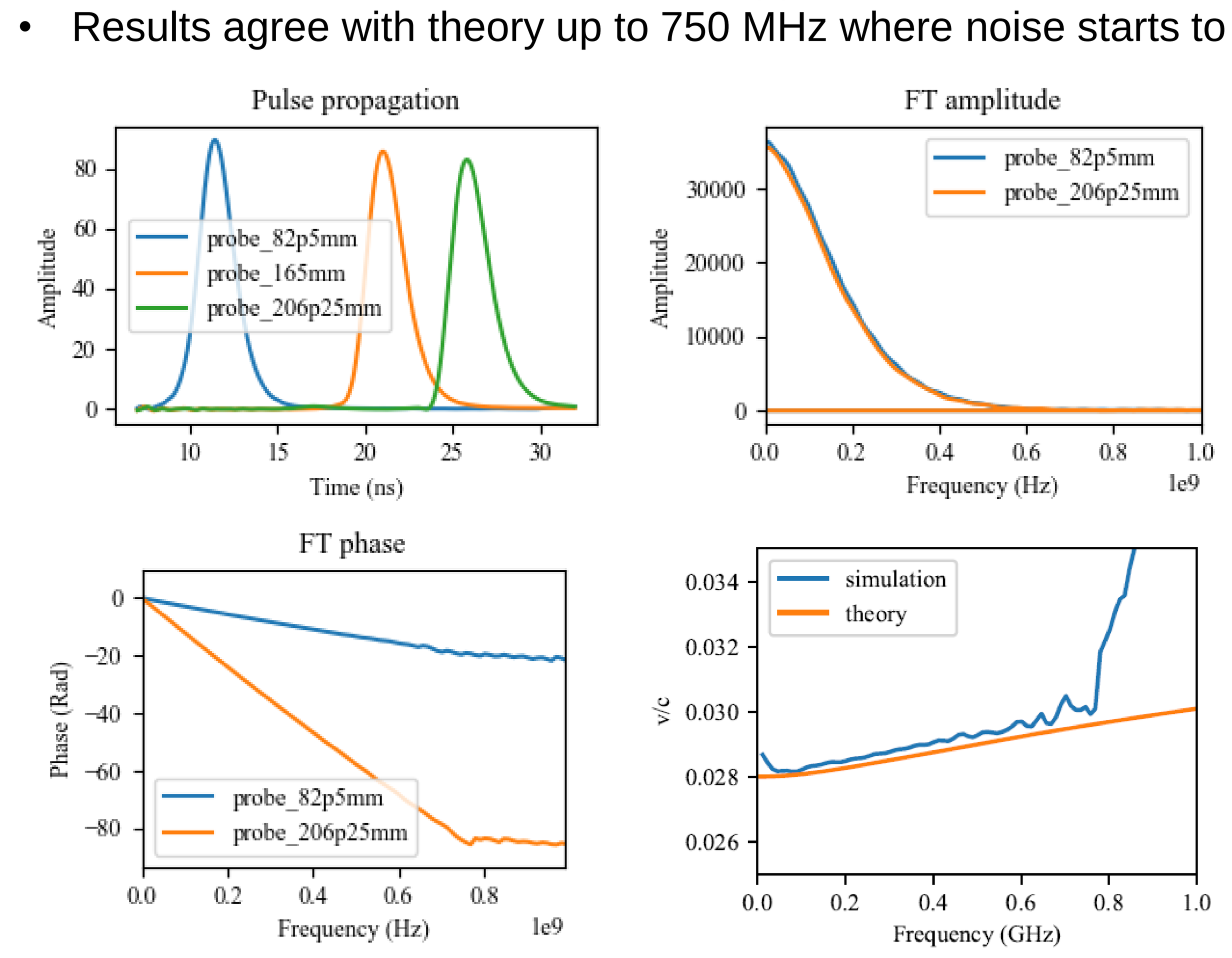


- Dielectric constant scaling
  - Require dielectric layer between inner conductor and helix to support the helix
  - The high and low frequency limits change at different rates with ε_r
  - Can set ε_r to make high and low frequency limits the same, but this isn't practical and variations of the phase velocity due to a higher ε_r can be reduced by using a small separation

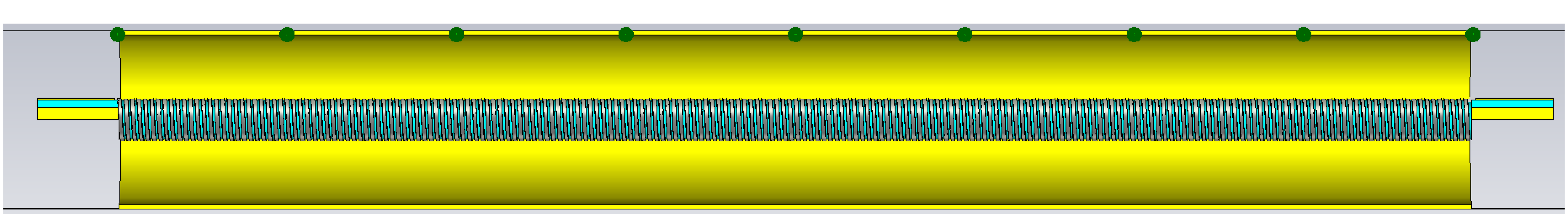


Dispersion reduction - simulation

- Time domain simulations performed in CST microwave studio
- The pulse at the pipe was measured along the transmission line
  - Pulses converted to frequency domain
  - Phase at two probes used to calculate phase velocity, $v_p(f) = \frac{Lf}{\phi_2 - \phi_1}$
    - L is probe separation, ϕ_i is the i^{th} probe
  - Results agree with theory up to 750 MHz where noise starts to dominate



Simulation geometry:
R_pipe = 20.65 mm
R_helix = 5 mm
R_rod = 4.5 mm
Pitch = 0.05 rad
ε_r = 3.5



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