Phase Shifter for Remote Controllable VTO Alternate

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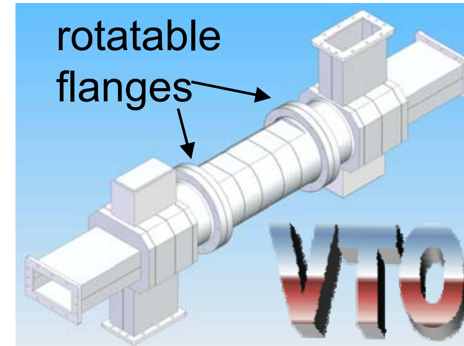
Motivation



- The VTO (variable tap-off) allows custom pair-wise tailoring of power distribution along cryomodules. It has been successfully tested and incorporated in the RF PDS for the ILCTA-NML at Fermilab.
- While mass production in industry would greatly reduce the VTO cost, making a few at a time at SLAC has been quite expensive (~$30K each).
- Readjusting the power distribution requires physically accessing the VTO's and depressurizing the waveguide line. It would not be easy, nor cheap, to make the VTO remote-controllable.

⇒ An alternate concept is presented which

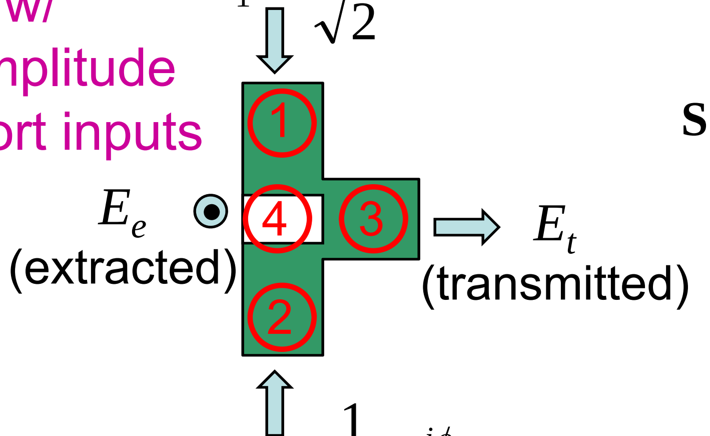
- makes maximal use of commercially available parts and
- is remote-controllable.

It incorporates a simple, well-matched phase shifter.

Tailoring Power Distribution with Pase Shifters and Magic-Tees

Magic-T w/ equal-amplitude in-line port inputs

$$E_1 = \frac{1}{\sqrt{2}} e^{i\phi_1}$$



$$E_2 = \frac{1}{\sqrt{2}} e^{i\phi_2}$$

$$\mathbf{S} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{pmatrix}$$

If ϕ_1 and ϕ_2 are changed in opposite senses by half the desired $\Delta\phi$, the coupled and through phases are unaffected as the amplitudes are adjusted.

$$E_e = \left(\frac{E_1}{\sqrt{2}} - \frac{E_2}{\sqrt{2}} \right) = \frac{1}{2}\left(e^{i\phi_1} - e^{i\phi_2} \right) = \frac{e^{i(\phi_2+\phi_1)/2}}{2} \left(e^{-i(\phi_2-\phi_1)/2} - e^{i(\phi_2-\phi_1)/2} \right)$$

$$= -ie^{i\left(\frac{\phi_1+\phi_2}{2}\right)} \sin\left(\frac{\phi_2-\phi_1}{2} \right)$$

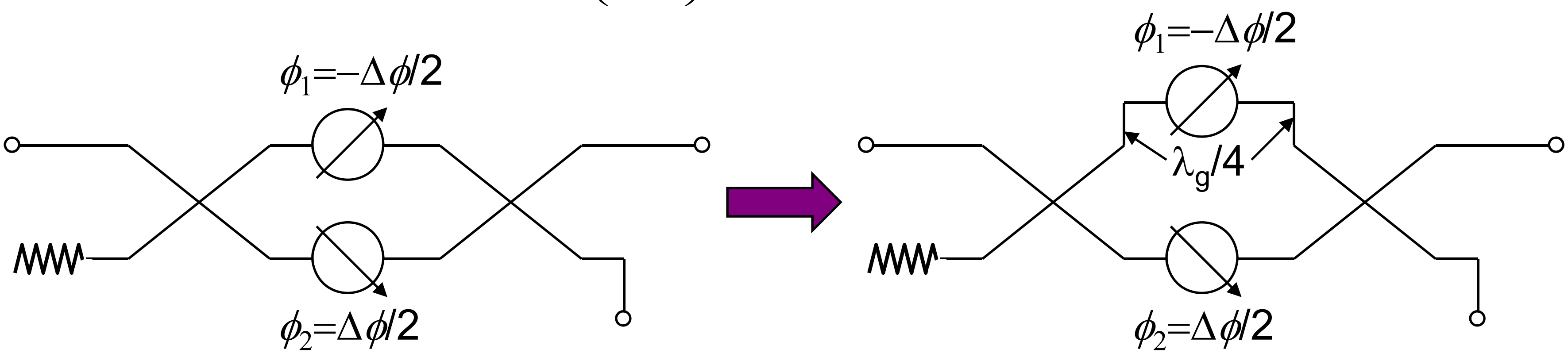
$$E_t = \left(\frac{E_1}{\sqrt{2}} + \frac{E_2}{\sqrt{2}} \right) = \frac{1}{2}\left(e^{i\phi_1} + e^{i\phi_2} \right) = e^{i\left(\frac{\phi_1+\phi_2}{2}\right)} \cos\left(\frac{\phi_2-\phi_1}{2} \right)$$

Required Phase Range

$$E_e = -ie^{i\left(\frac{\phi_1+\phi_2}{2}\right)}\sin\left(\frac{\Delta\phi}{2}\right)$$

$$E_t = e^{i\left(\frac{\phi_1+\phi_2}{2}\right)}\cos\left(\frac{\Delta\phi}{2}\right)$$

$\|E_e\|$	$\Delta\phi$
0	0°
¼	60°
1/3	70.53°
½	90°
1	180°



If we add -90° phase length in path one, the required range of $\Delta\phi$ shifts to -90°– 90°, and we see that the phase shifters need only range between 0° and 90°.

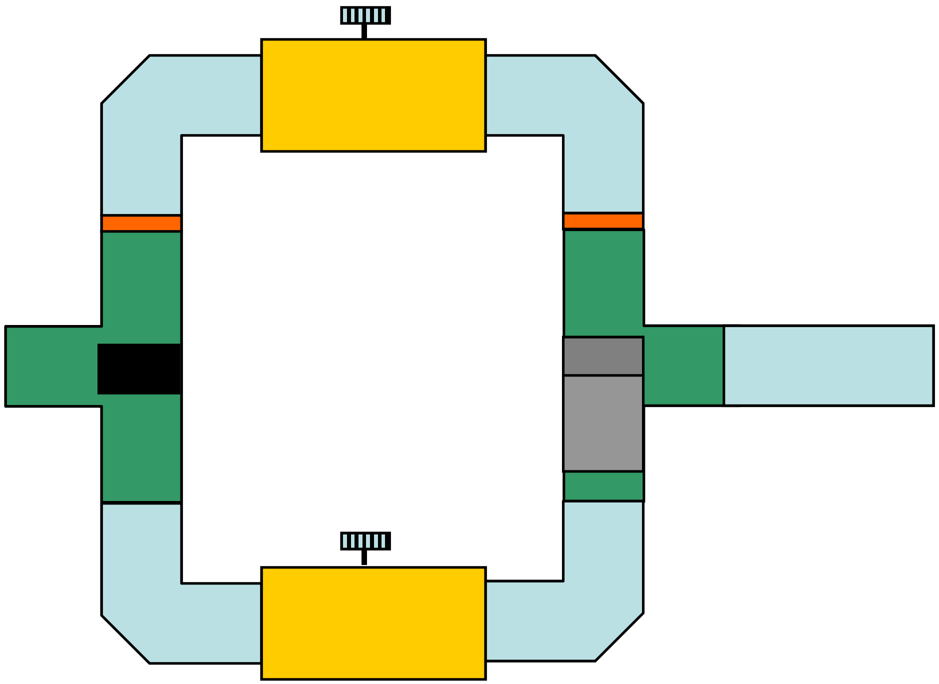
$$E_e = e^{i\left(\frac{\phi_1+\phi_2}{2}+\frac{\pi}{4}\right)}\sin\left(\frac{\Delta\phi}{2}+\frac{\pi}{4}\right)$$

$$E_t = e^{i\left(\frac{\phi_1+\phi_2}{2}-\frac{\pi}{4}\right)}\cos\left(\frac{\Delta\phi}{2}+\frac{\pi}{4}\right)$$

$\|E_e\|$	ϕ_1	ϕ_2	$\Delta\phi$
0	90°	0°	-90°
¼	60°	30°	-30°
1/3	54.735°	35.265°	-19.47°
½	45°	45°	0°
1	0°	90°	90°

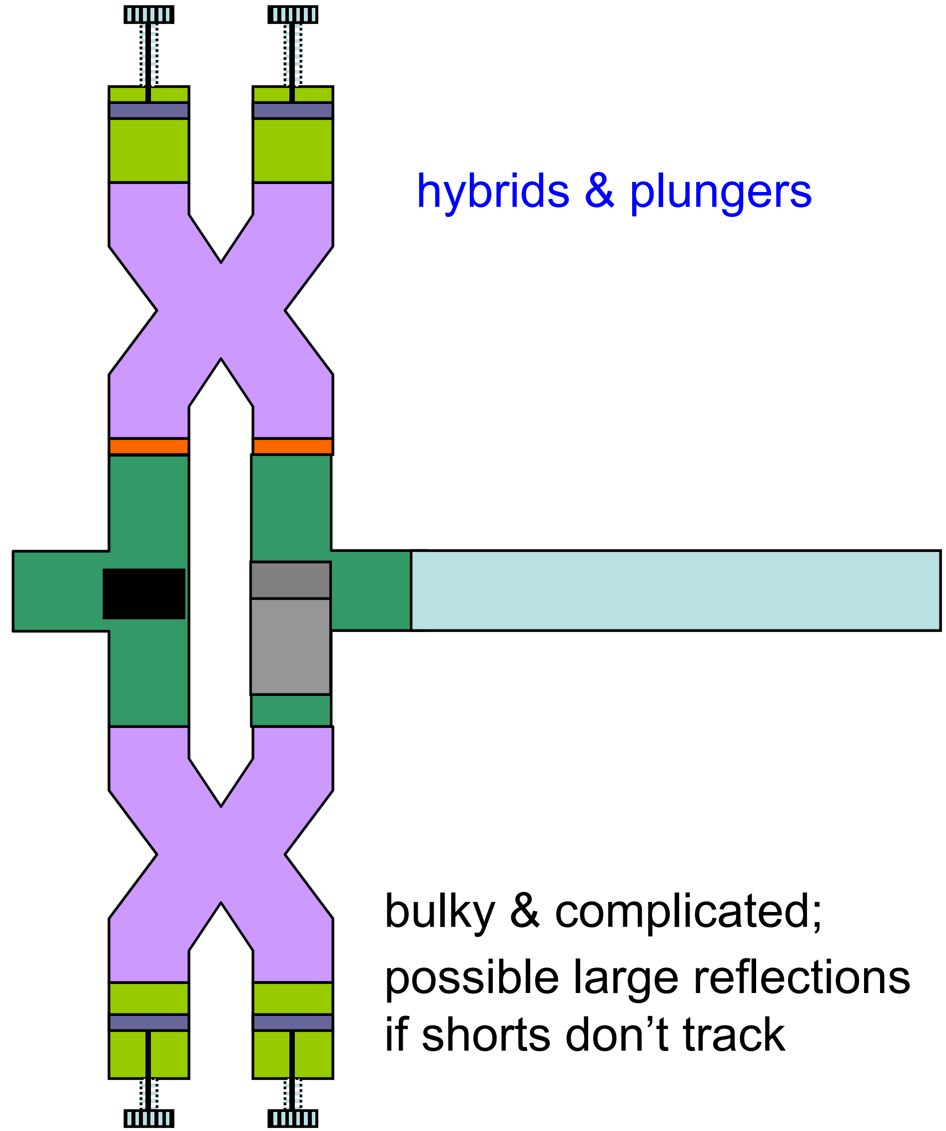
Possible Configurations

in-line phase shifters



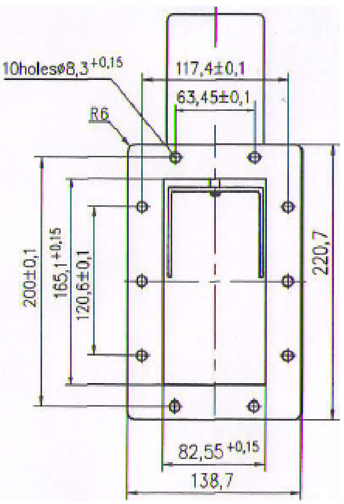
reflections too large for main line
(up to -23 dB for DESY/SPA Ferrite design,
fine in feeds buffered by circulators)

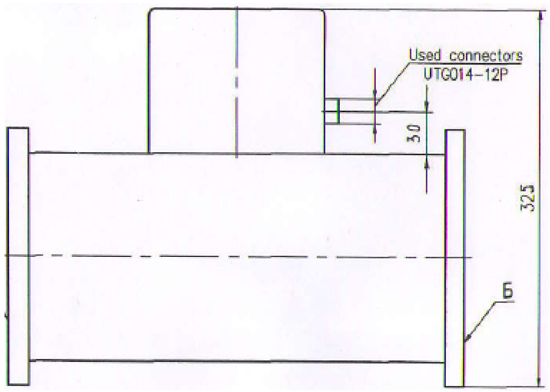
hybrids & plungers



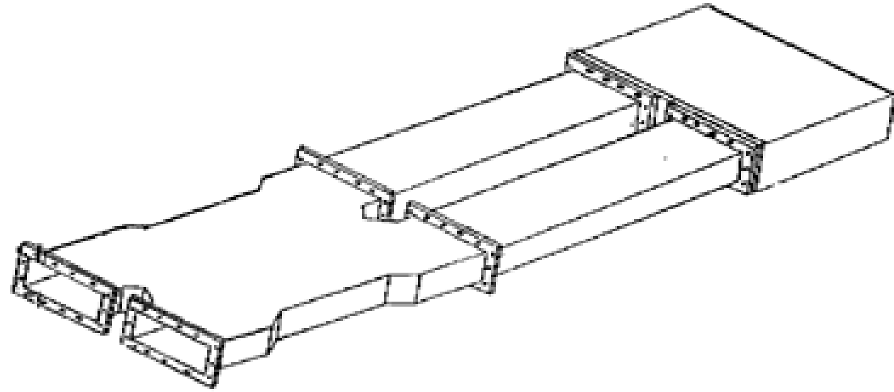
bulky & complicated;
possible large reflections
if shorts don't track

Available Phase Shifters



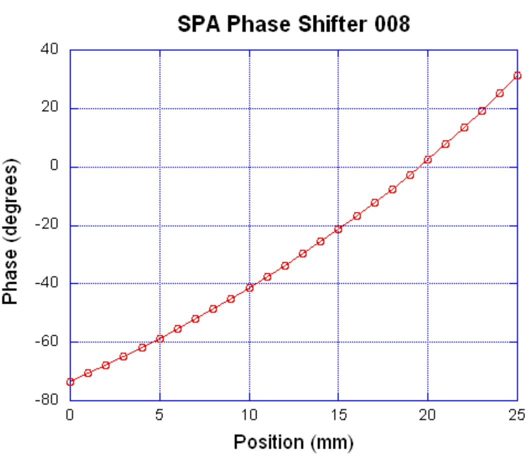


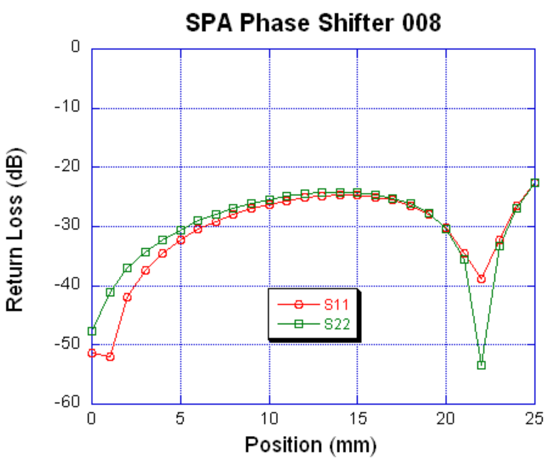
S.P.A. Ferrite / DESY



MEGA Ind.

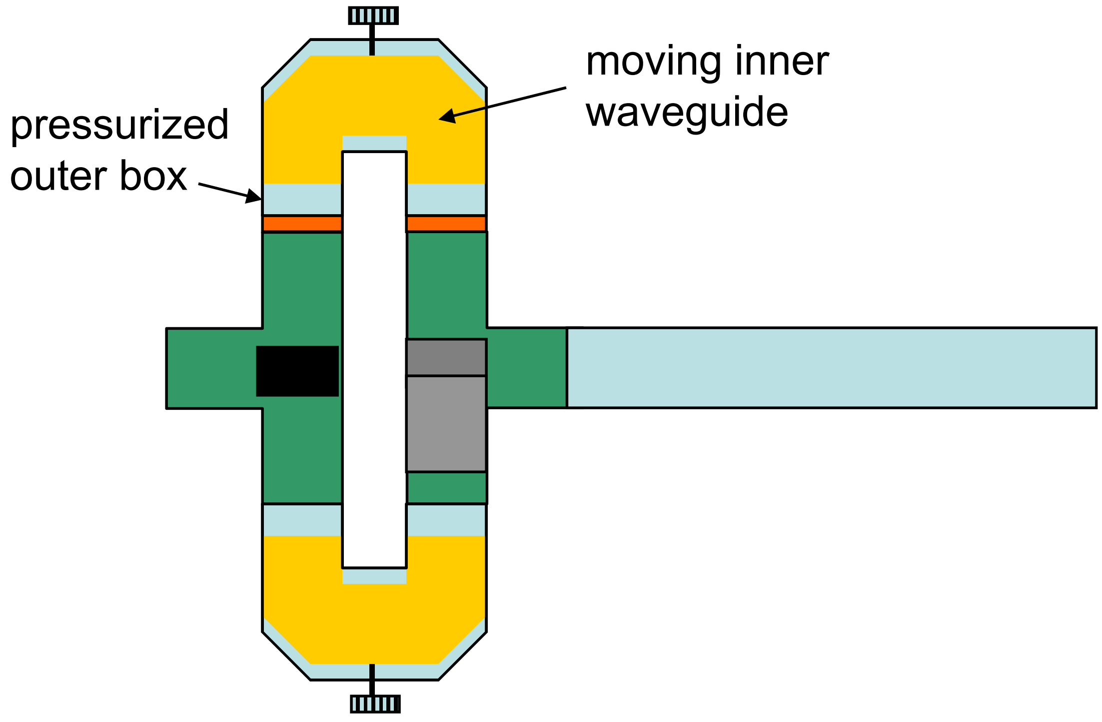
Impedance Matcher





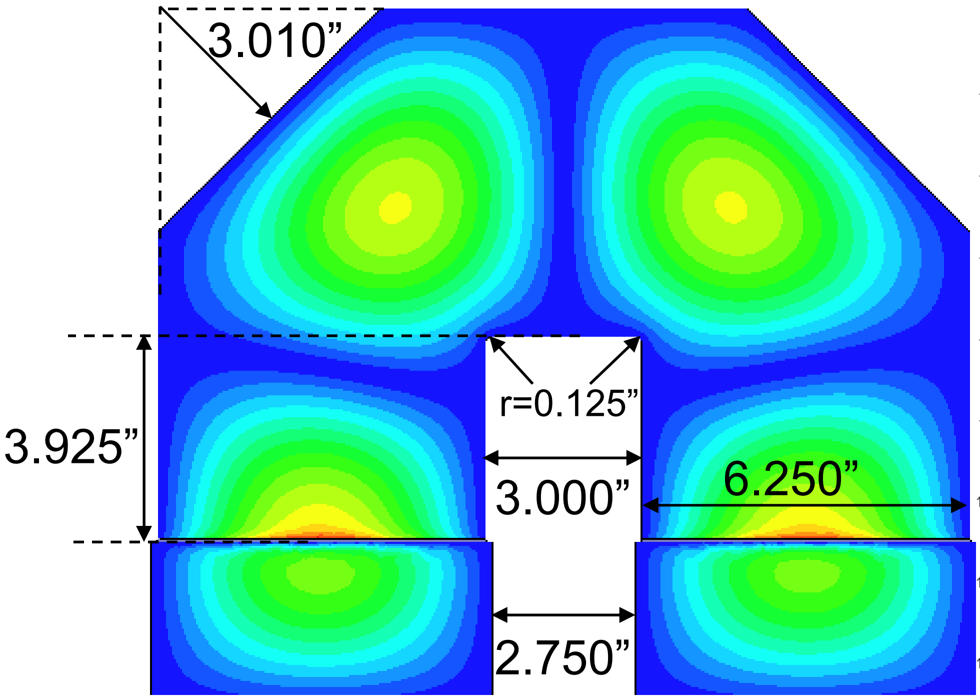
available design not pressurizable

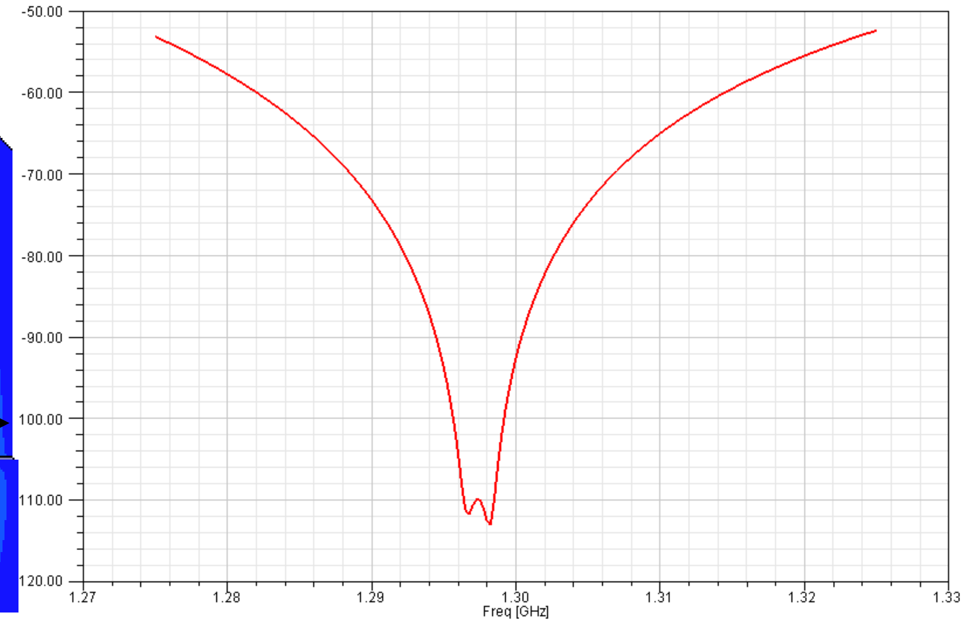
Trombone Phase Shifter



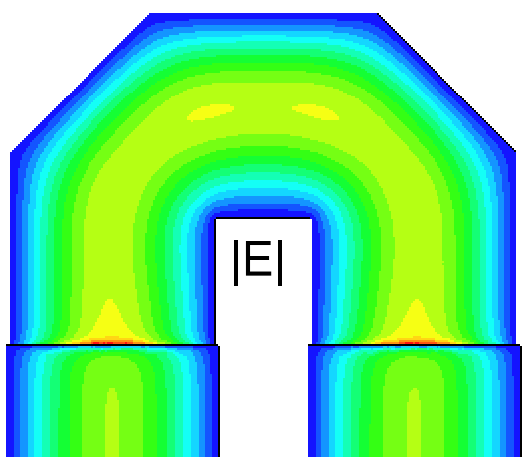
- takes advantage of required U-bends;
- match ideally unaffected by position;
- no bellows

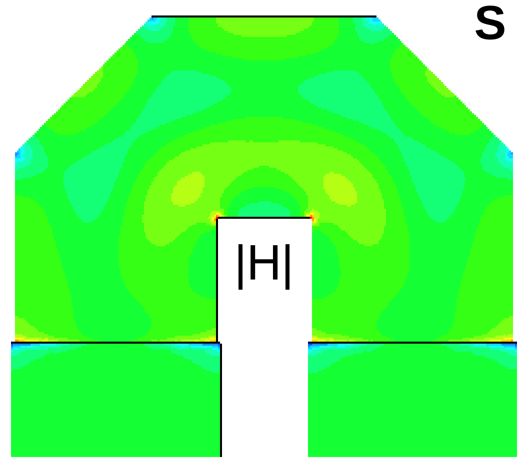
RF Design





S = (2.367e-005, -75.5) (1, -161)
(1, -161) (2.367e-005, -67.2)





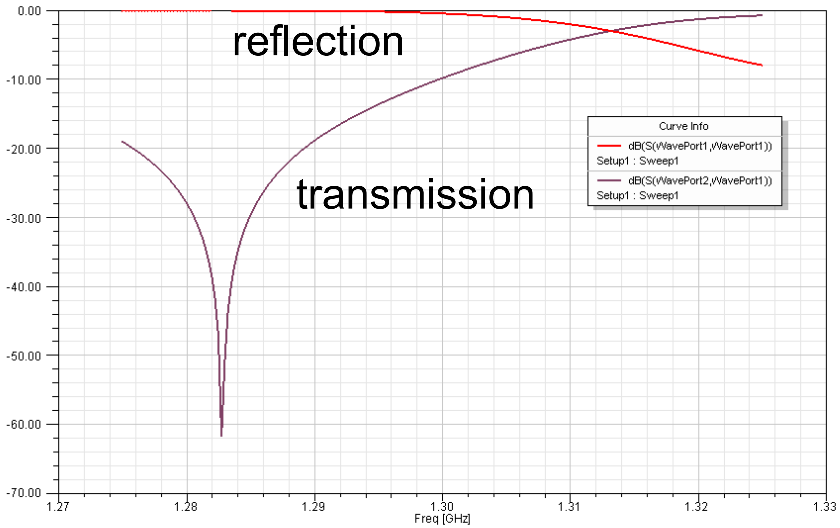
needed motion range:

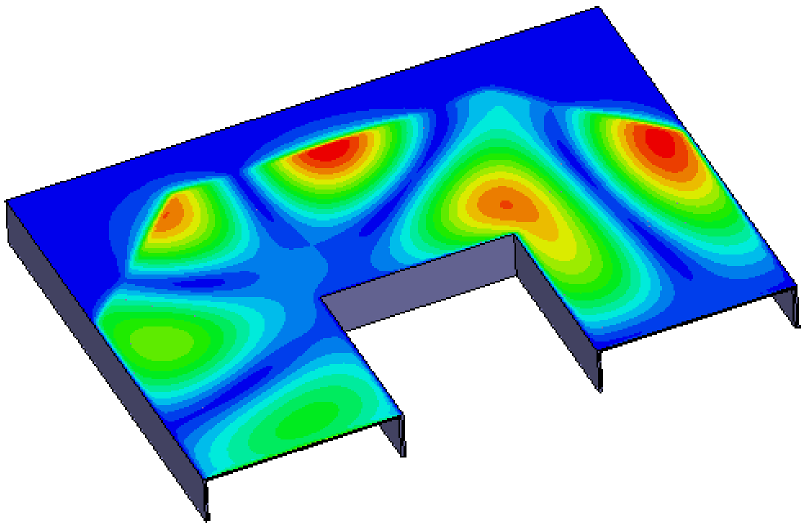
$\lambda_g/8 = 1.586”$

(path change = $\lambda_g/4$)

The Gap Problem

~1.91% is coupled into the 0.083” gap, with very little reflection.





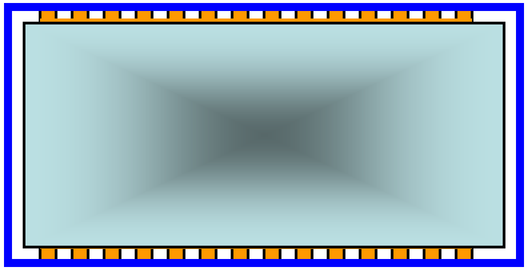
Non-negligible power couples into gap between moving waveguide and outer walls.

The excited gap mode has different wavelength than the interior waveguide mode.

Gap is connected to open volumes that change as phase shifter is moved.

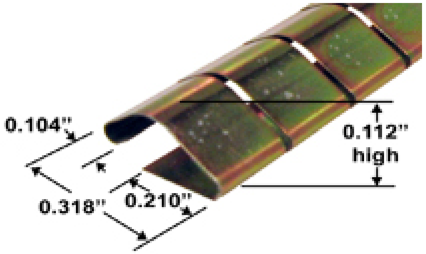
Potential gap resonances can ruin match, absorb power, and cause breakdown.

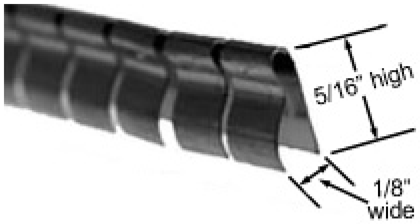
Fingers



Cutting off the gap with springy finger stock along the top and bottom should suffice.

No longitudinal currents along side walls.

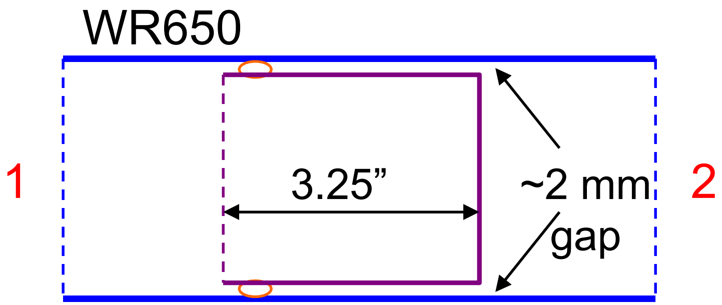




Beryllium copper not acceptable for safety reasons;

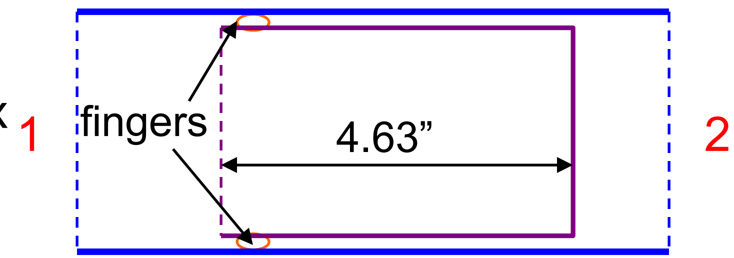
potential rf breakdowns could produce beryllium dust.

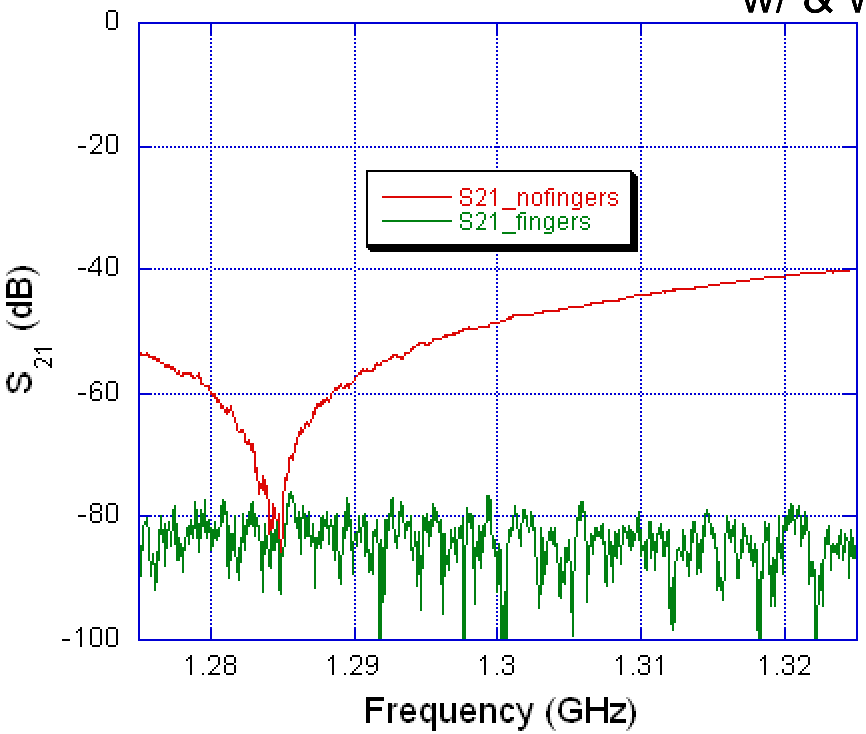
Test of Effect of Fingers Along Top and Bottom of Waveguide Insert

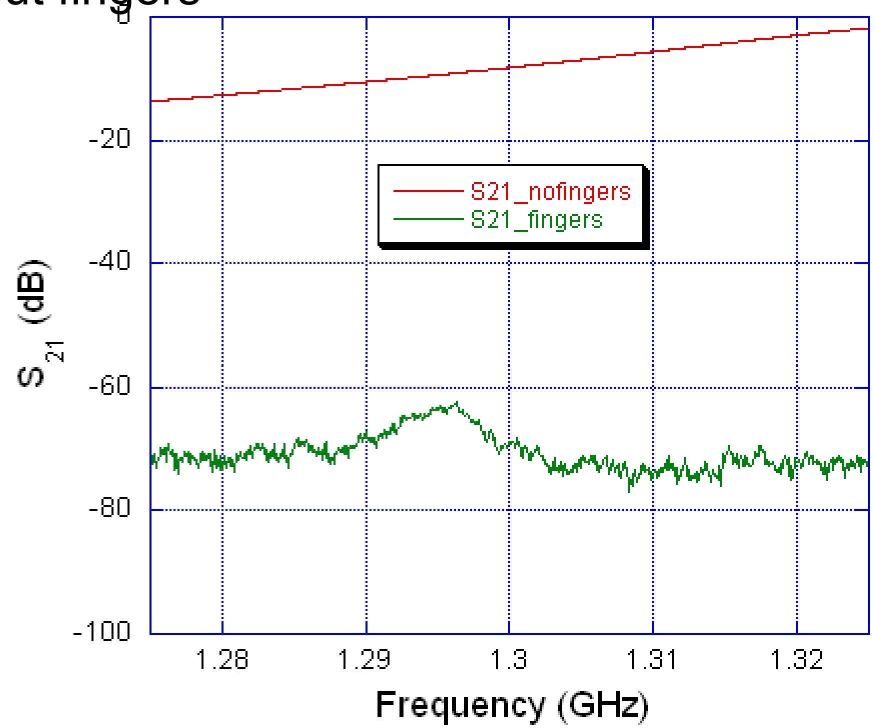


transmission
around closed box
inserts measured

w/ & w/out fingers



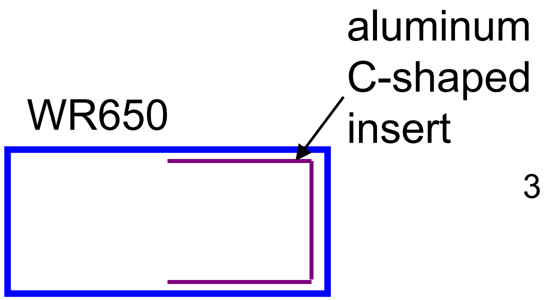




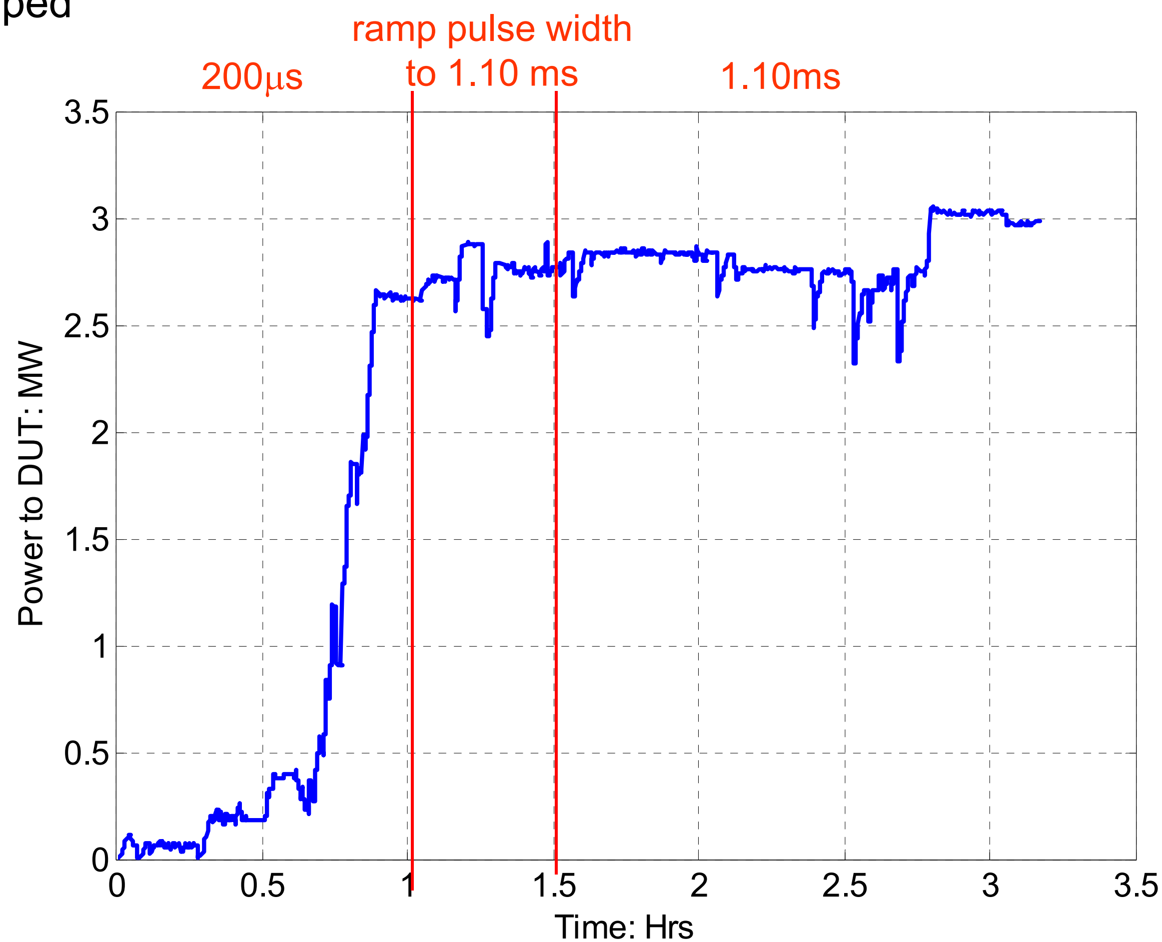
-48.7 dB → -89.8 dB

-8.21 dB (15%) → -69.0 dB

High-Power Test of Waveguide Insert



30 psi N_2



No breakdown from device under test, 8 breakdown from waveguide

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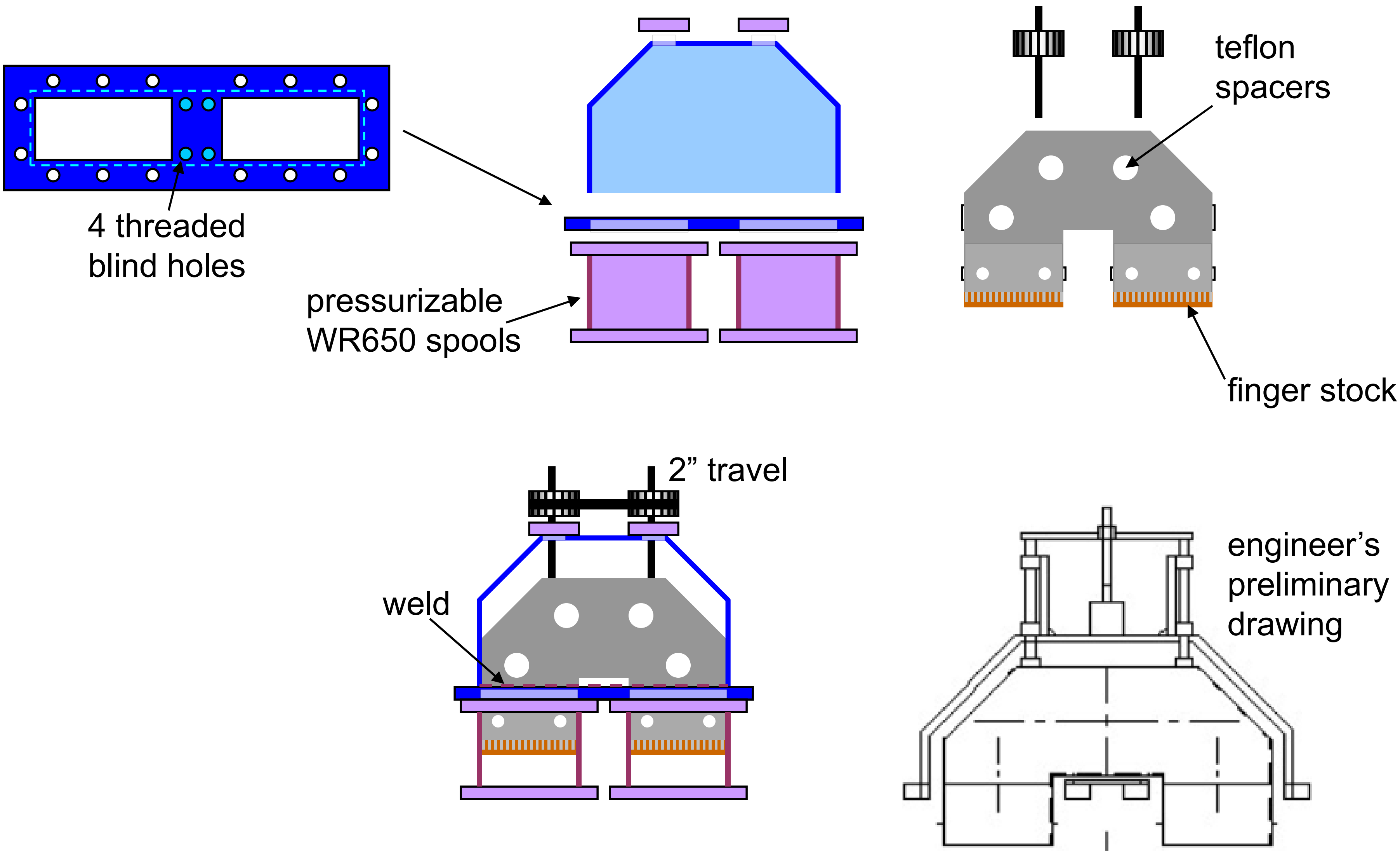
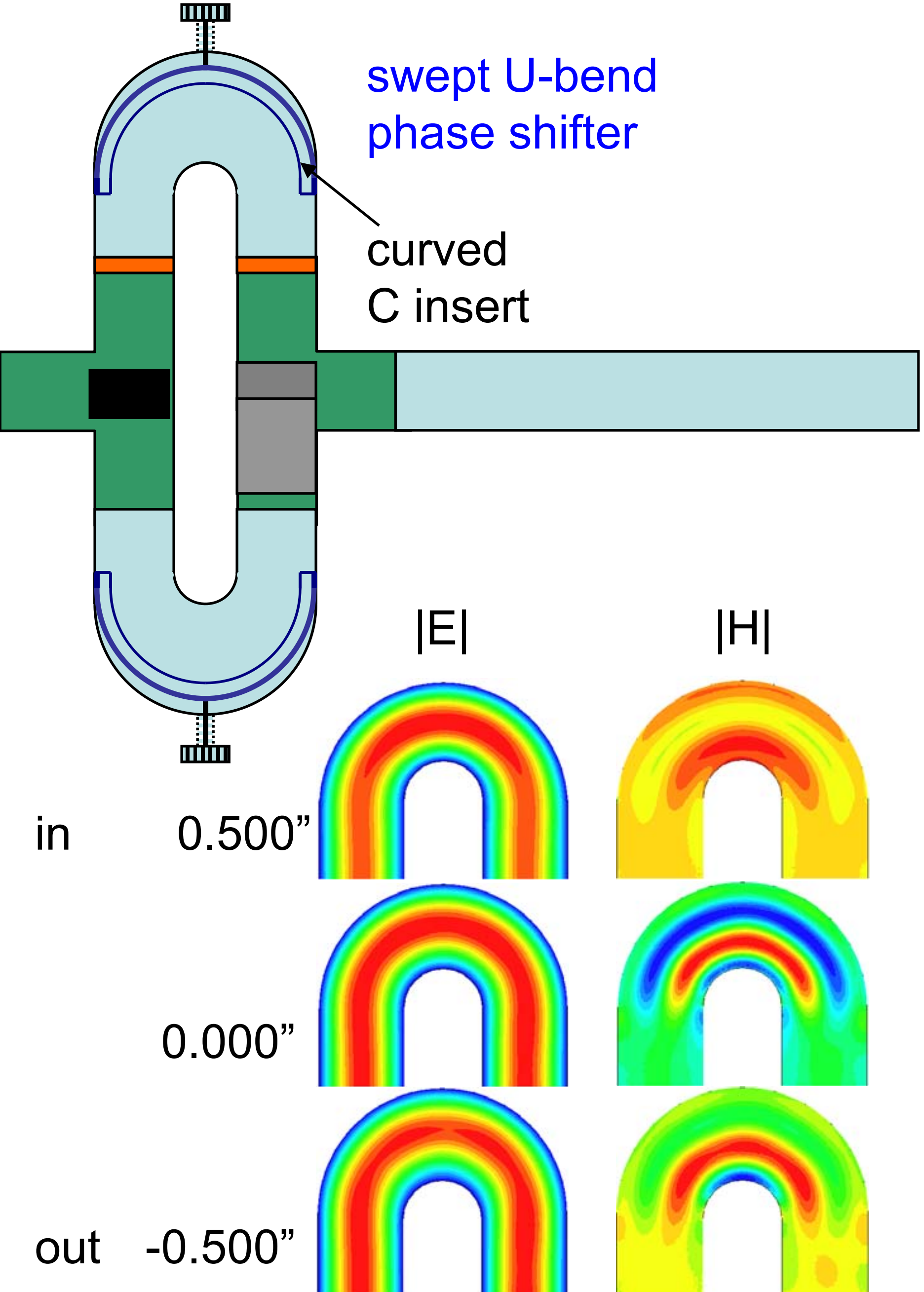
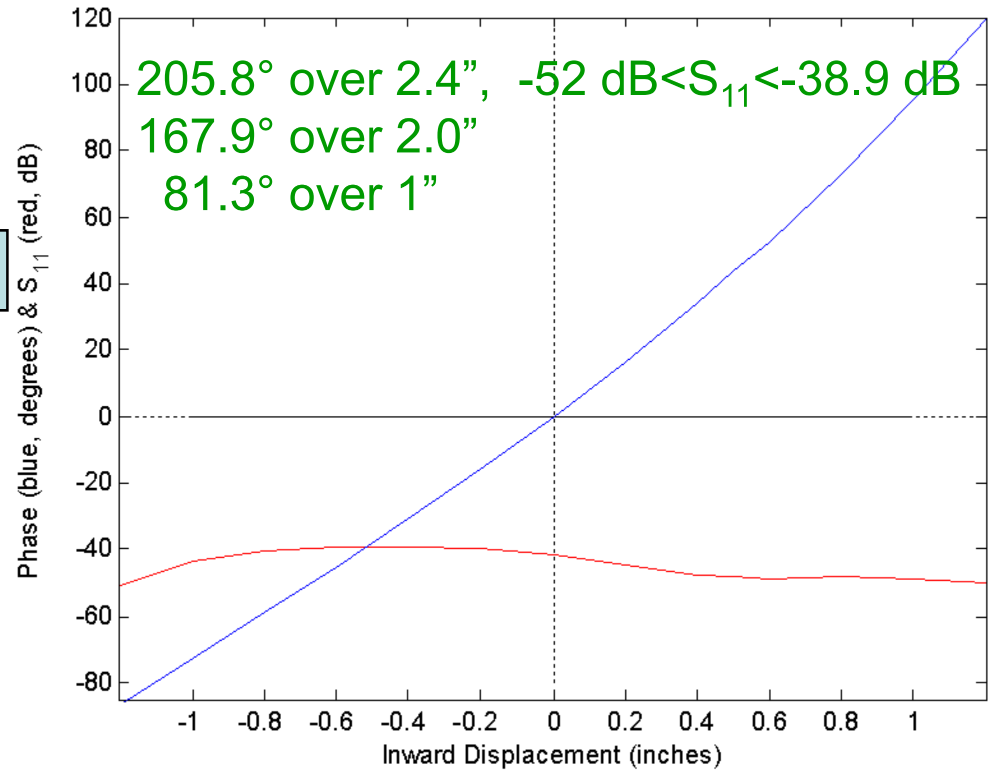
Conceptual Mechanical Design



Another Idea Considered





- lighter insert than trombone phase shifter
- no sudden discontinuity like SPA p.s.

But gap problem not yet dealt with here!