Power Distribution System R&D at SLAC

Christopher Nantista

ILC08

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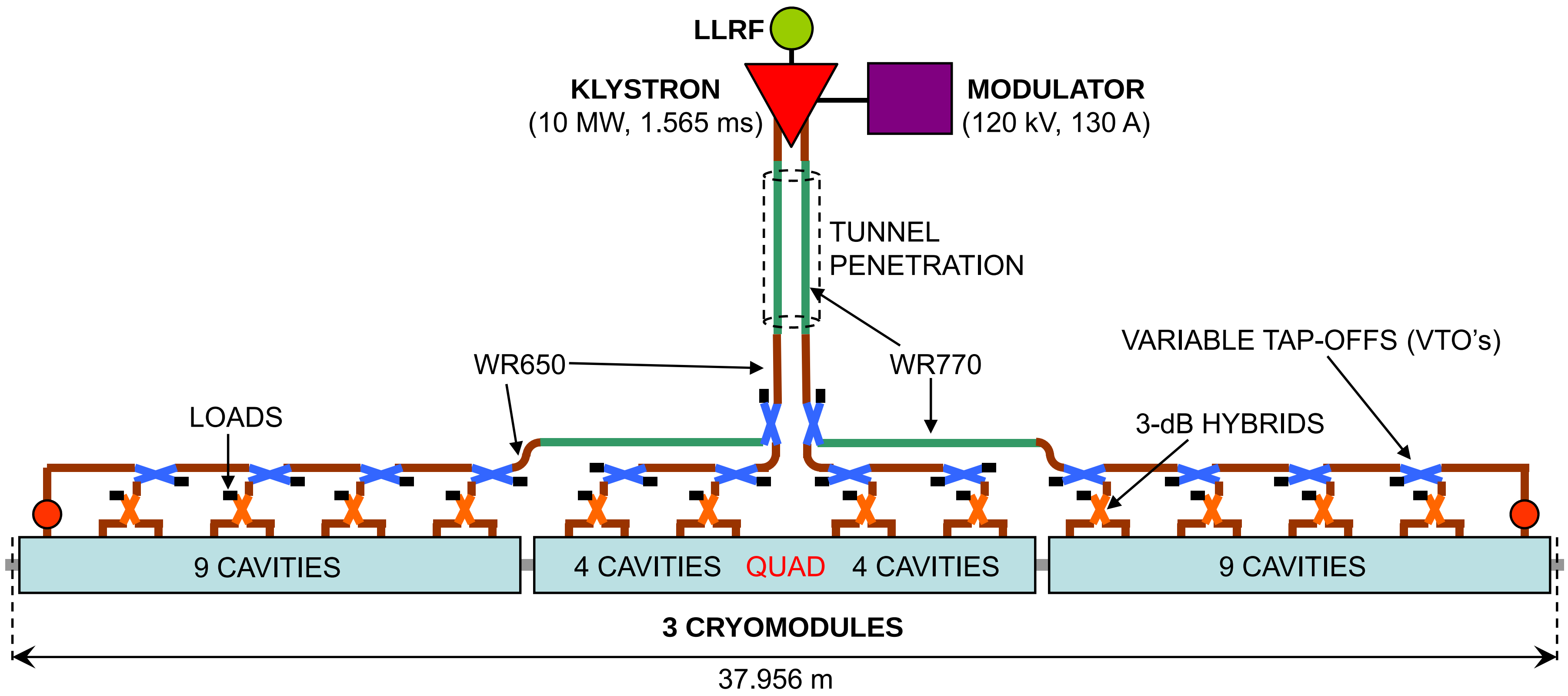
Layout of ACD High-Power RF Power Distribution System (PDS)

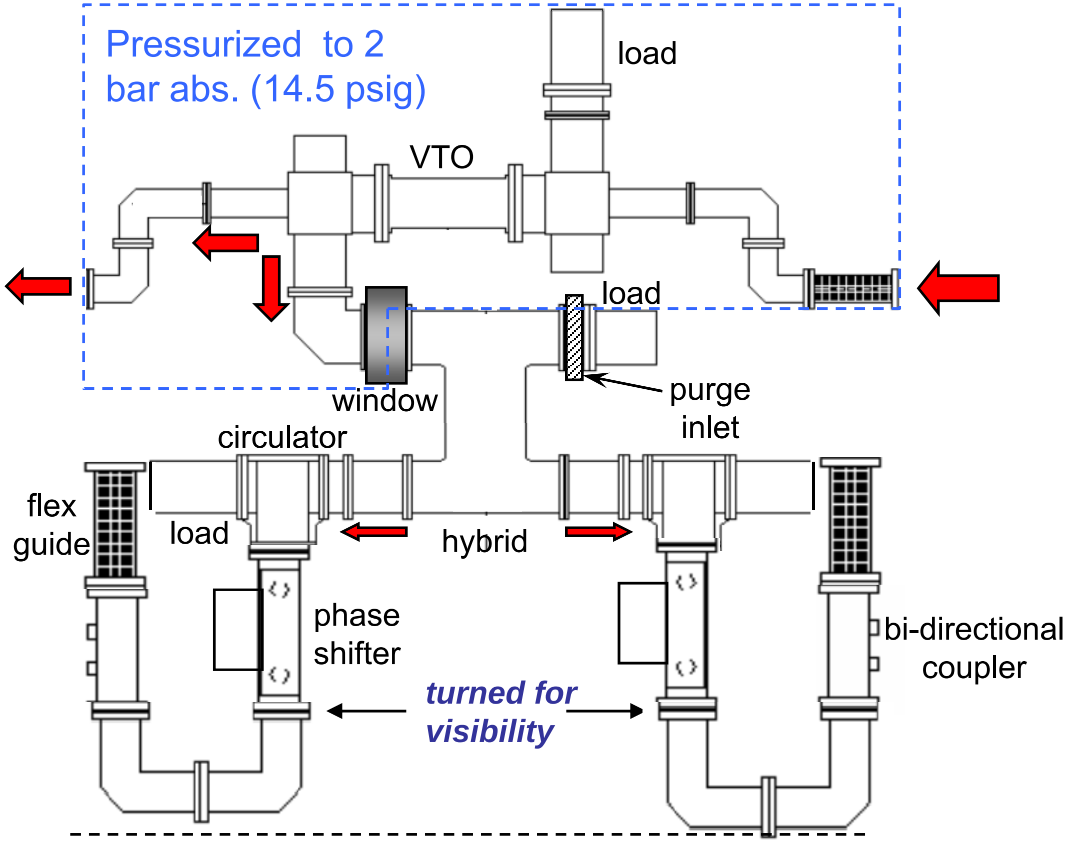


2 level splitting with VTO's and hybrids

BENEFITS OVER LINEAR BCD:

- fewer types of splitters (2 vs. 9) – simplicity, cost reduction
- power division adjustable by pairs – improved gradient/power efficiency
- permits elimination of (most) circulators – cost and transmission loss reduction

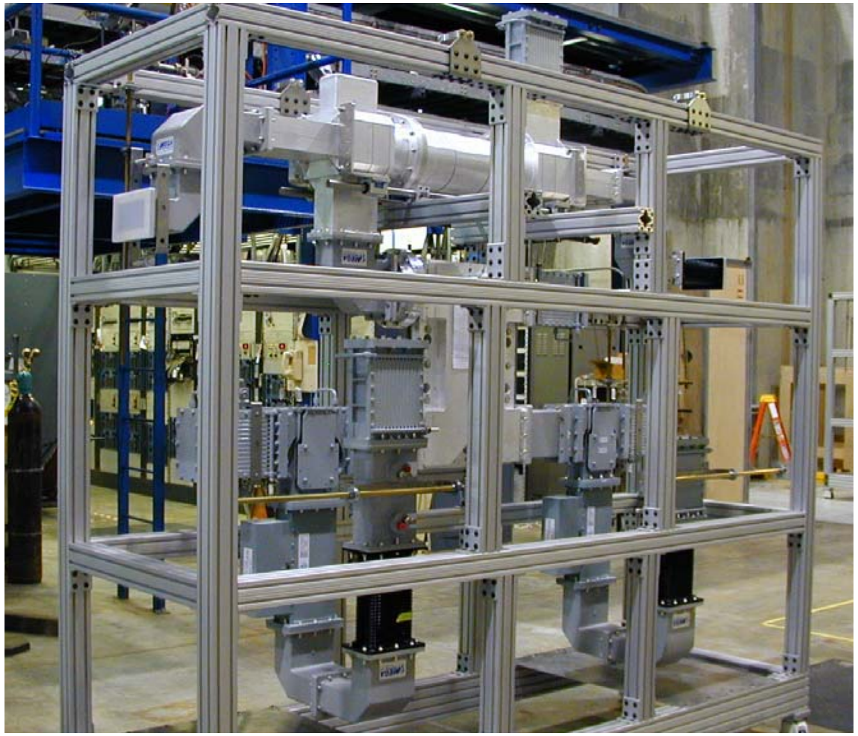
Modular 2-Cavity PDS Unit for NML

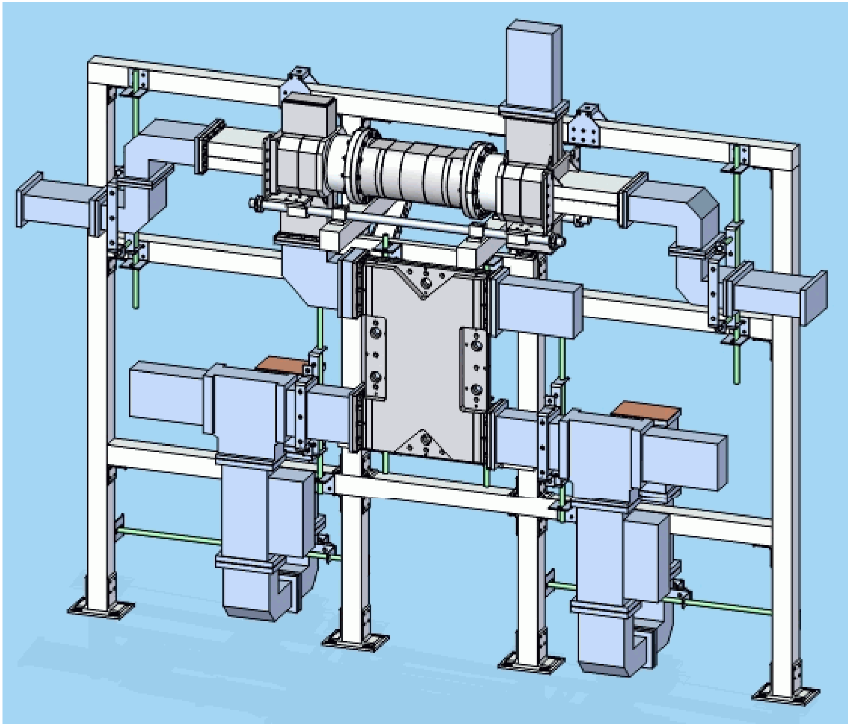


COMPONENTS (by vendor):

- SLAC – VTO's & hybrids
- S.P.A. Ferrite – isolators, loads, phase shifters & directional couplers
- Mega – mitered bends, straights & semi-flex guides
- Ibfm – modified pillbox windows
- Pacific Rubber & Packing – Mark VI Gask-O-Seal waveguide gaskets

RF PDS Unit



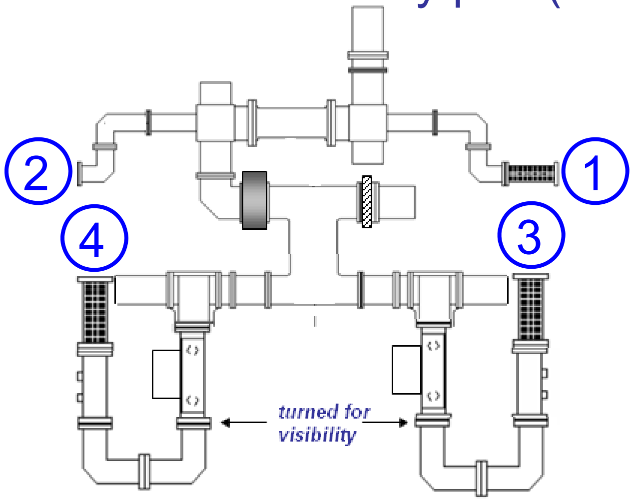


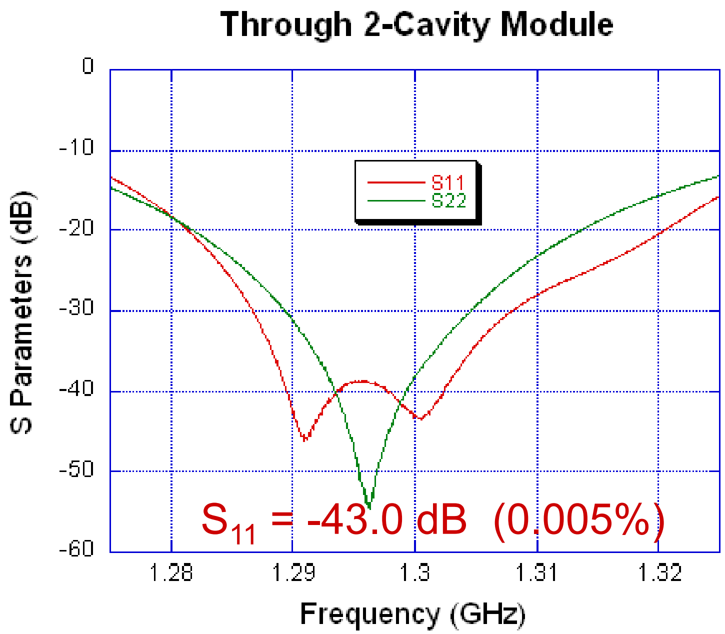
The first (of 4) 2-cavity units of our RF power distribution system for Fermilab's first NML cryomodule is delivered. The other three are complete and about to be high-power tested and shipped.

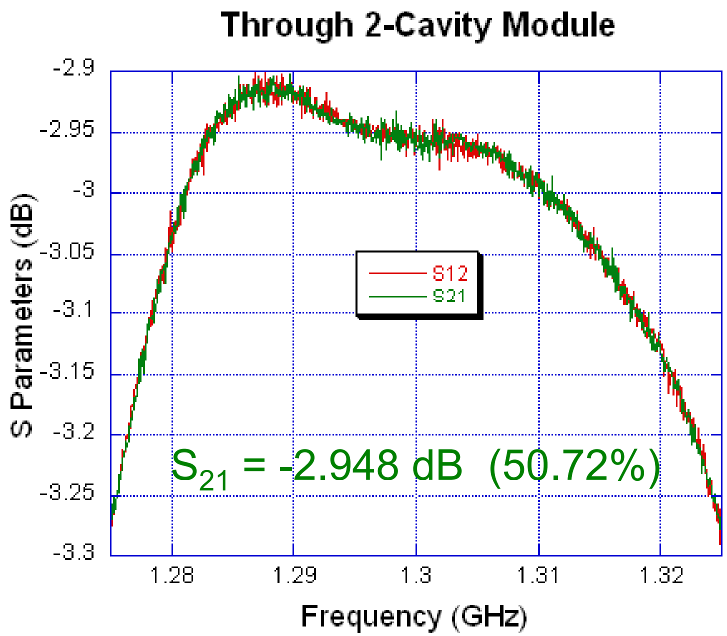
When installed, the front wall of the 80/20® frame will be removed, and the U-bends reversed to go under the remaining wall.

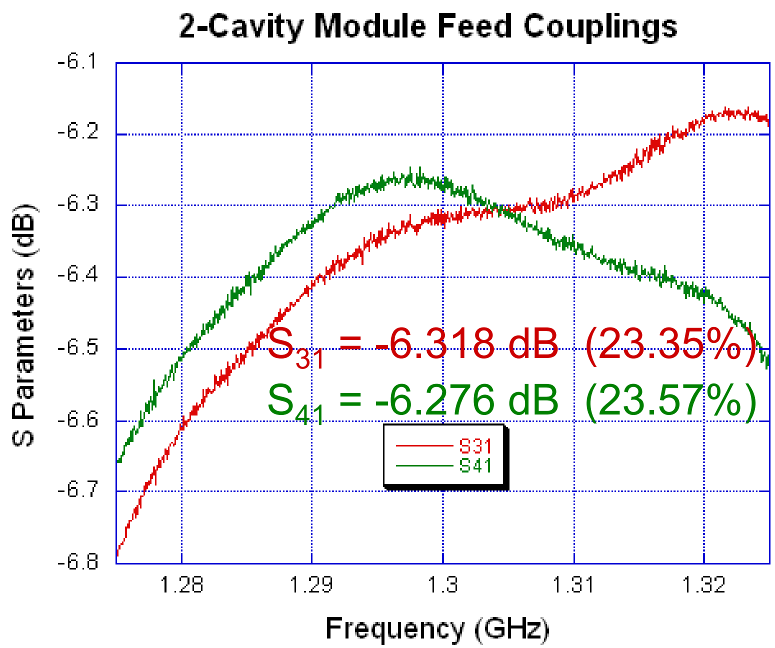
Cold Test of PDS Unit

VTO set for 3^{rd} cavity pair (~3 dB).









Measurement Analysis

POWER:

2.36% of power missing (expect ~3% from meas. and est. component losses)

Pair power division between cavity feeds equal to within 1%.

Slightly more than ½ power sent through to allow for downstream losses.

PHASE:

Phases of S_{31} and S_{41} initially within 1.7° (1.5 mm) of each other (adjustable with phase shifter).

Module through phase error = ~-6.7° (easily absorbed in next modules phase shifters).

SPACING:

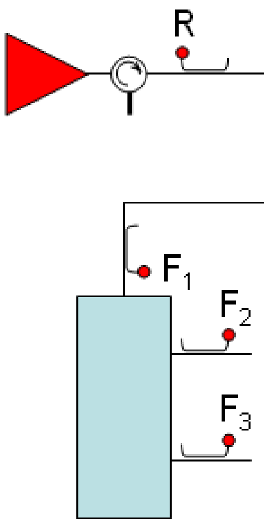
Feed spacing measures ~1.3827m, 1 mm short (semi-flex guides can absorb).

Module length measures ~2.7674m, exact to measurement resolution.

High Power Test of PDS Unit

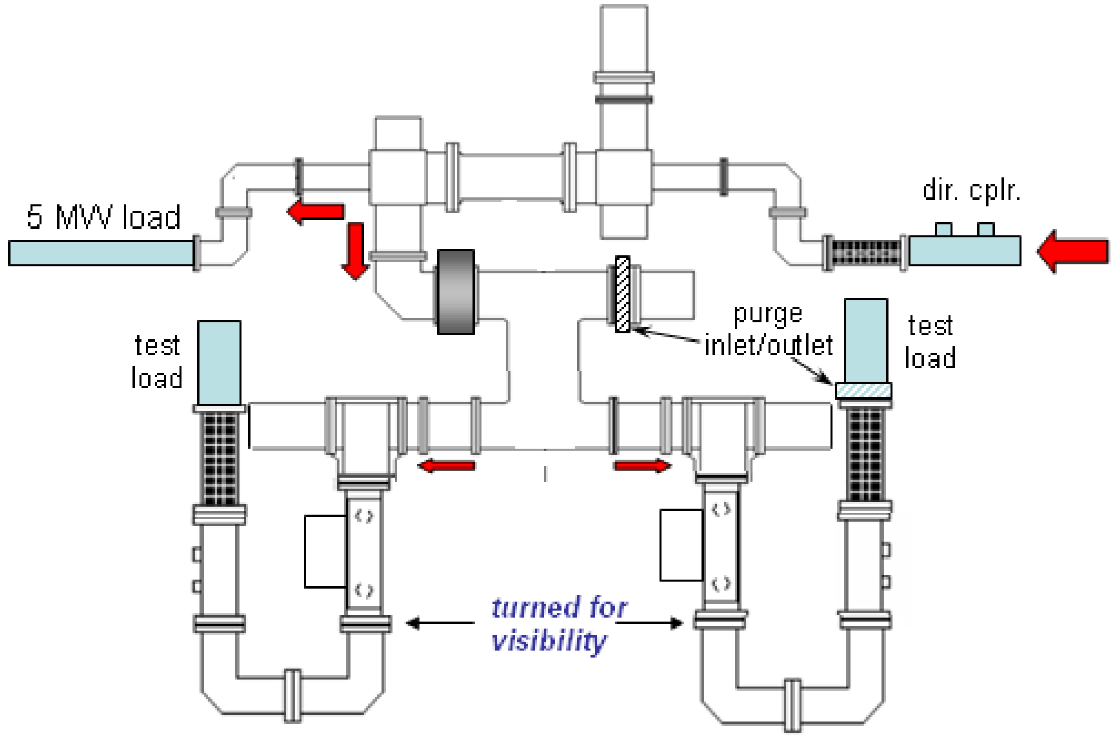
The CM1-UNIT 3 Assembly (~3 dB) was high power tested, first @ 3 bar and then 2 bar press.

Power was stepped up to ≥1.5 MW, 1.2 ms (our maximum pulse width) so each feed saw at least 360 kW (~10% more than needed for 35 MV/m, 9 mA acceleration at ILC).



<u>Interlocks</u>

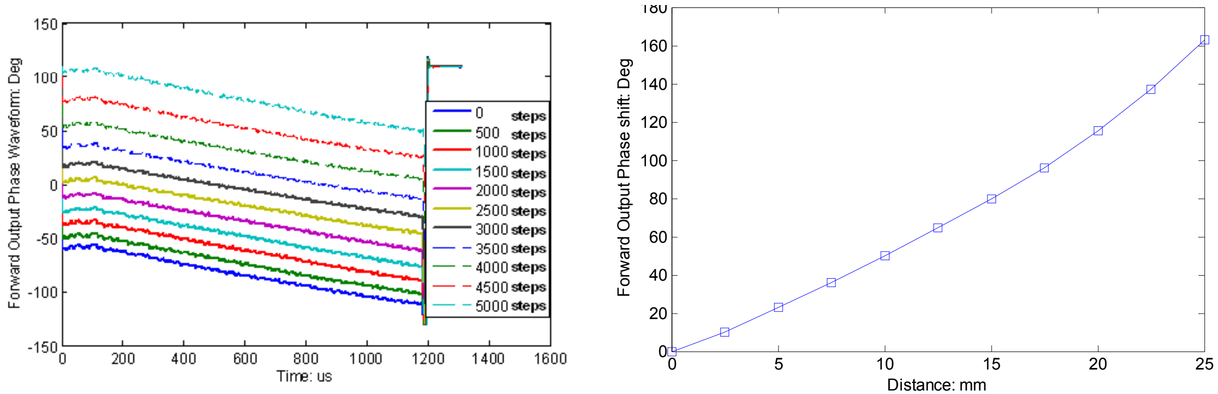
1) R
2) F_1-F_2
3) F_1-F_3



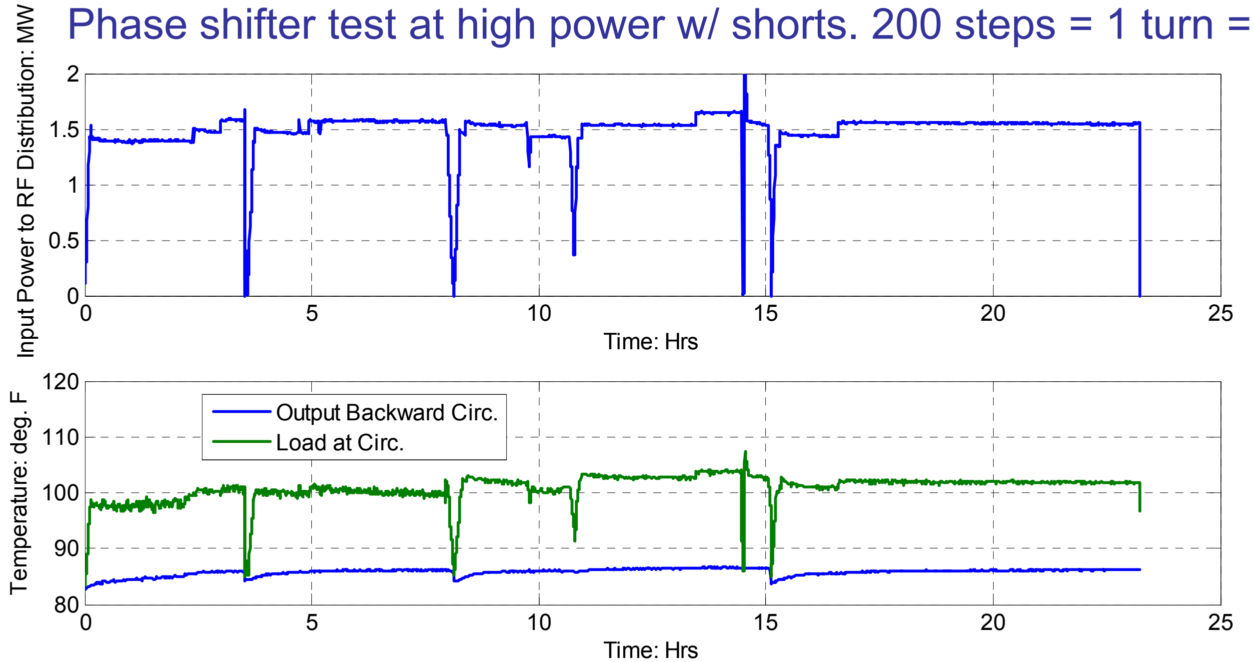
In addition to the reflected signal near the klystron, power was interlocked to missing energy signals comparing the system input to each feeds forward dir. cplr. signal to protect against breakdowns downstream of the circulators.

We ran both as shown and then again with the test loads replaced with shorts for worst case full reflection. The phase shifters were moved at full power to shift the standing wave.

High Power Test Data



Phase shifter test at high power w/ shorts. 200 steps = 1 turn = 1 mm.

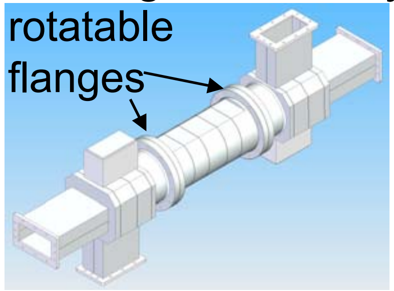


~24 hour stability test at 1.5 MW, 1.2 ms, shorted. Dips represent discontinuities in operation (we can't run unmanned). The temperature of the circulator is fairly stable at the ~86° F spec.

We detected no rf breakdowns during PDS high power testing.

Setting the VTO Couplings

The couplings of the VTO (variable tap-off) is mechanically adjusted by rotation of its central section. The four VTO's along an 8-cavity cryomodule should be set as follows, in order of power flow.



Nominal:

$$C_n = \frac{1}{N+1-n}$$

n	$C_n = P_c / P_i$	$\alpha_n = 1/2 \sin^{-1}\sqrt{C_n}$
1	1/4	15.00°
2	1/3	17.63°
3	1/2	22.50°
4	1	45.00°

Accounting for estimated transmission losses:

$$C_n = \frac{T^{N-n}}{\sum_{m=0}^{N-n} T^m}$$

unit transmission efficiency
T = ~0.986

n	$C_n = P_c / P_i$	$\alpha_n = 1/2 \sin^{-1}\sqrt{C_n}$
1	0.245	14.83°
2	0.329	17.49°
3	0.496	22.40°
4	1.000	45.00°

Accounting for transmission losses and tailoring gradients:

$$C_n = \frac{G_n T^{N-n}}{\sum_{m=0}^{N-n} G_{N-m} T^m}$$

T = ~0.986

lower gradient limit in each cavity pair

G_1 = 26.6 MV/m
G_2 = 31.1 MV/m
G_3 = 30.6 MV/m
G_4 = 22.5 MV/m

n	$C_n = P_c / P_i$	$\alpha_n = 1/2 \sin^{-1}\sqrt{C_n}$
1	0.2352	14.51°
2	0.3647	18.58°
3	0.5728	24.59°
4	1.000	45.00°

Running w/ Beam or w/o Circulators

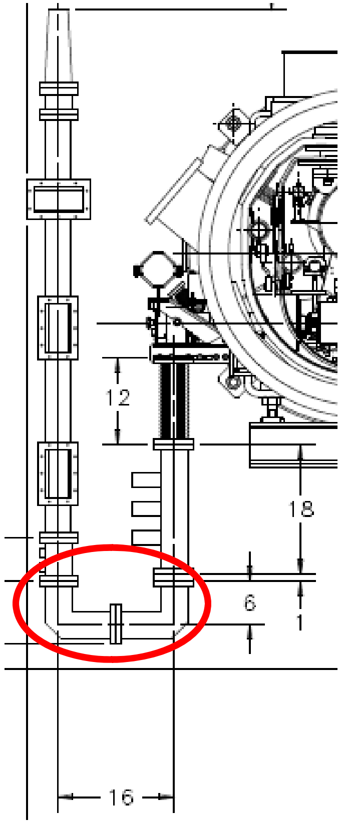
Because the first NML cryomodules have cavity spacing 1.3836m (6 λ_0), rather than 1.3260m (5.75 λ_0), the cavities must be fed with the same phase for synchronism with the relativistic beam.

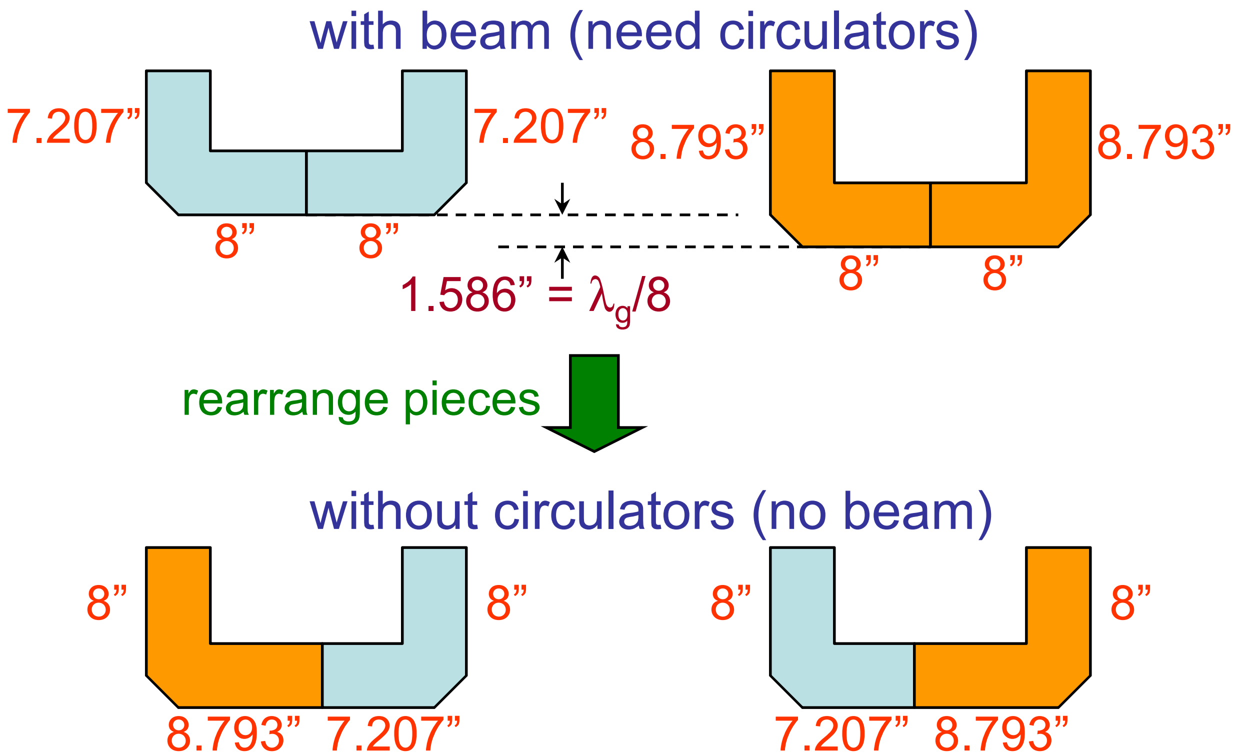
The hybrid introduces a $\pi/2$ phase difference, which must be removed by asymmetric feeds.

This destroys the hybrid reflection cancellation, so we need to retain circulators here for beam operation.

However, we'd like to test circulatorless operation, e.g. cavity field stability, even if without beam.

Our U-bends are designed to allow operation in either mode by a simple reconfiguration.

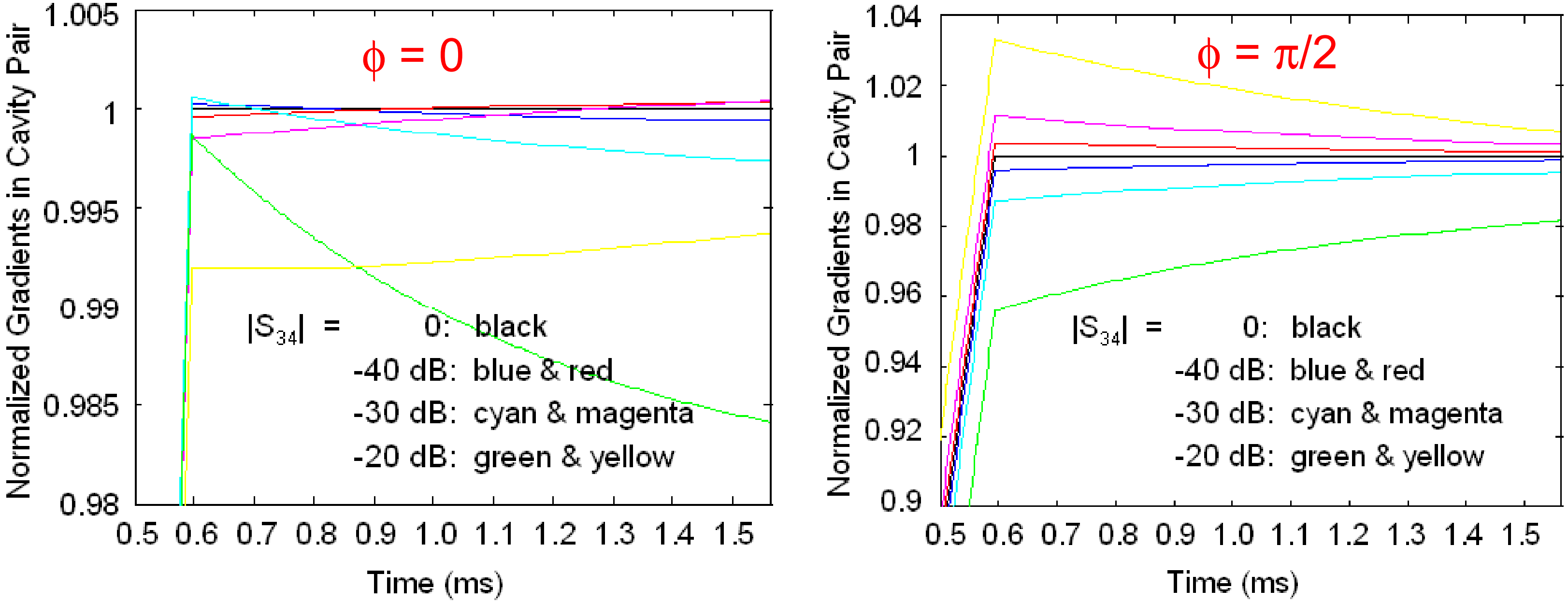




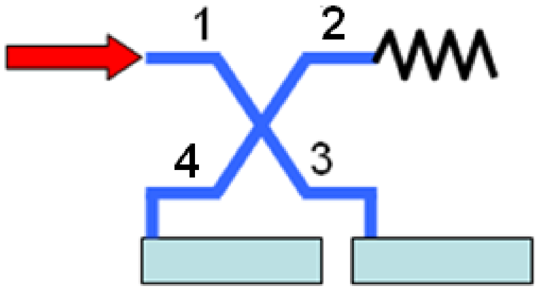
Cavity Simulation Without Circulators

Omitting circulators can result in higher inter-cavity coupling. To get a feel for the effect on field stability, numerical simulations were done.

Identical, perfect cavities and a lossless, symmetric hybrid coupling network with equal coupling but *imperfect port isolation* were assumed



Simulated cavity field “flat-tops” with imperfect isolation between hybrid-coupled cavities at coupling phases 0 and $\pi/2$. Pairs of colors represent the pair of cavities.



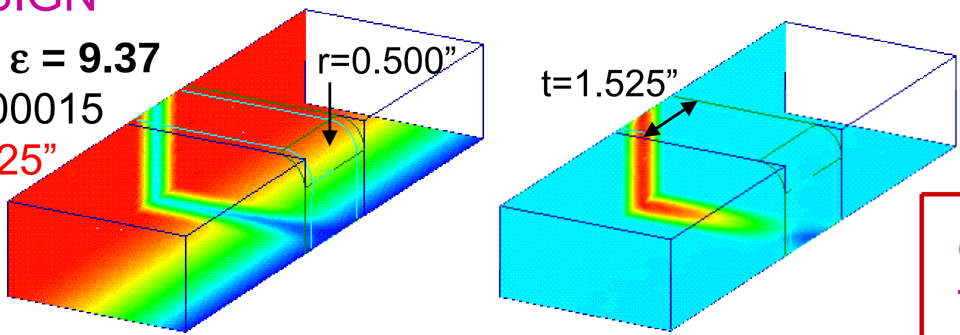
Achievable hybrid port isolation: -42—48 dB
(based on 4 SLAC and 1 MEGA hybrid measured)
→ transient gradient variation < ~0.001%

Dielectric Plug Window

We've developed a simple, cheaper, more compact substitute for the pillbox window.

RF DESIGN

Alumina: ε = **9.37**
tanδ = 0.00015
→ t = 1.525"



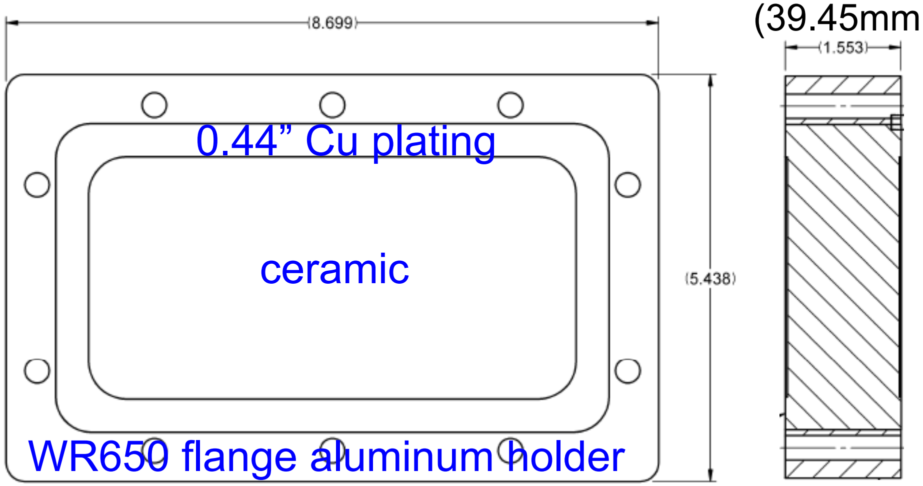
E_{pk}(720kW) = 338 kV/m H_{pk}(650kW) = 2.72 kA/m

reflection: -66.6 dB
transmission: -.00477 dB (99.89%)

heating:
0.11%×650kW×1.6ms×5Hz=5.72 W

MECHANICAL DESIGN

1.553"
(39.45mm)

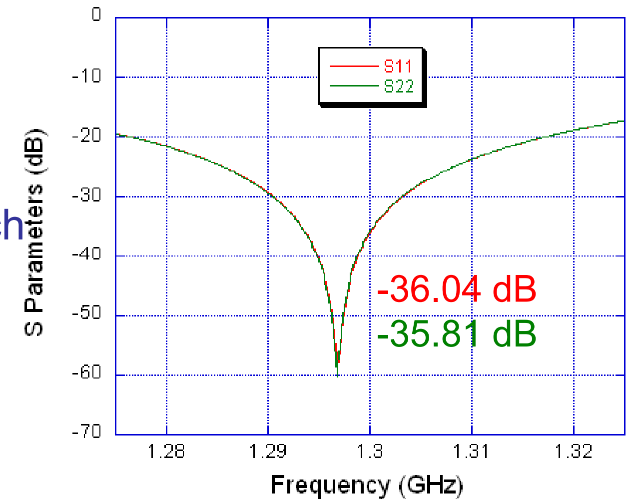


Ceramic blocks with rounded edges are ground to the design thickness and then thickly plated around the edge with copper and placed in shrink-fit holder flanges. The gaskets seal to the copper and lock it in place.

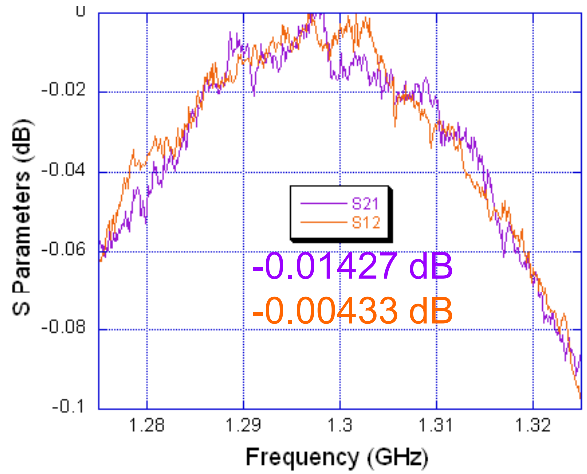
COLD TEST

-36 dB match @ 1.3 GHz

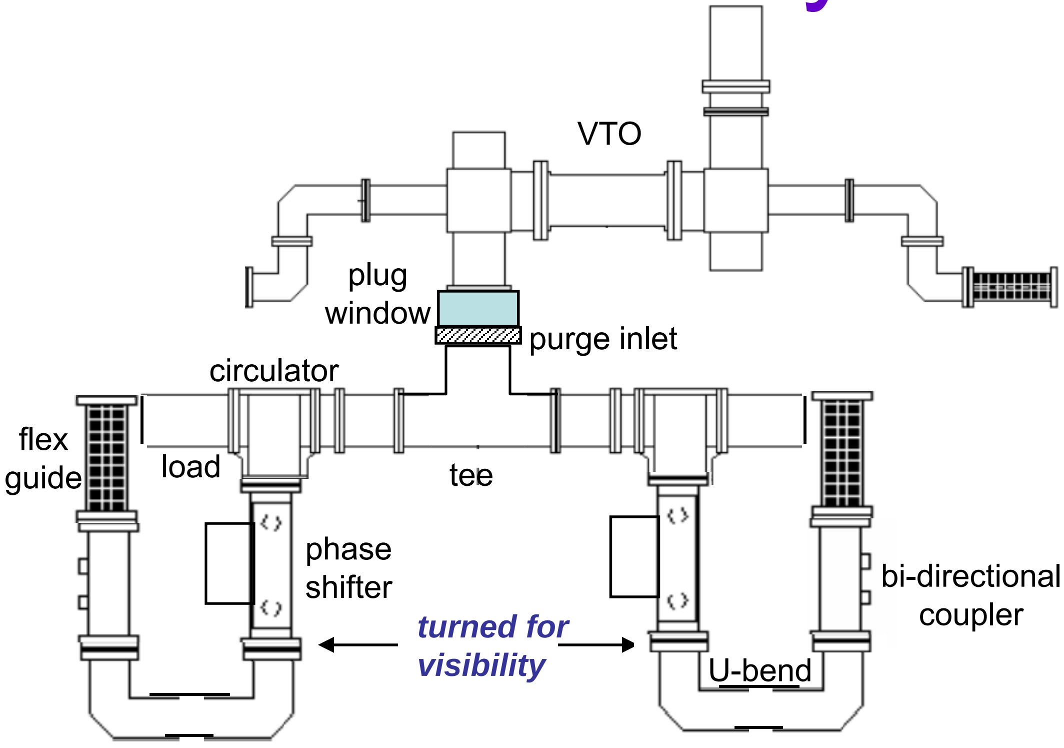
Minimum:
-59.6 dB @ 1.2969 GHz



transmission loss:
0.1–0.3%



PDS Unit for NML Cryomodule 2



Planned Changes:

- replace pillbox window with ceramic plug window
- replace hybrid with shunt tee
- replace double E-plane bends with single U-bend (eliminate flange joint)

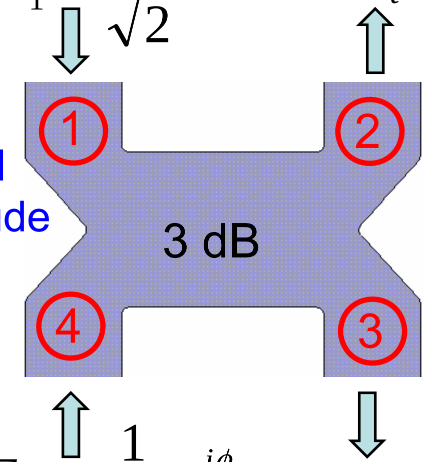
2nd cryomodule also has wrong cavity spacing for circulatorless beam operation

We'll also explore making VTO fabrication more economical.

Tailoring Power Distribution with Spacers and 3 dB Hybrids

$E_1 = \frac{1}{\sqrt{2}} e^{i\phi_1}$ $\qquad$ E_t (transmitted)

2 equal amplitude inputs



$E_2 = \frac{1}{\sqrt{2}} e^{i\phi_2}$ $\qquad$ E_e (extracted)

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

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.

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

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

$$E_t = \left(i \frac{E_1}{\sqrt{2}} + \frac{E_2}{\sqrt{2}} \right) = \frac{1}{2} \left(e^{i(\phi_1 + \pi/2)} + e^{i\phi_2} \right) = e^{i\left(\frac{\phi_1 + \phi_2}{2} + \frac{\pi}{4}\right)} \cos\left(\frac{\phi_1 - \phi_2}{2} + \frac{\pi}{4} \right)$$

$$C = \left|\frac{E_e}{E_i}\right|^2 = \cos^2\left(\frac{\Delta\phi}{2} + \frac{\pi}{4}\right), \quad T = \left|\frac{E_t}{E_i}\right|^2 = \cos^2\left(\frac{-\Delta\phi}{2} + \frac{\pi}{4}\right) = \sin^2\left(\frac{\Delta\phi}{2} + \frac{\pi}{4}\right)$$

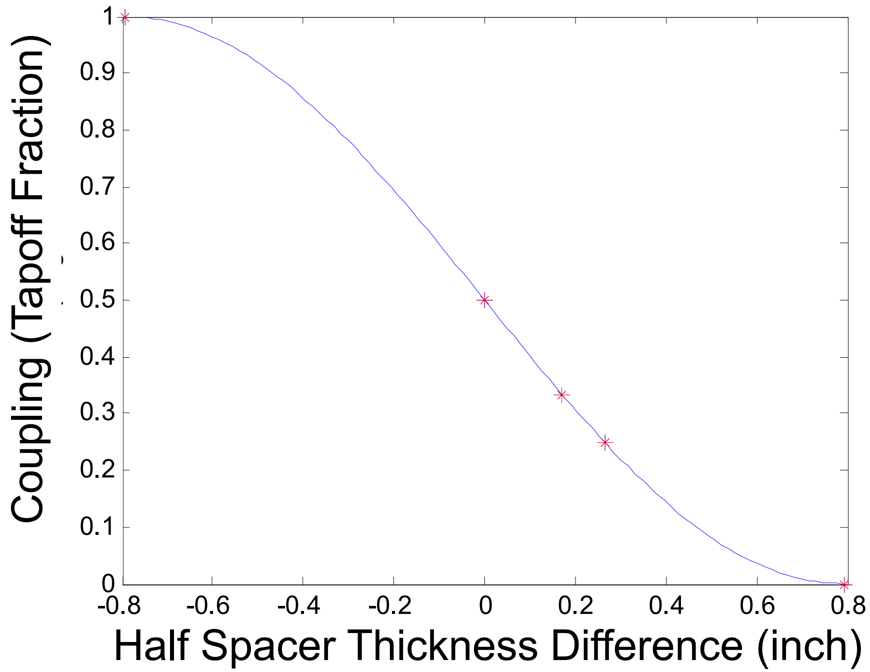
$$C = \begin{cases} 0, & \Delta\phi = \pi/2 & \Delta L = 3.1712'' \\ 1/4, & \Delta\phi = \pi/6 & \Delta L = 1.0572'' \\ 1/3, & \Delta\phi = 19.471^\circ & \Delta L = 0.6860'' \\ 1/2, & \Delta\phi = 0 & \Delta L = 0'' \\ 1, & \Delta\phi = -\pi/2 & \Delta L = -3.1712'' \end{cases}$$

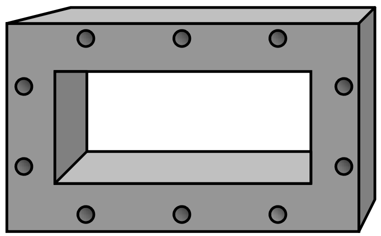
<u>$\Delta L/4$ (2 U-bends)</u>

± 0.7928”
± 0.2643”
± 0.1715”
± 0.000”
- ± 0.7928”

spacer thicknesses
T = 1.000” ± $\Delta L/4$

.00881”/degree in thickness of spacers





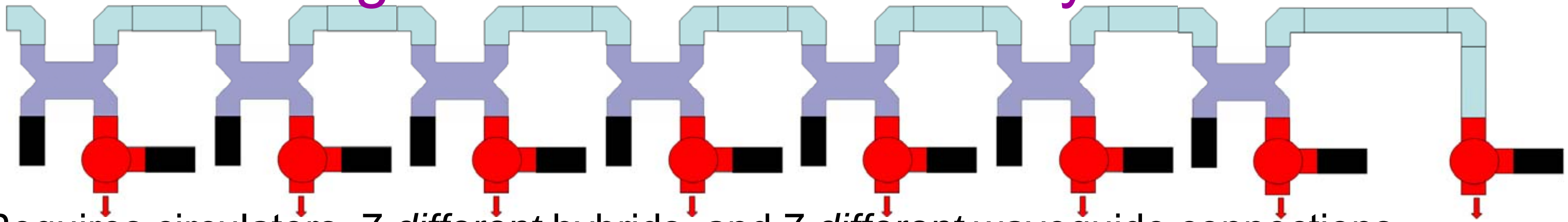
<u>Nominal Set (2 each)</u>

1.7928”	0.2072”
1.2643”	0.7357”
1.1715”	0.8285”
1.0000”	1.0000”

Adjust for system losses and for specific desired relative power levels.

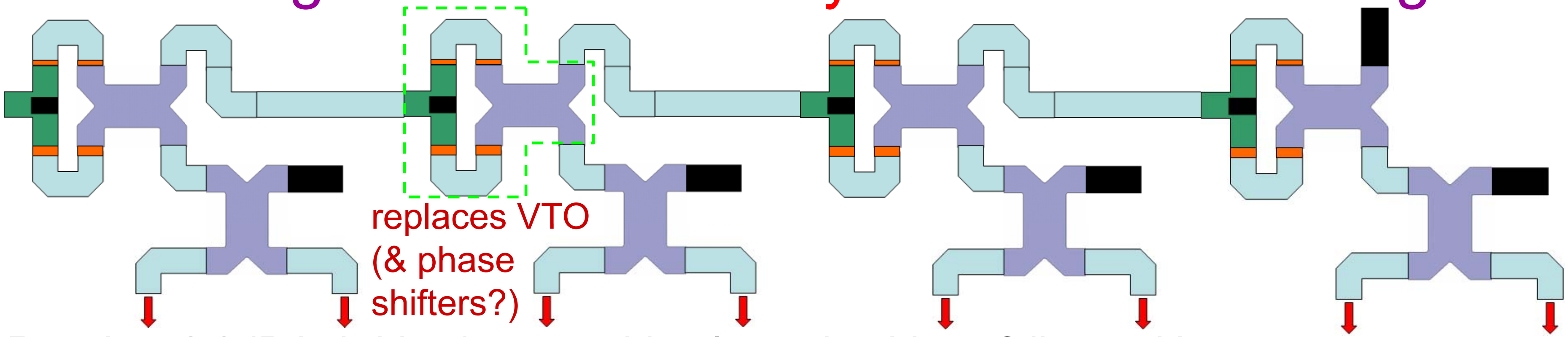
Insert between flanges and connect with single set of long bolts or threaded rods.

Configuration With Fixed Cavity Power



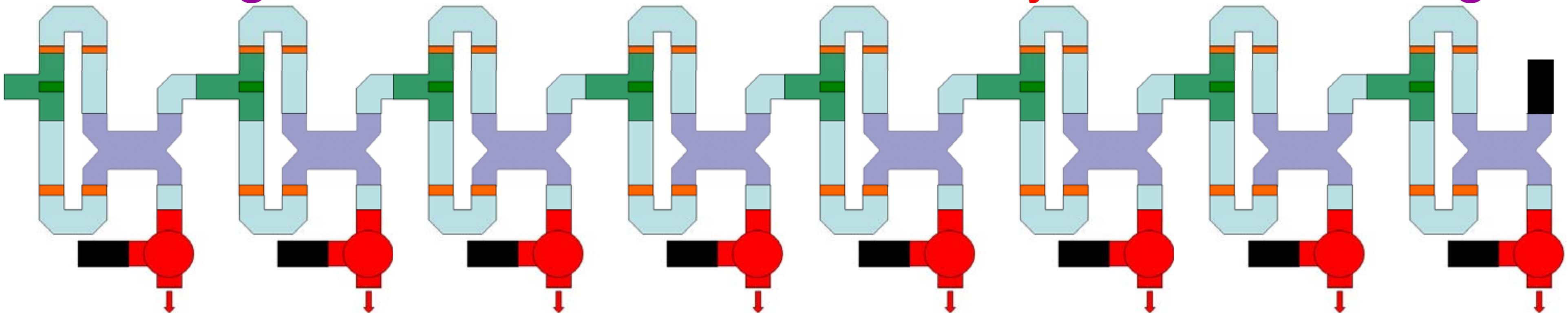
Requires circulators, 7 *different* hybrids, and 7 *different* waveguide connections.

Configuration With Cavity Pair Power Tailoring



Requires 8 3dB hybrids, 4 waveguide *T*'s, and pairing of like cavities.

Configuration With Individual Cavity Power Tailoring



Requires circulators, 8 3dB hybrids, and 8 waveguide *T*'s.