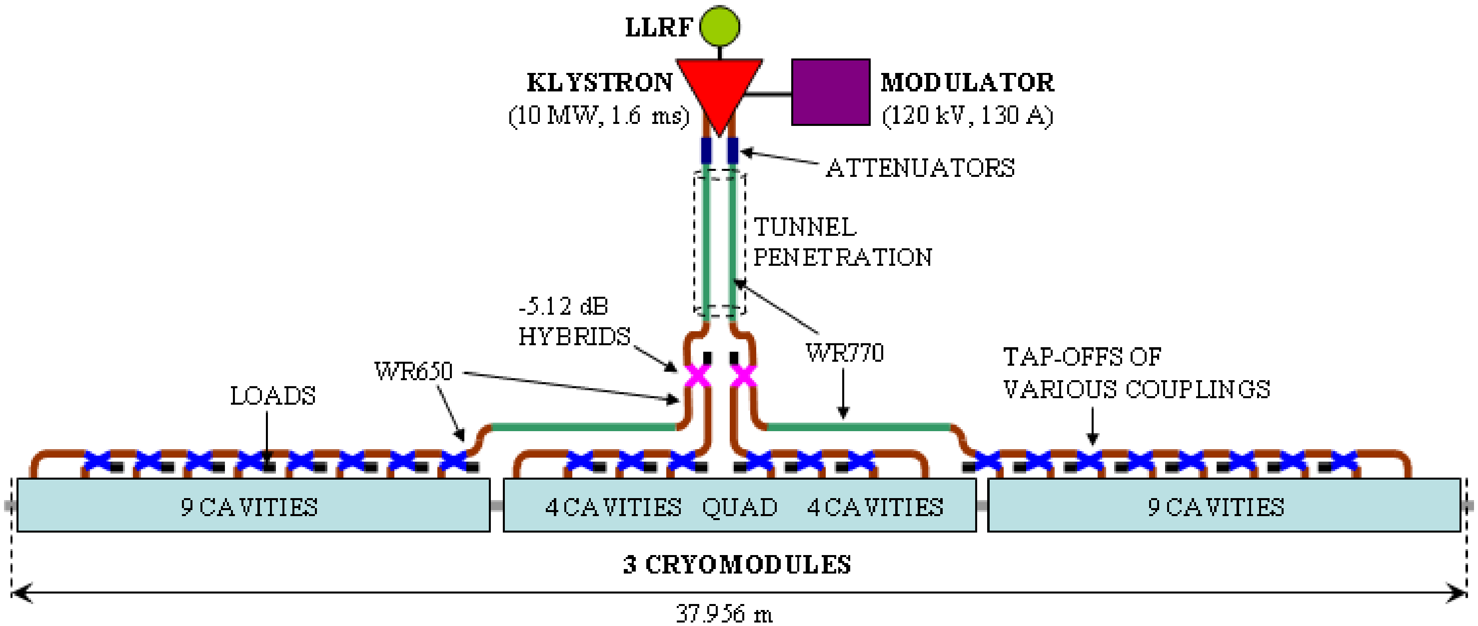
Power Distribution System (PDS) Design and R&D Status

Christopher Nantista
SLAC
SCRF Meeting @ Fermilab
April 24, 2008

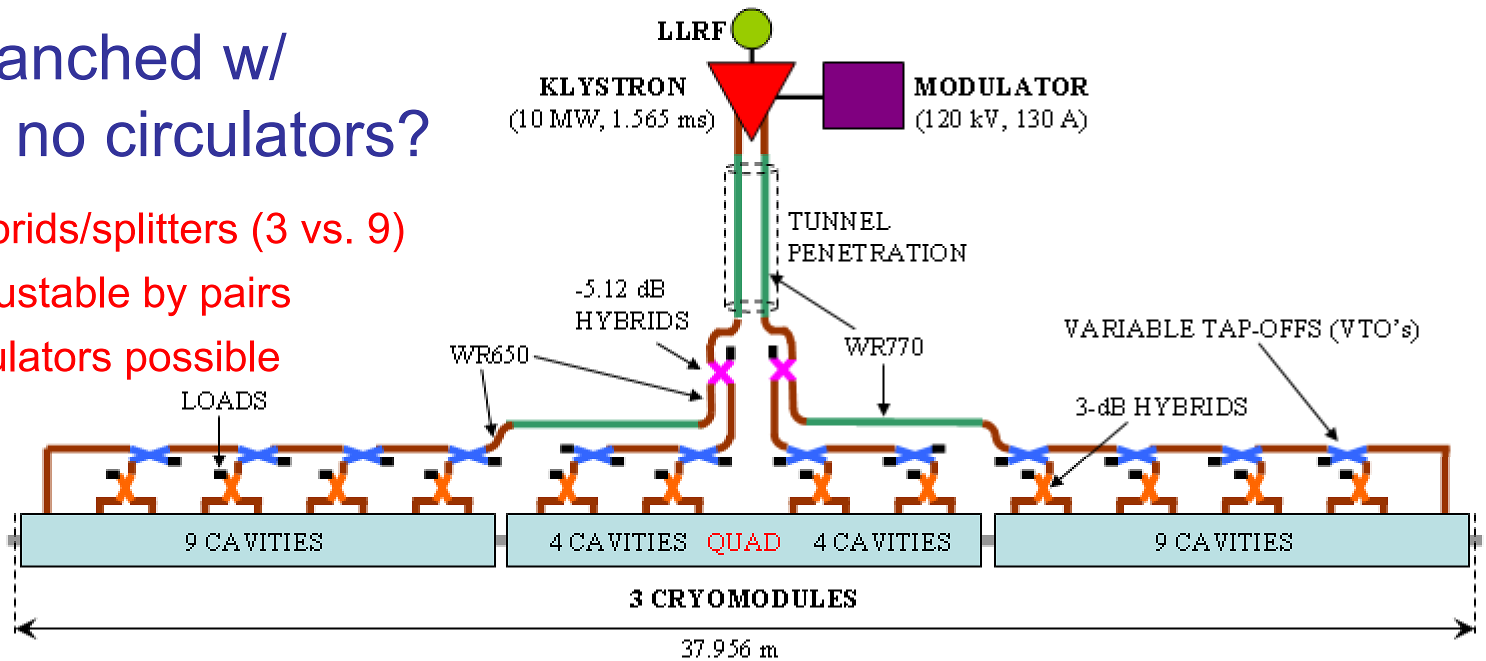
Basic Distribution Scheme

BCD: linear

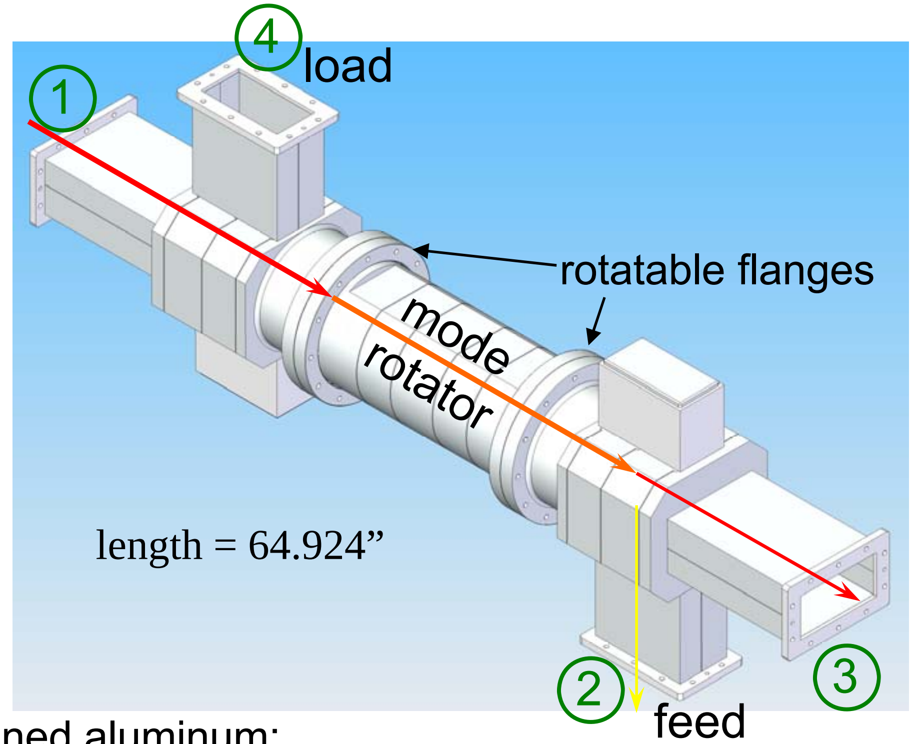


ACD: semi-branched w/
VTO's & no circulators?

- Fewer types of hybrids/splitters (3 vs. 9)
- Power division adjustable by pairs
- Elimination of circulators possible



Variable Tap-Off (VTO) Design

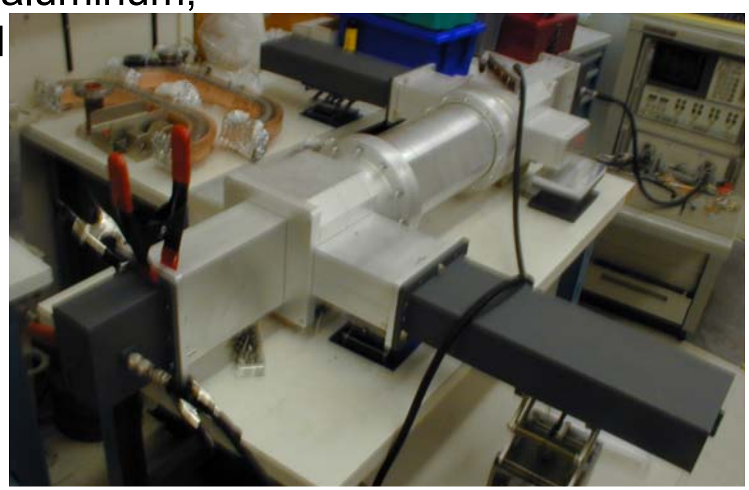


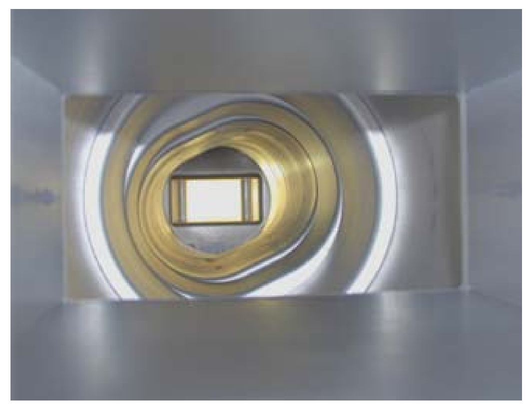
$$|\mathbf{S}| = \begin{bmatrix} 0 & \sqrt{C} & \sqrt{1-C} & 0 \\ \sqrt{C} & 0 & 0 & \sqrt{1-C} \\ \sqrt{1-C} & 0 & 0 & \sqrt{C} \\ 0 & \sqrt{1-C} & \sqrt{C} & 0 \end{bmatrix}$$

Coupling is a function of center rotation angle α.

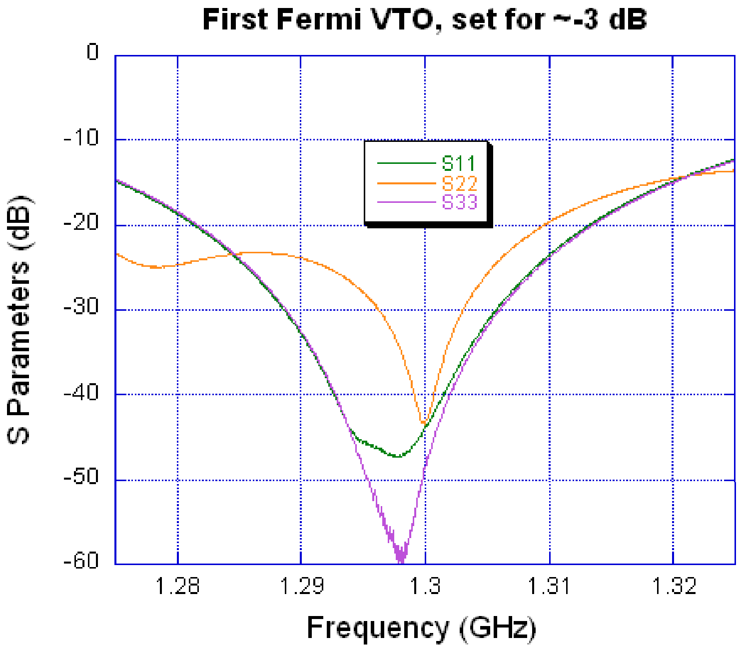
$C = P_c / P_i$	$\alpha = 1/2 \sin^{-1}\sqrt{C}$
0	0.00°
1/4	15.00°
1/3	17.63°
1/2	22.50°
1	45.00°

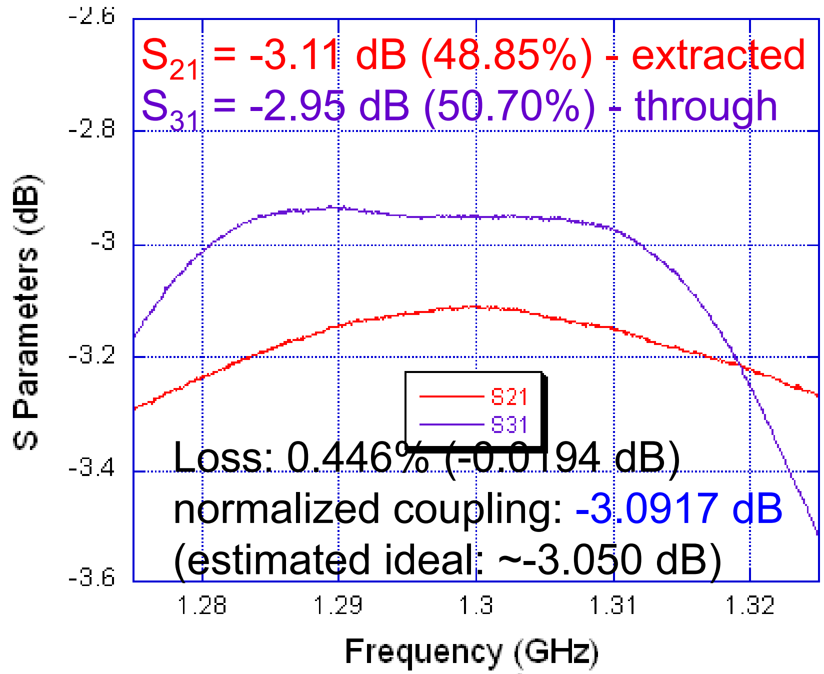
machined aluminum;
dip-brazed



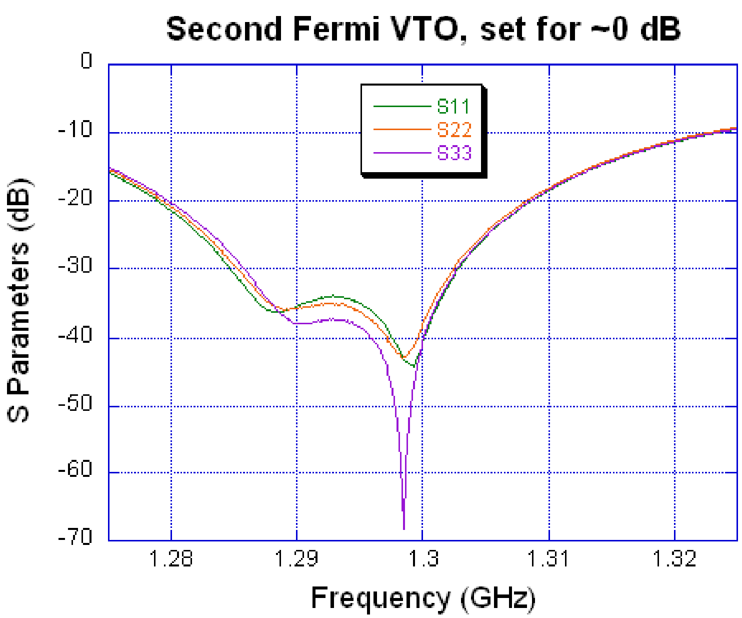


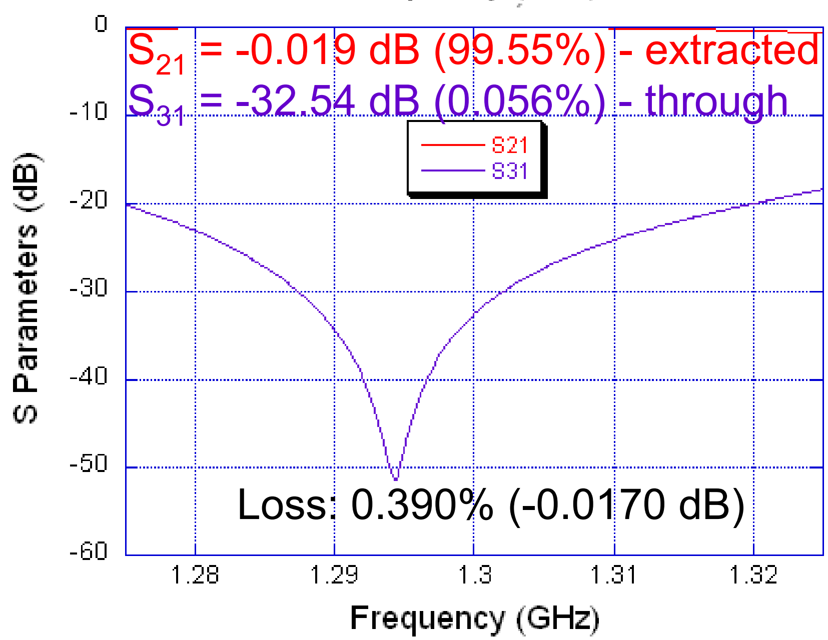
VTO Cold Test Results





~22.5°



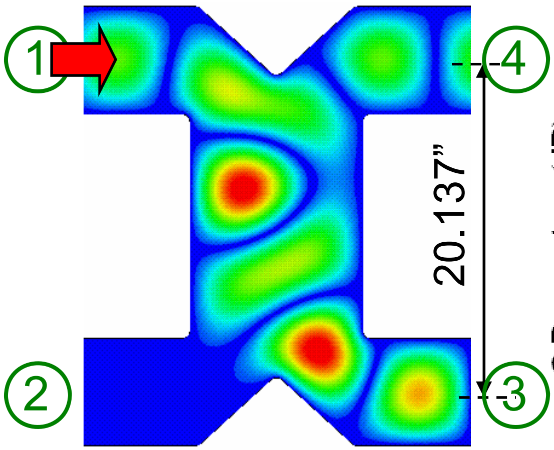


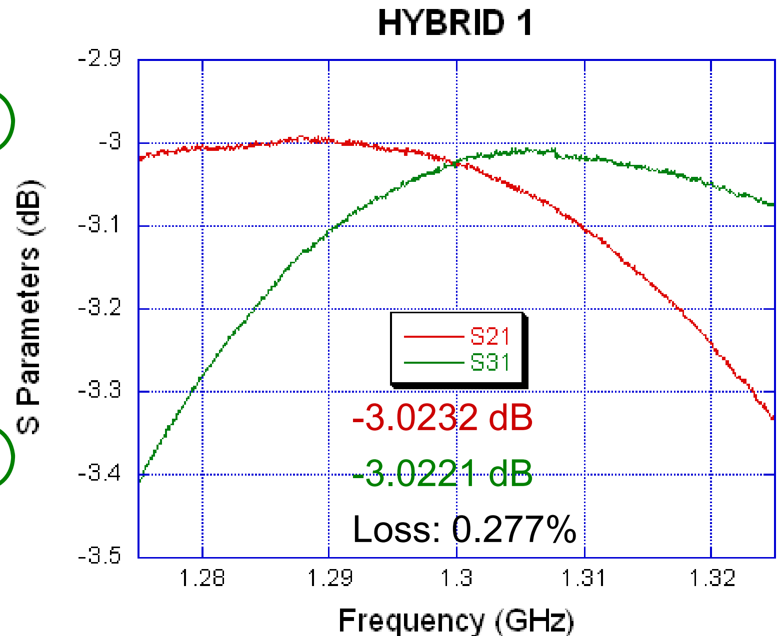
~45°

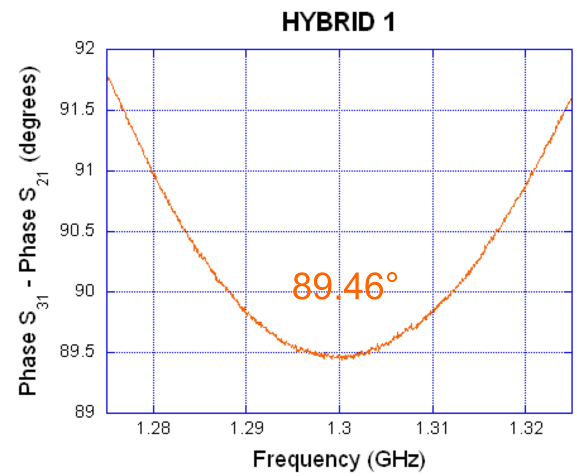
3 dB Hybrid

Typical cold test measurements:

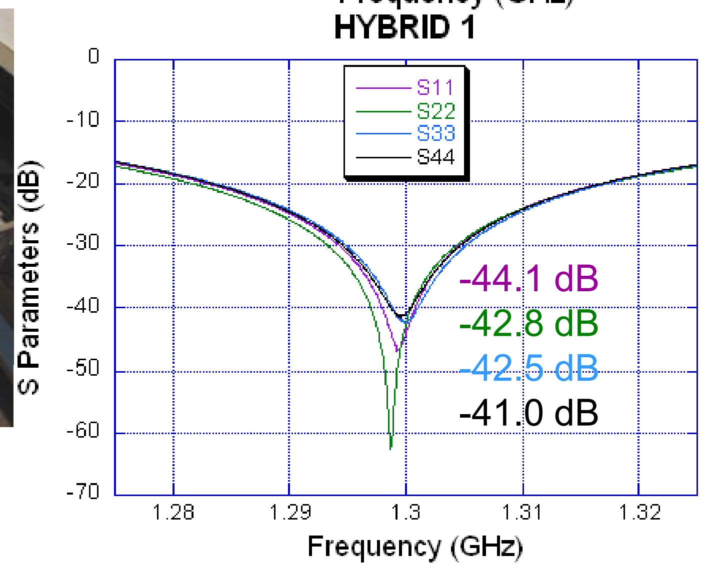
HFSS model

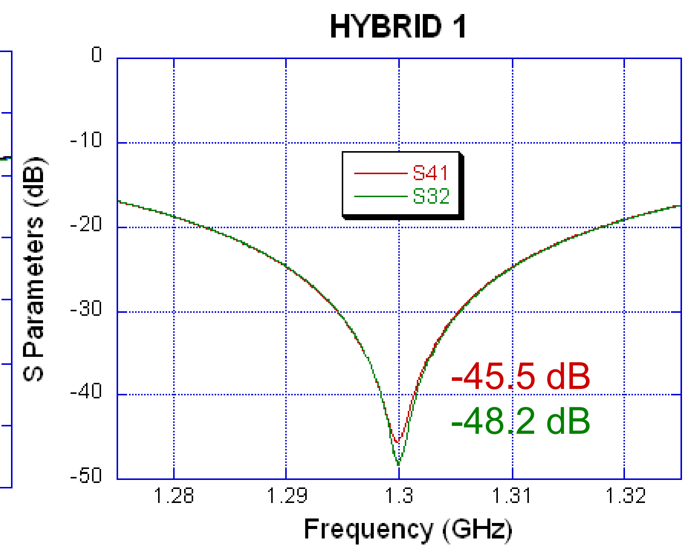






dip brazed aluminum



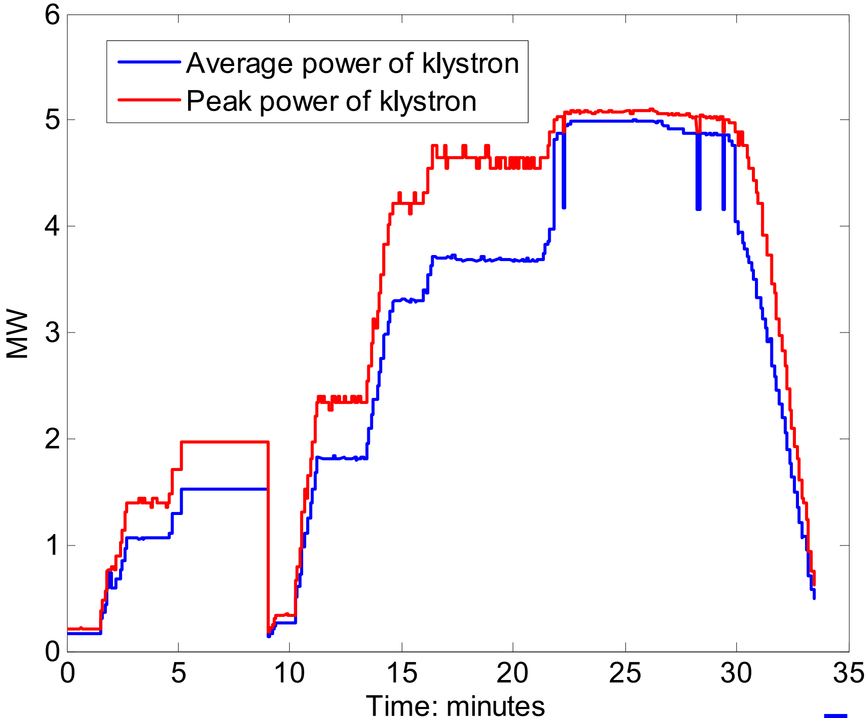


High Power Tests

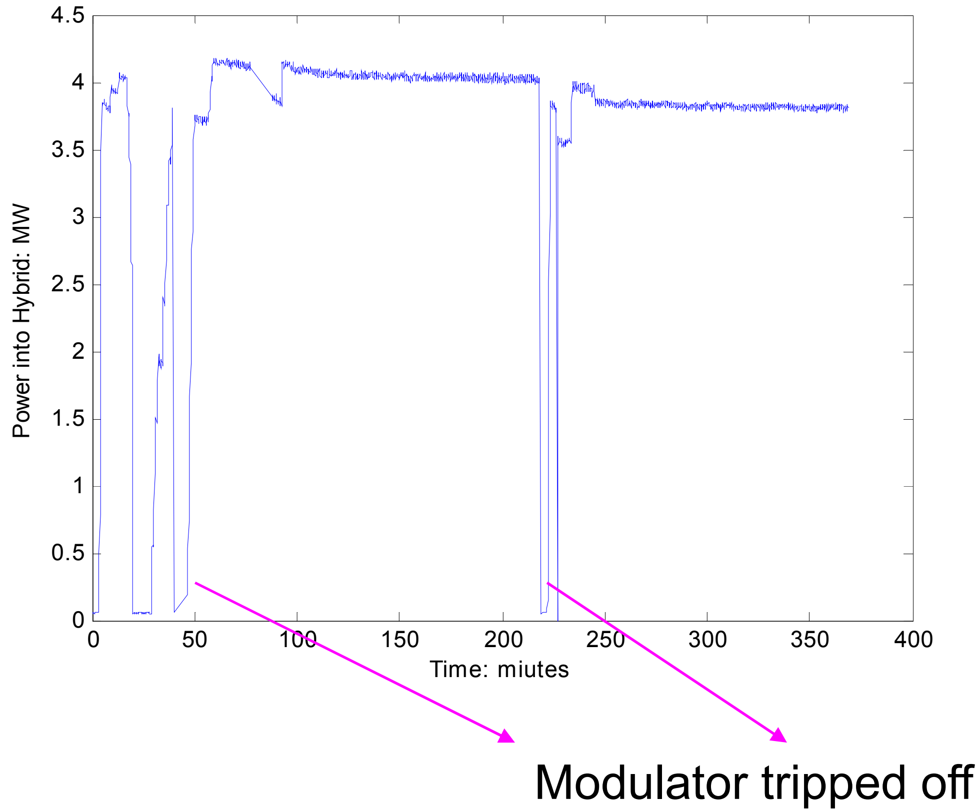
VTO

VTO -75Degrees test Jul-12-2007

The width of RF is 1ms and the repeat frequency is 1Hz



Hybrid



Hybrid has been tested at 4MW for few hours at the pressure of 0psig. No breakdown during the test.

Faya Wang

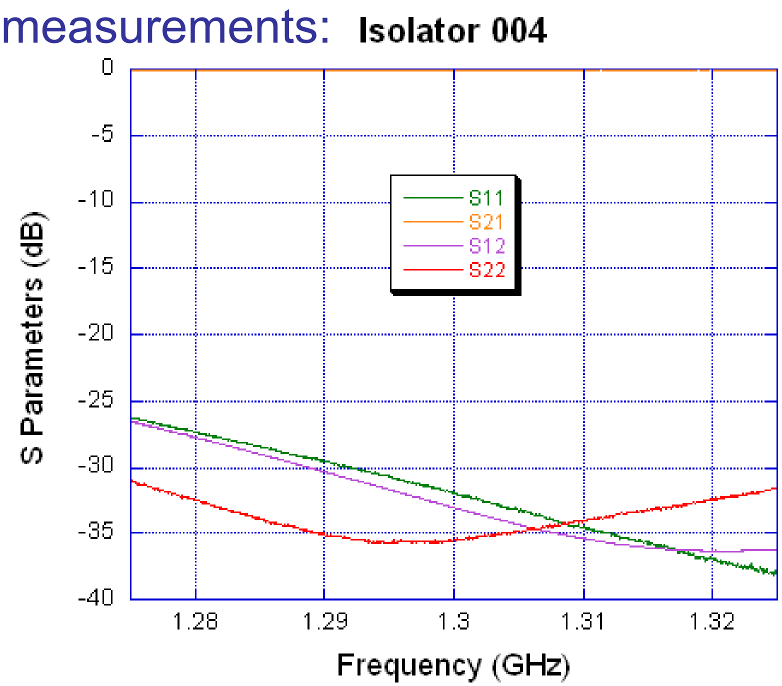
Isolator (Circulator w/ Load)

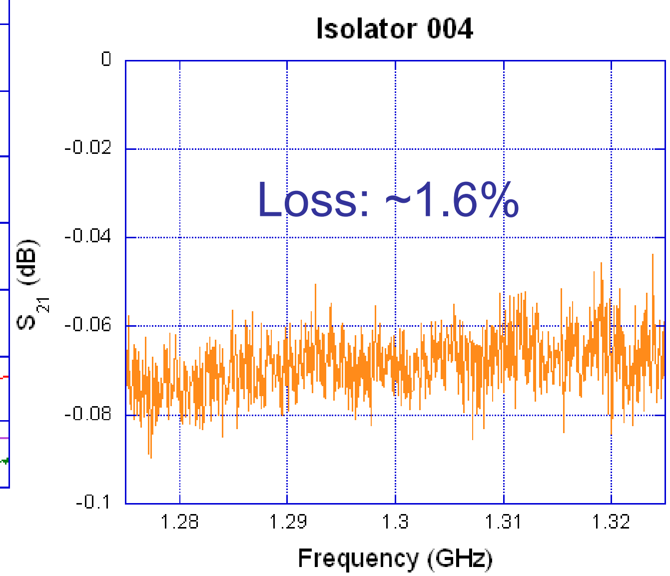
S.P.A. Ferrite Ltd.
St. Petersburg, Russia

1MW Load

Typical load match < -35 dB

Typical cold test measurements:



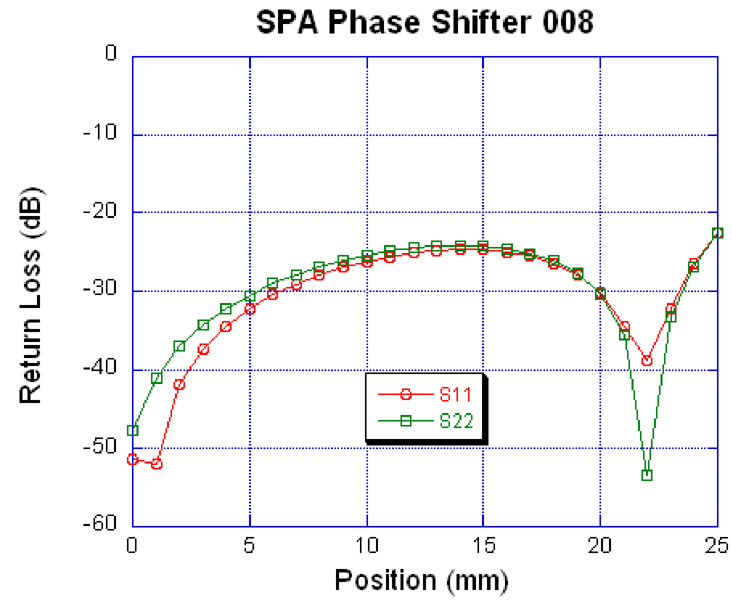


Phase Shifter

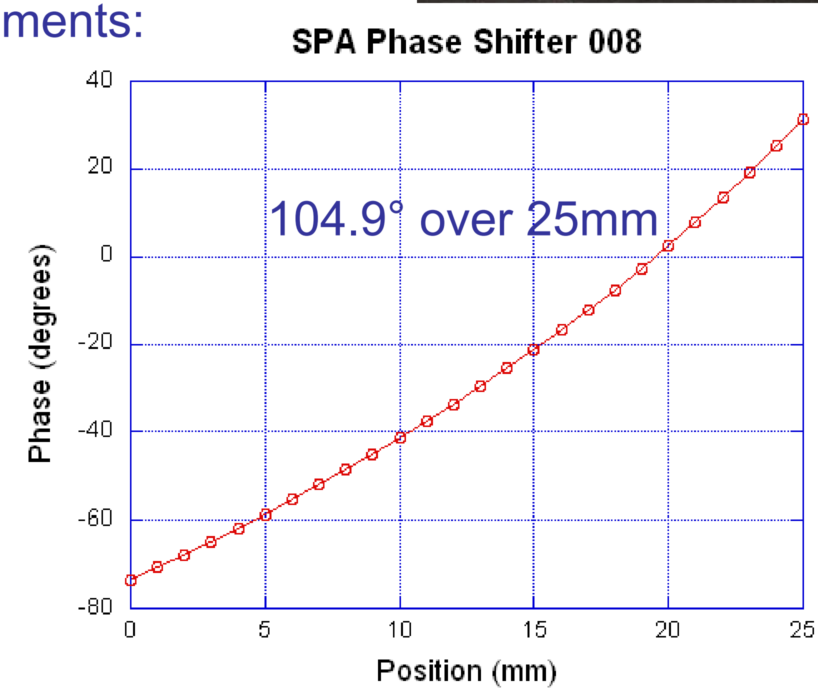
S.P.A. Ferrite Ltd.
St. Petersburg, Russia

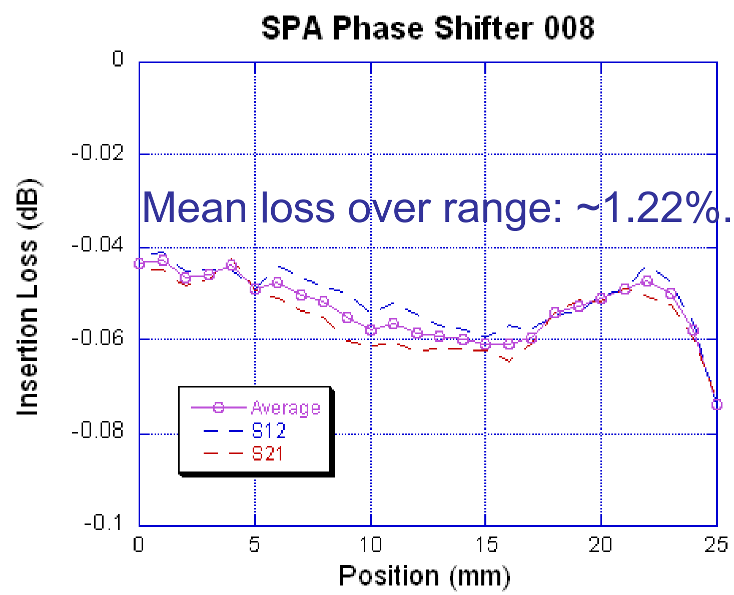
DESY design

motorized moving side wall

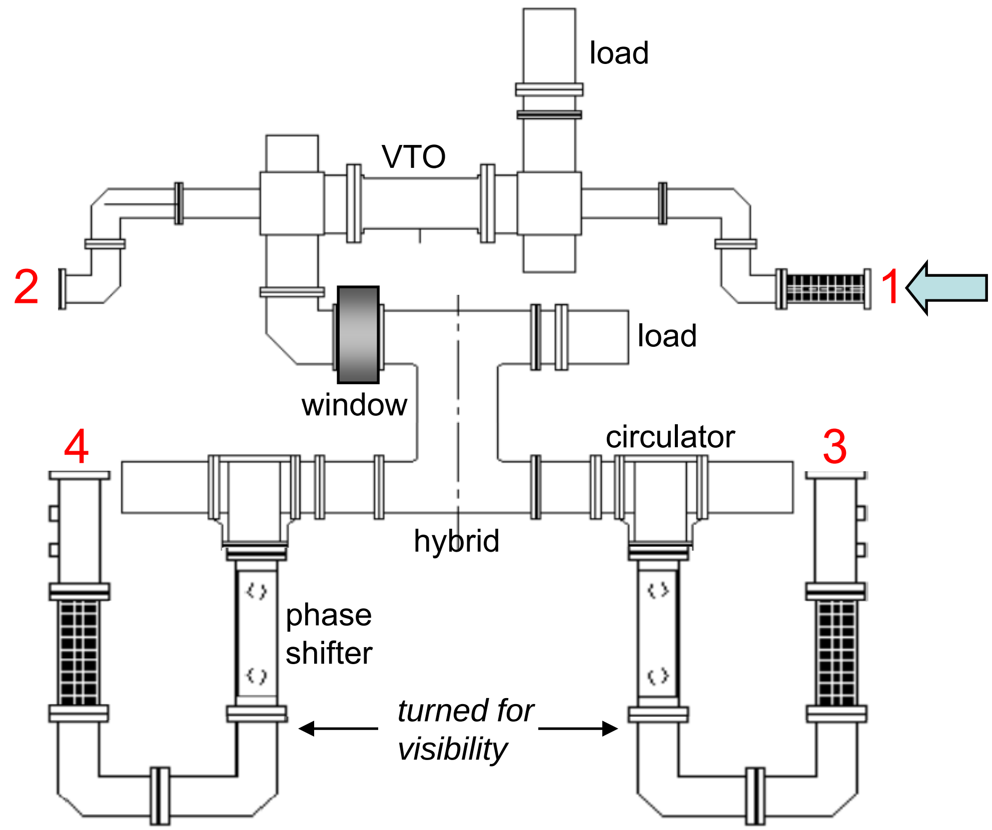


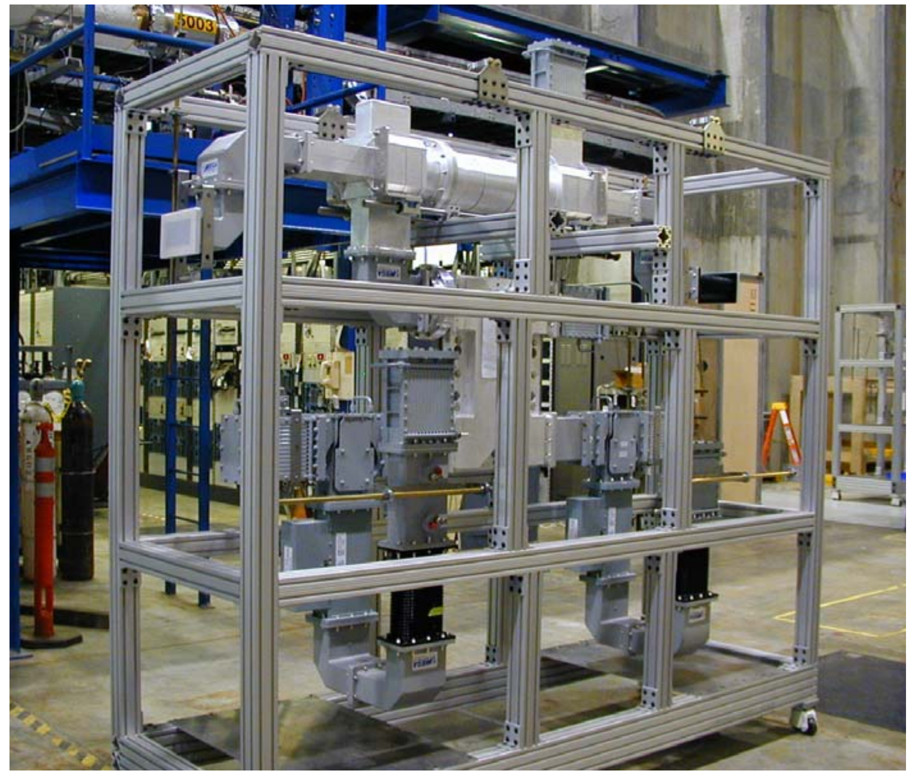
Typical cold test measurements:





RF PDS Module Cold Test





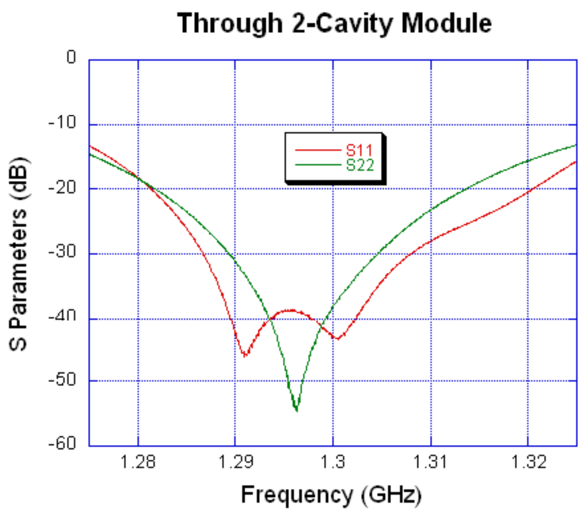
The first 2 (of 4) 2-cavity modules of our RF power distribution system for Fermilab's first NML cryomodule are assembled. The first is cold tested and ready for high-power testing. It incorporates:

SLAC VTO and hybrid
Ibfm window (for pressurization of high-power volume)
S.P.A. Ferrite isolators and loads
Mega bends and flex guides (and dir. cplrs. while awaiting S.P.A. pieces)

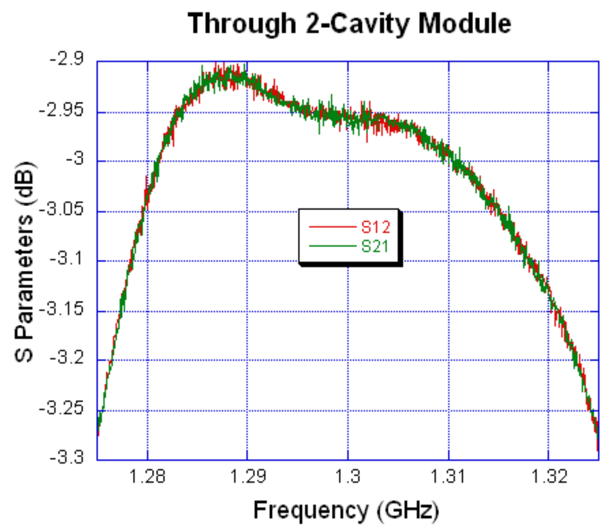
C. Nantista

COLD TEST RESULTS:

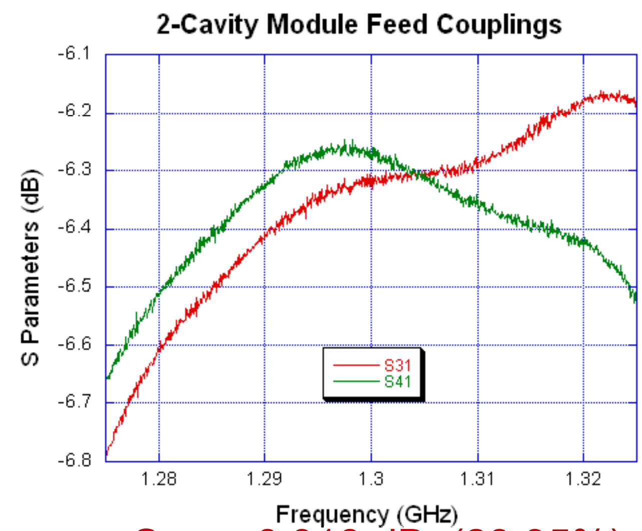
VTO set for 2nd to last cavity pair (~3 dB).



S_{11} = -43.0 dB (0.005%)



S_{21} = -2.948 dB (50.72%)



S_{31} = -6.318 dB (23.35%)

S_{41} = -6.276 dB (23.57%)

POWER

2.36% of power missing (-0.104 dB) ⇒ Expect roughly:

Bends:		0.41%
VTO:		0.446%
Window:	0.493×0.088% =	0.043%
Hybrid:	0.493×0.42% =	0.207%
Circulators:	0.493×1.78% =	0.878%
Phase shifters:	0.493×0.55% =	0.271%
Flex guides:	0.62% + 0.493×0.62% =	0.926%
		~3.18%

Pair power division 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° 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, compared to 1.3837m coupler spacing.

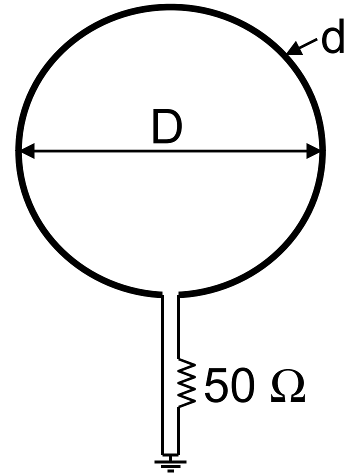
Module length measures ~2.7674m, exact to measurement resolution.

C. Nantista

RF Leak Checking

The safety administrative threshold for human exposure to our pulsed rf flux is 1.08 kW/m^2 (see IEEE C95.1 2005 Table8, p. 24 and Note f, p. 26).

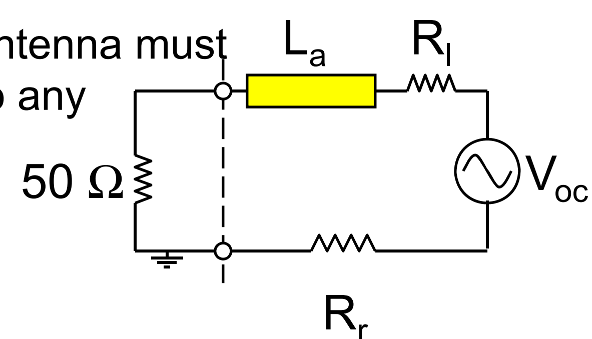
To avoid human exposure to unacceptable RF field levels during monitoring and the difficulty of measuring pulsed flux, we will test waveguide systems at low power, using a CW signal generator and a loop antenna prior to running with klystron power.



With our 1" diameter loop antenna, 1.08 kW/m^2 should read 15.4 dBm on the spectrum analyzer. With a 15 dBm signal generator replacing rf power of up to 5 MW (an 82 dB difference) we need to set our threshold at ~-67 dBm.

With the uncertainties in our calibration, let us add a safety margin of 20 dB and try to keep leakage below ~-87 dBm.

Of course, in addition to being swept around the sytem, the loop antenna must be turned and twisted in different orientations to assure coupling to any radiated fields.

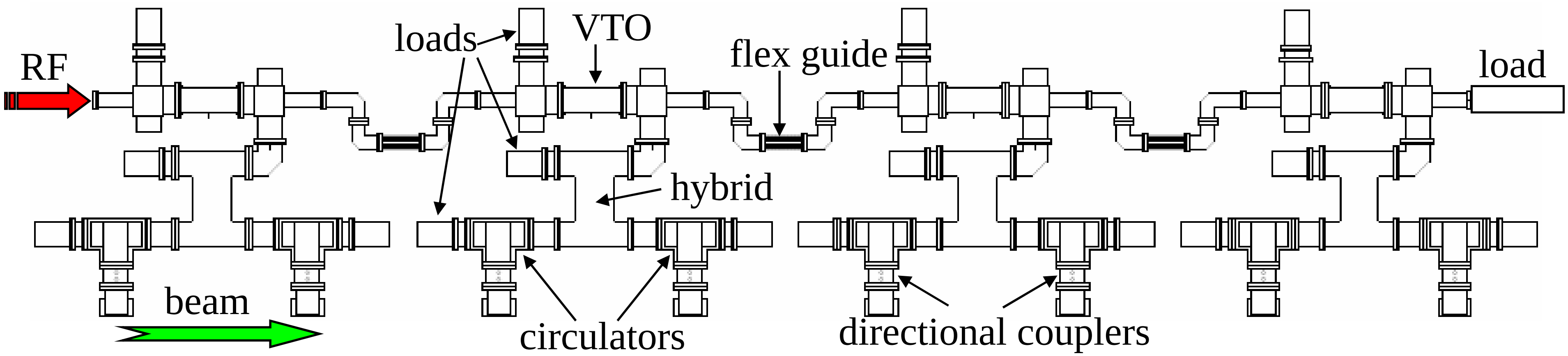


$$|V_L| = \left|\frac{Z_L}{Z_L + Z_a}\right| 4k_0\sqrt{2\eta_0}\int_0^{D/2}\sqrt{D^2/4 - x^2}\cos k_0 x\,dx\,S^{1/2} \approx 0.04015\,\mathrm{V}\sqrt{S(\mathrm{W/m^2})}$$

~0.108 (dominated by loop inductance)

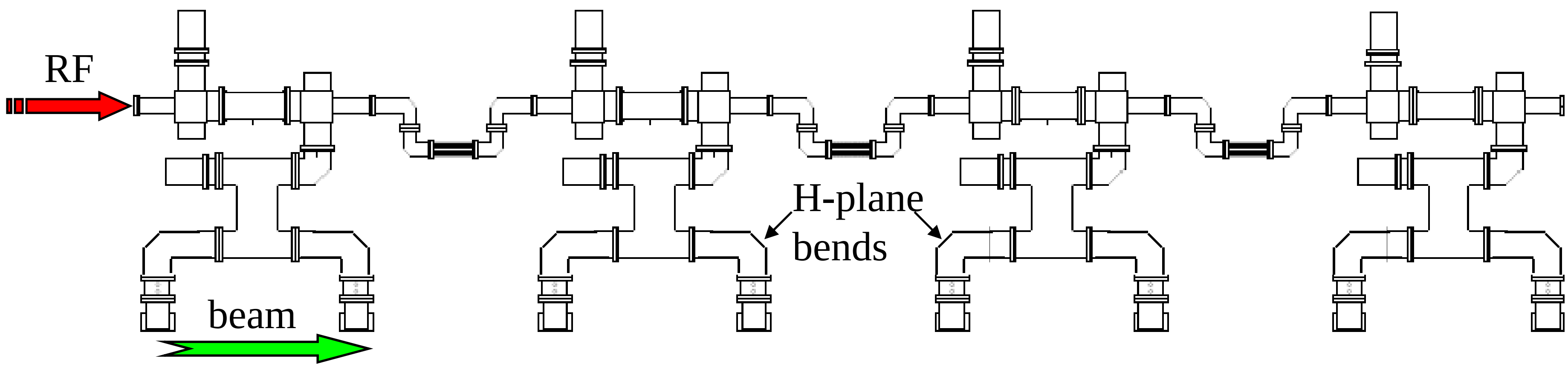
Alternative RF Distribution Layout

with circulators:



VTO's allow pair-wise adjustment of power distribution.

without circulators:



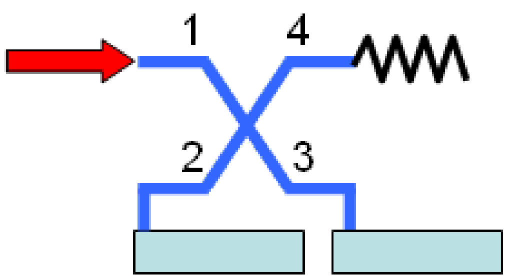
Hybrid feeding of equal-Q cavity pairs directs reflected power into hybrid loads.

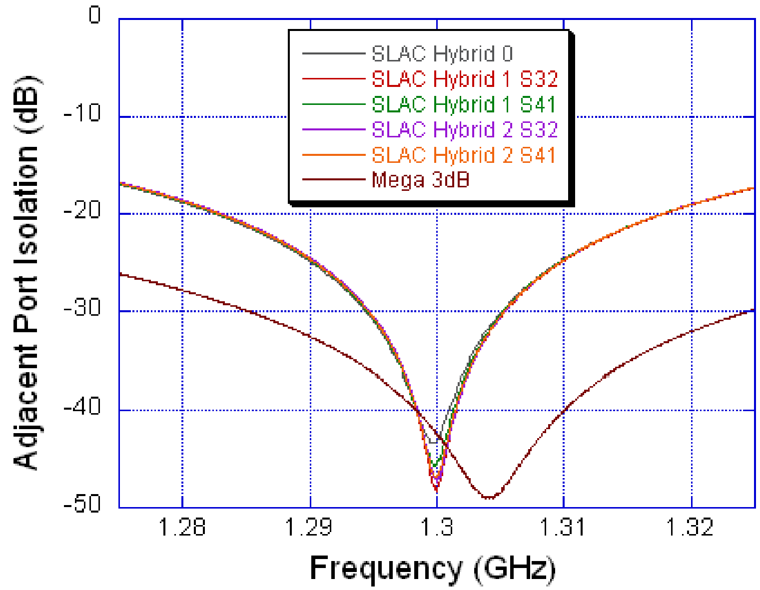
No Circulators

Will elimination of circulators result in inter-cavity coupling problems due to insufficient cavity isolation?

Typical L-band Hybrid port isolation measurements:

-42–48 dB





To get a feel for the effect of coupling alone, assume a pair of identical cavities and a lossless, symmetric coupling network with equal coupling but imperfect port isolation. Let ϕ be the phase length from the hybrid ports to the cavities (with $\angle S_{23}$ set to 0). A MATLAB program was used to integrate the coupled differential equations for the fields with various $|S_{23}|$ amplitudes and ϕ values, producing the following results*.

* Justin Keung of University of Pennsylvania obtained similar results with his Penn Virtual Cavity (PVC) program.

Coupled Field Equations

$$\frac{dE_2^e}{dt} = -\frac{1}{\tau}\left(E_2^e + E_{eb\infty}\right) + \frac{\alpha}{\tau}E_2^+$$

$$\frac{dE_3^e}{dt} = -\frac{1}{\tau}\left(E_3^e - iE_{eb\infty}\right) + \frac{\alpha}{\tau}E_3^+$$

Emitted Fields

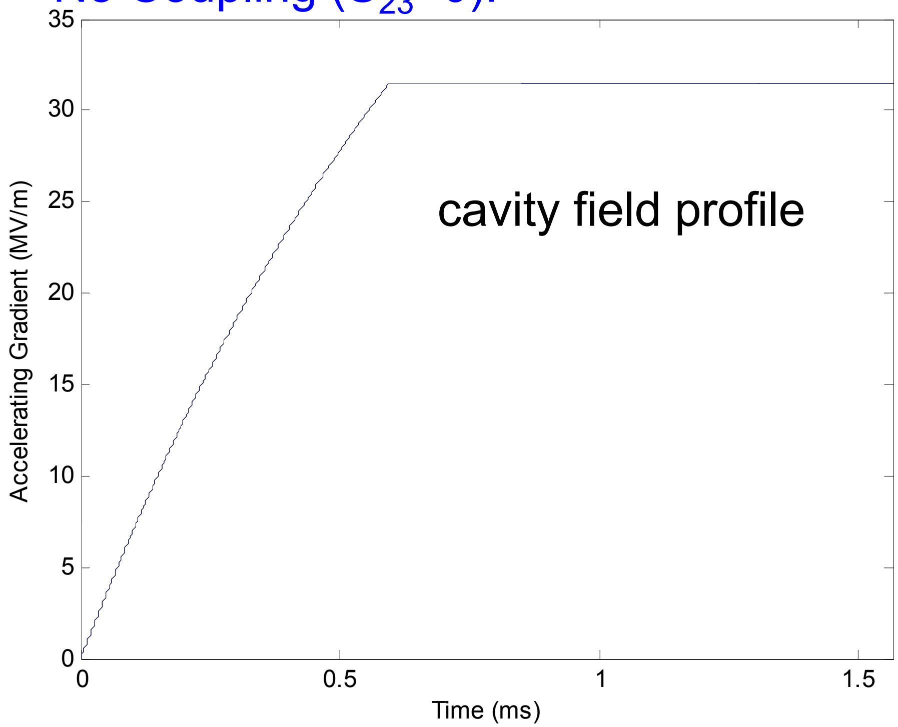
$$\alpha = \frac{2\beta}{1+\beta} = 2\left(1 - Q_L / Q_0\right)$$

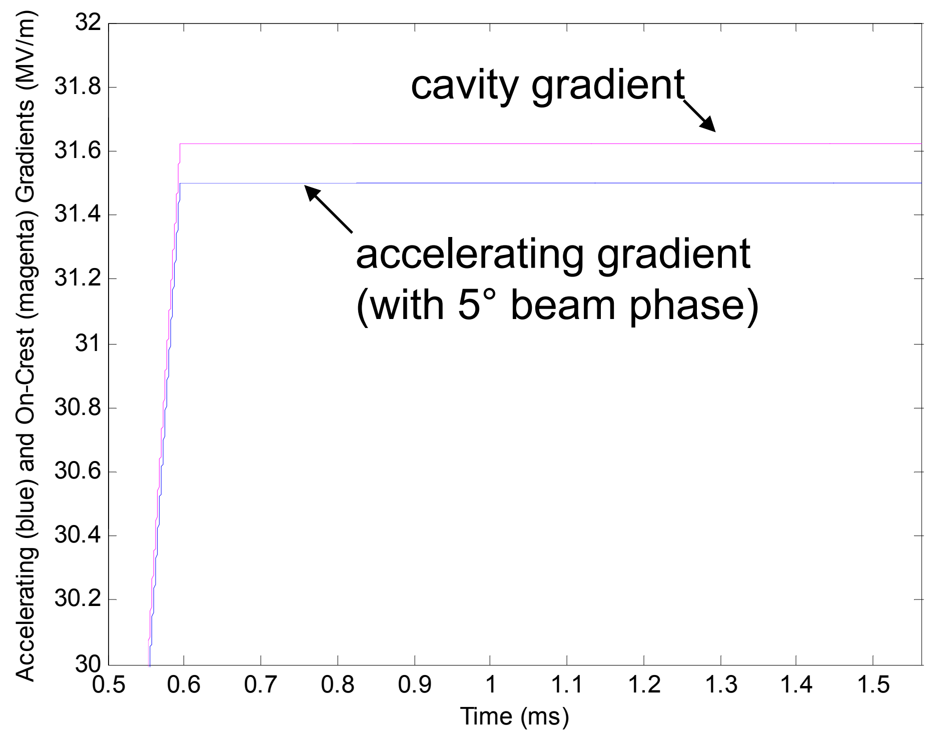
$$\frac{dE_2^+}{dt} = \frac{S_{23}e^{i2\phi}}{1 - S_{23}^2 e^{i4\phi}}\frac{1}{\tau}\left\{-\left(E_3^e - iE_{eb\infty}\right) + \alpha E_3^+ - S_{23}e^{i2\phi}\left[-\left(E_2^e + E_{eb\infty}\right) + \alpha E_2^+\right]\right\}$$

$$\frac{dE_3^+}{dt} = \frac{S_{23}e^{i2\phi}}{1 - S_{23}^2 e^{i4\phi}}\frac{1}{\tau}\left\{-\left(E_2^e + E_{eb\infty}\right) + \alpha E_2^+ - S_{23}e^{i2\phi}\left[-\left(E_3^e - iE_{eb\infty}\right) + \alpha E_3^+\right]\right\}$$

Incident Fields

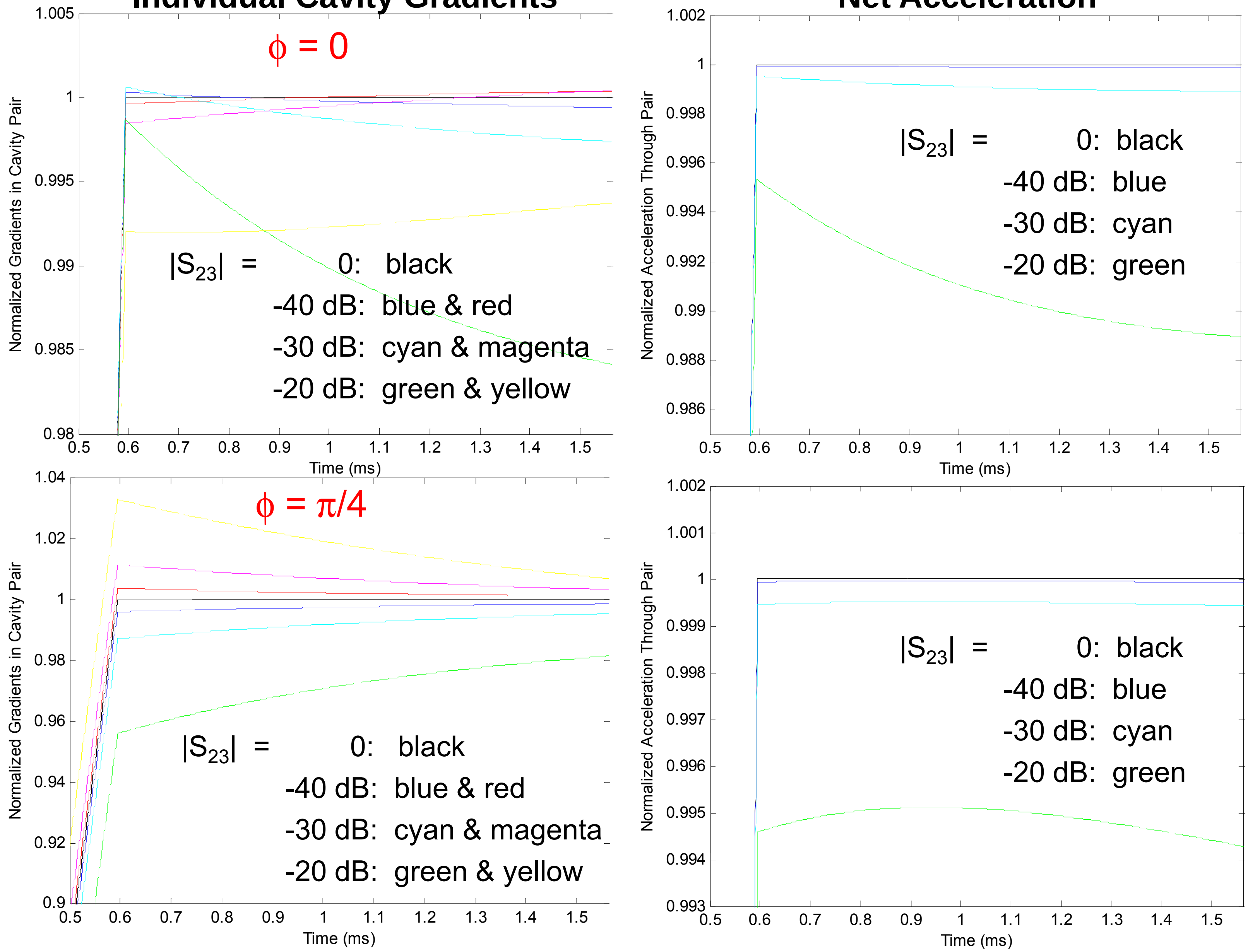
No Coupling (S_{23}=0):





Simulation of Cavity Pair Coupling Through Hybrid w/o Circulators

Individual Cavity Gradients | **Net Acceleration**



Typical measured isolation: -42—48 dB → gradient variation << 0.1%

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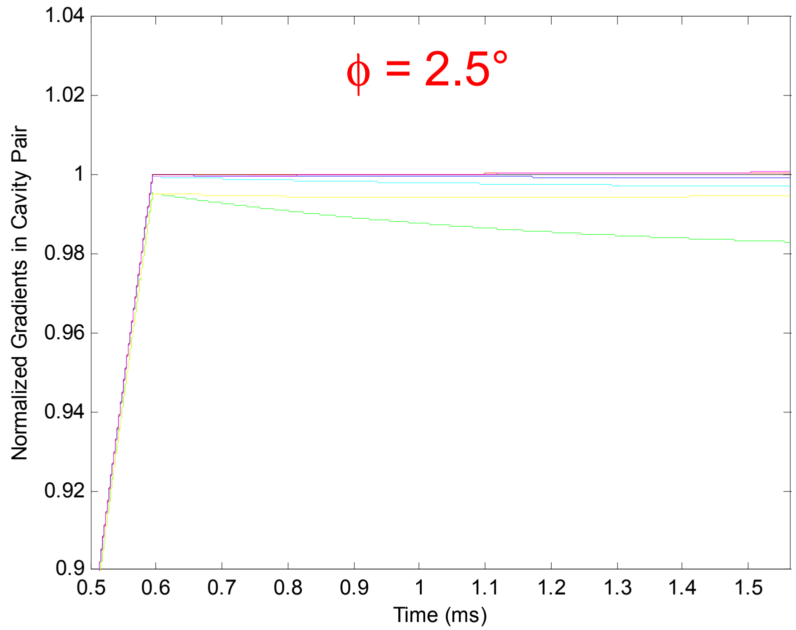
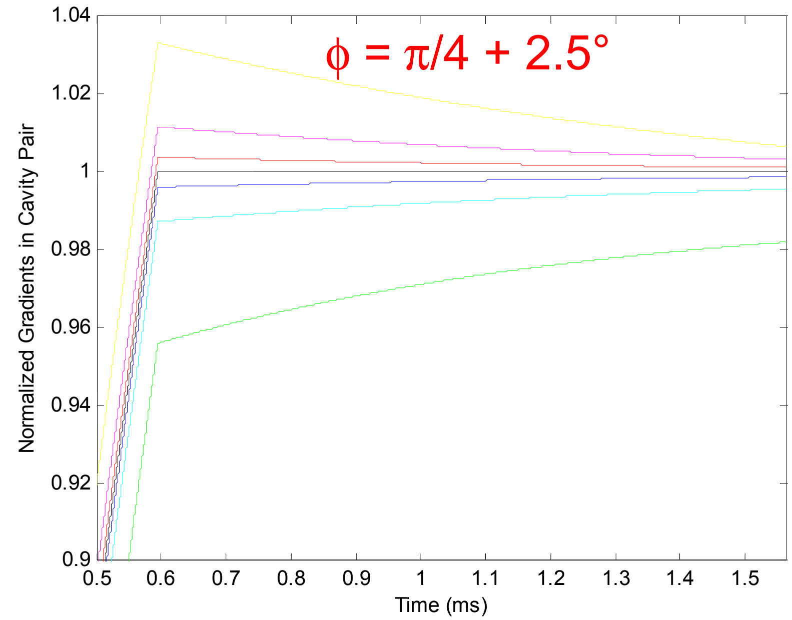
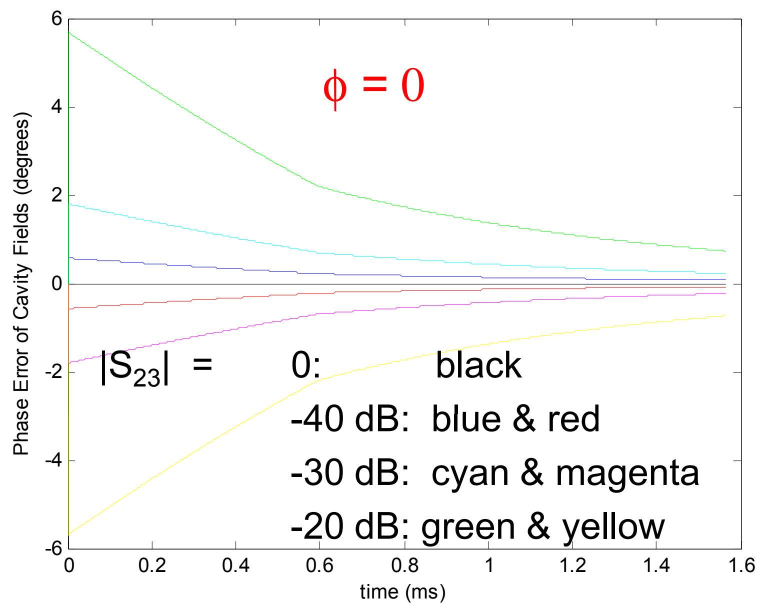




-40 dB, best phase (47.5°): Mean acceleration = 0.999949, Spread = 8.76×10^{-6}

-40 dB, worst phase (2.5°): Mean acceleration = 0.999911, Spread = 6.47×10^{-5}

Cavity Phase:

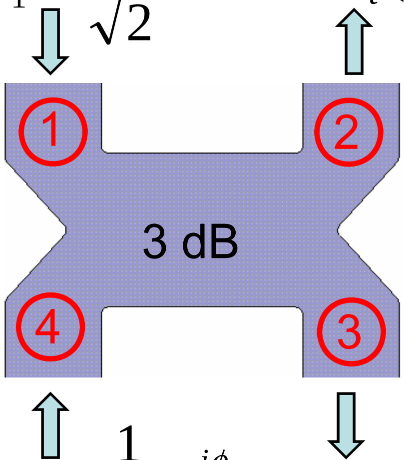


For $\phi = \pi/4$ and $3\pi/4$, the cavity field phases are flat, and for $\pi/2$, they're reversed.

Tailoring Power Distribution With Spacers and 3 dB Hybrids

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

equal amplitude inputs



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

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

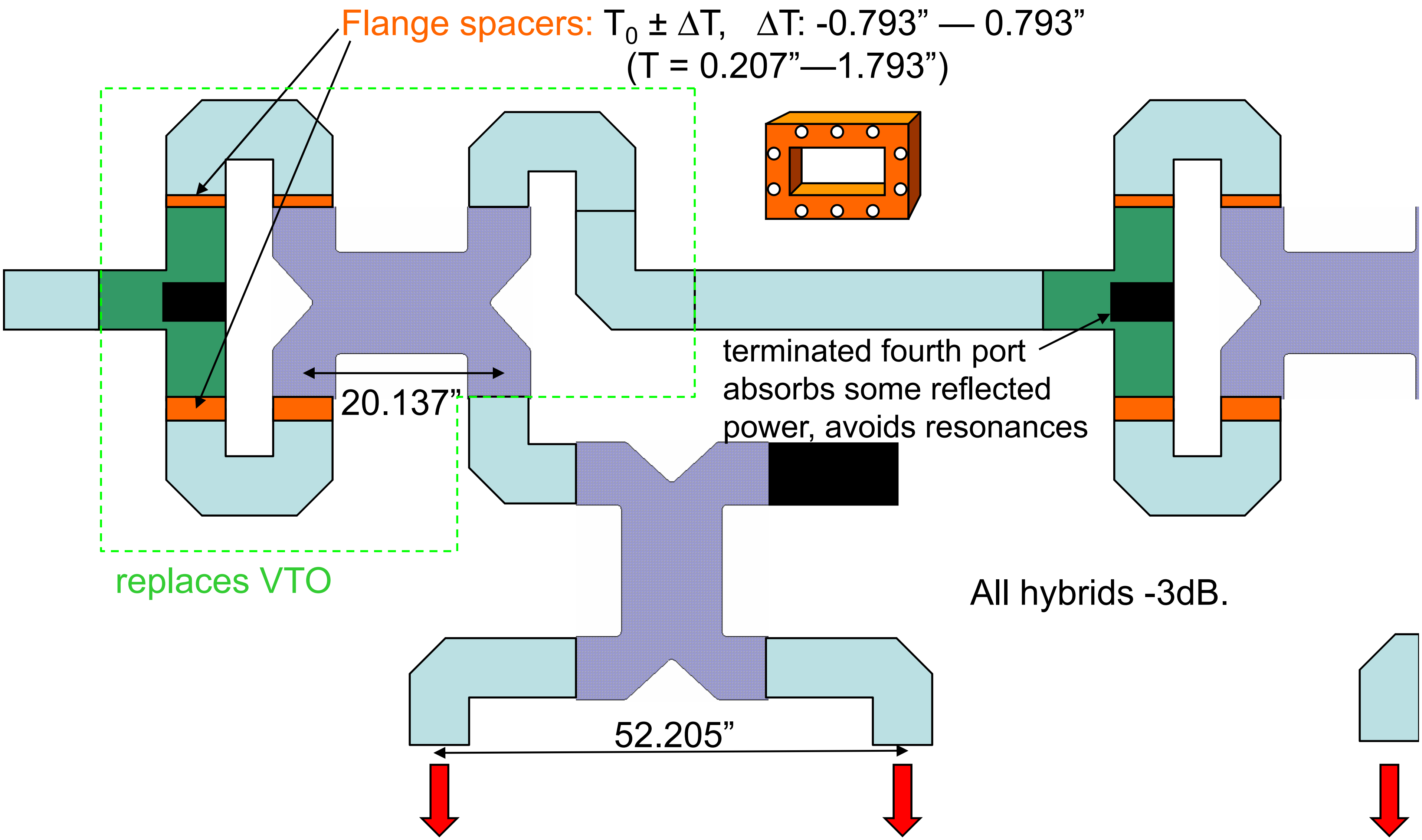
If ϕ_1 and ϕ_2 are changed in opposite senses by half the desired $\Delta\phi$, the coupled and through phases are unaffected as the amplitudes are adjusted.

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

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

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

Alternative to VTO



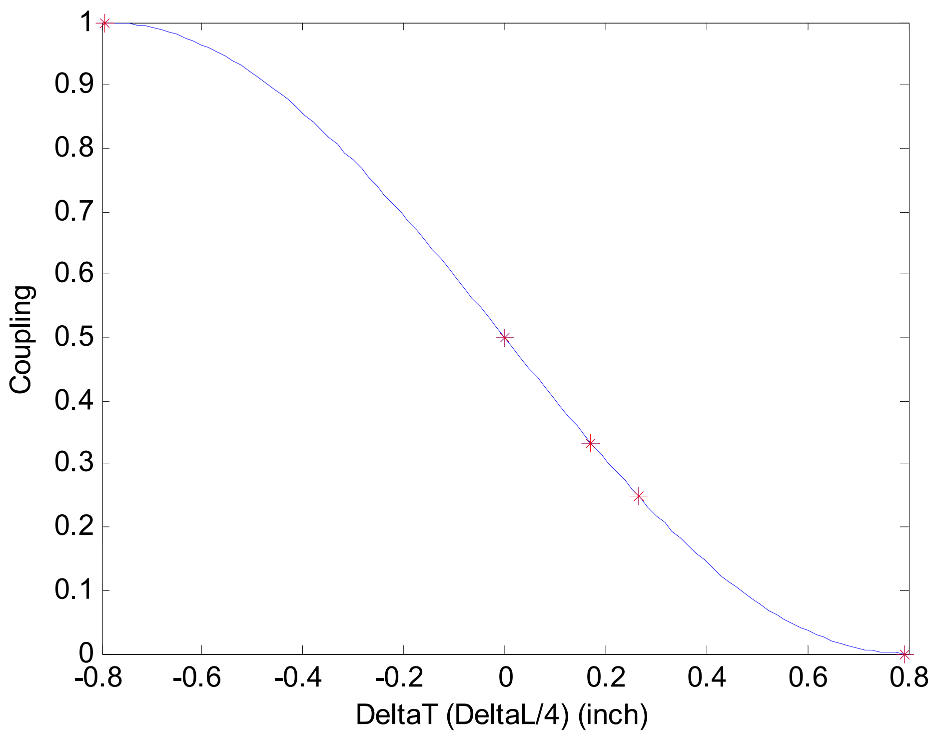
$$C = \left|\frac{E_e}{E_i}\right|^2 = \cos^2\left(\frac{\Delta\phi}{2} + \frac{\pi}{4}\right), \qquad T = \left|\frac{E_t}{E_i}\right|^2 = \cos^2\left(\frac{-\Delta\phi}{2} + \frac{\pi}{4}\right) = \sin^2\left(\frac{\Delta\phi}{2} + \frac{\pi}{4}\right)$$

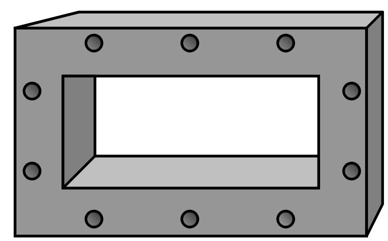
C	$\Delta\phi$	ΔL	$\Delta L/4$ (2 U-bends)
0	$\Delta\phi = \pi/2$	$\Delta L = 3.1712''$	± 0.7928”
1/4	$\Delta\phi = \pi/6$	$\Delta L = 1.0572''$	± 0.2643”
1/3	$\Delta\phi = 19.471^\circ$	$\Delta L = 0.6860''$	± 0.1715”
1/2	$\Delta\phi = 0$	$\Delta L = 0''$	± 0.000”
1	$\Delta\phi = -\pi/2$	$\Delta L = -3.1712''$	- ± 0.7928”

T = 1.000” ± $\Delta L/4$

Nominal Set (2 each)

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

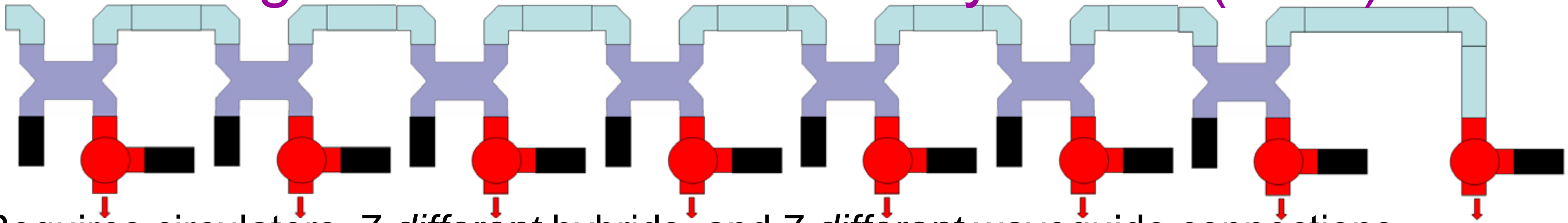




Adjust for system losses and for specific desired relative power levels.

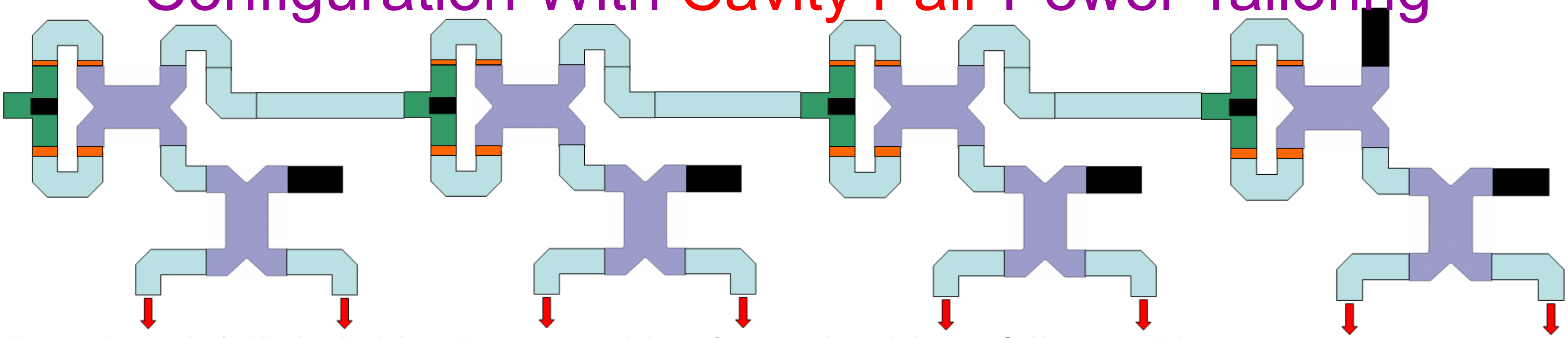
Insert between flanges and connect with single set of long bolts or threaded rods. (Extra gasket required if gaskets used)

Configuration With Fixed Cavity Power (BCD)



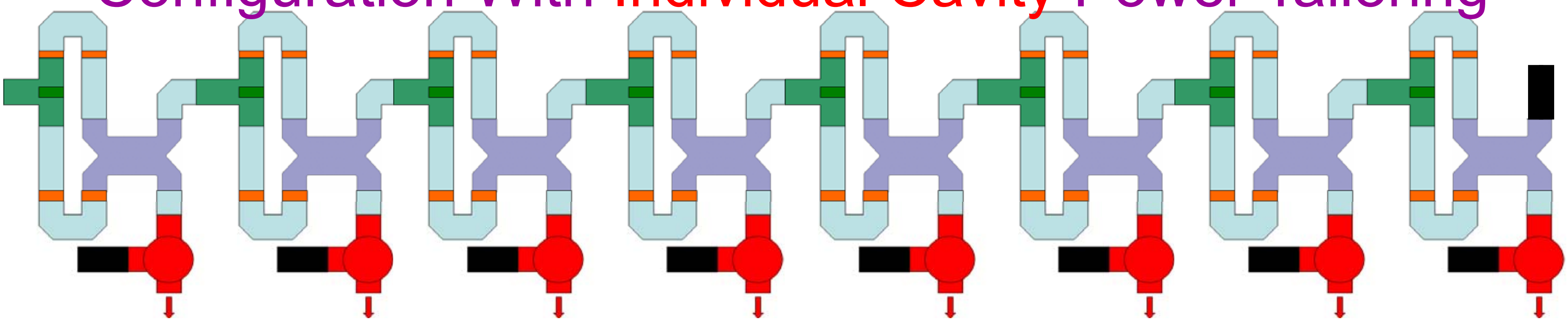
Requires circulators, 7 *different* hybrids, and 7 *different* waveguide connections.

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.

Conclusions & Plans

- We have all parts for the Fermilab NML RF distribution system (except for overdue dir. cplrs.). 2 of 4 modules are assembled and awaiting high-power testing. After testing, the modules will be shipped assembled to Fermilab for installation.

- Simulations suggest that with pairing of cavities to allow identical Q_L's, elimination of circulators should not pose a problem to field stabilization. This will be experimentally demonstrated when we run at NML in the circulatorless configuration.

- We are exploring other options to reduce the system cost, including eliminating phase shifters, simplifying the VTO fabrication or replacing the latter with alternate assemblies. A balance will have to be struck between system flexibility and cost (see Chris Adolphsen's talk later).