# On the RF system of the ILC

Sami G. Tantawi

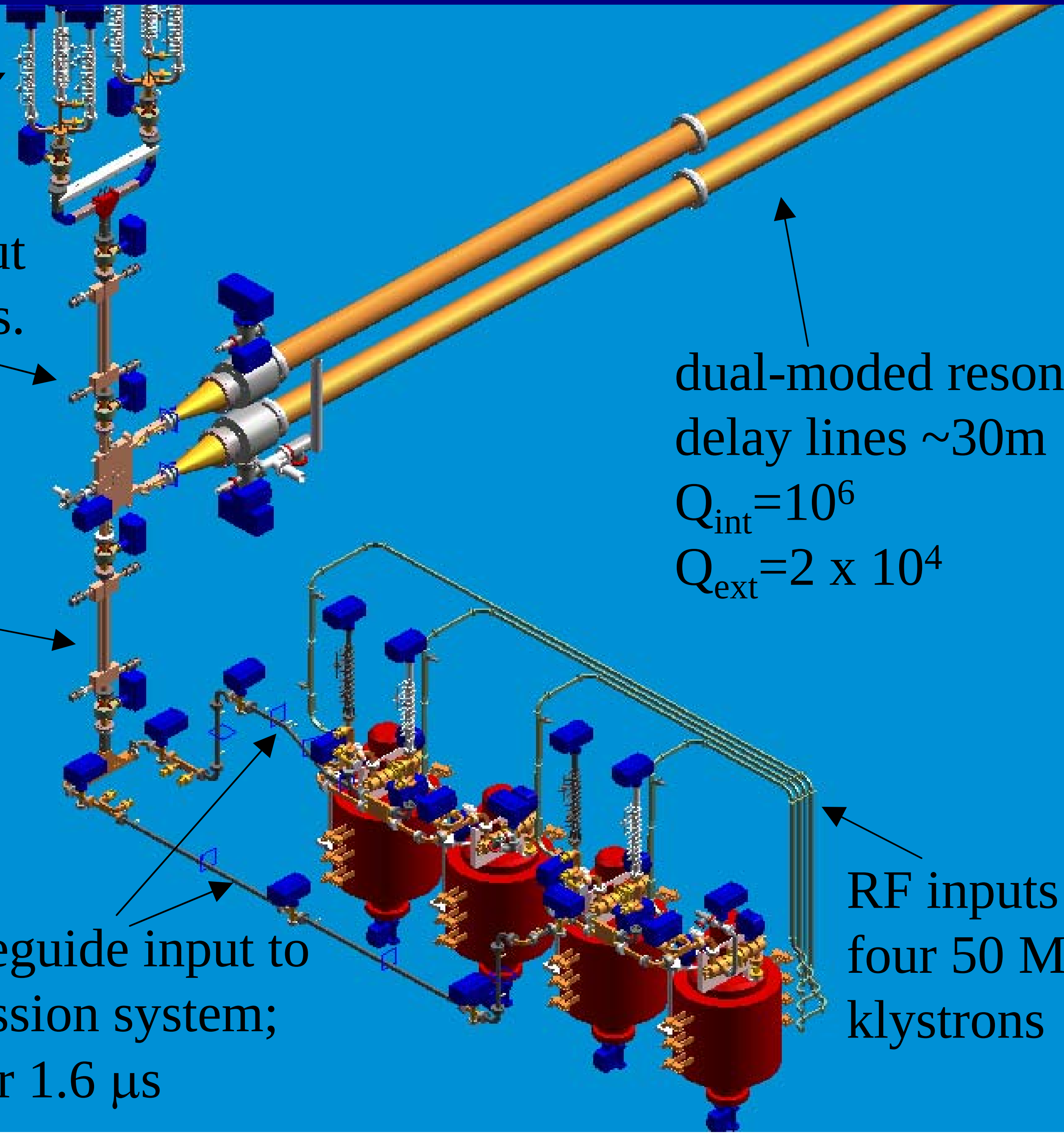
Chris Nantista
Valery Dolgashev
Jiquan Guo

SLAC

# Outline

- This talk is a collection of thoughts about the rf system based on our experience with X-band system!
- Review of the X-band RF systems
- The main linac division into separate system, A bad idea
- Examples from a system point:
  - The distribution system and relations to structure spacing
  - Rf source developments and relations to modulator and couplers
- Some thoughts on couplers

# Experimental RF Pulse Compression System



output load trees

compressed output
~600 MW, 400 ns.

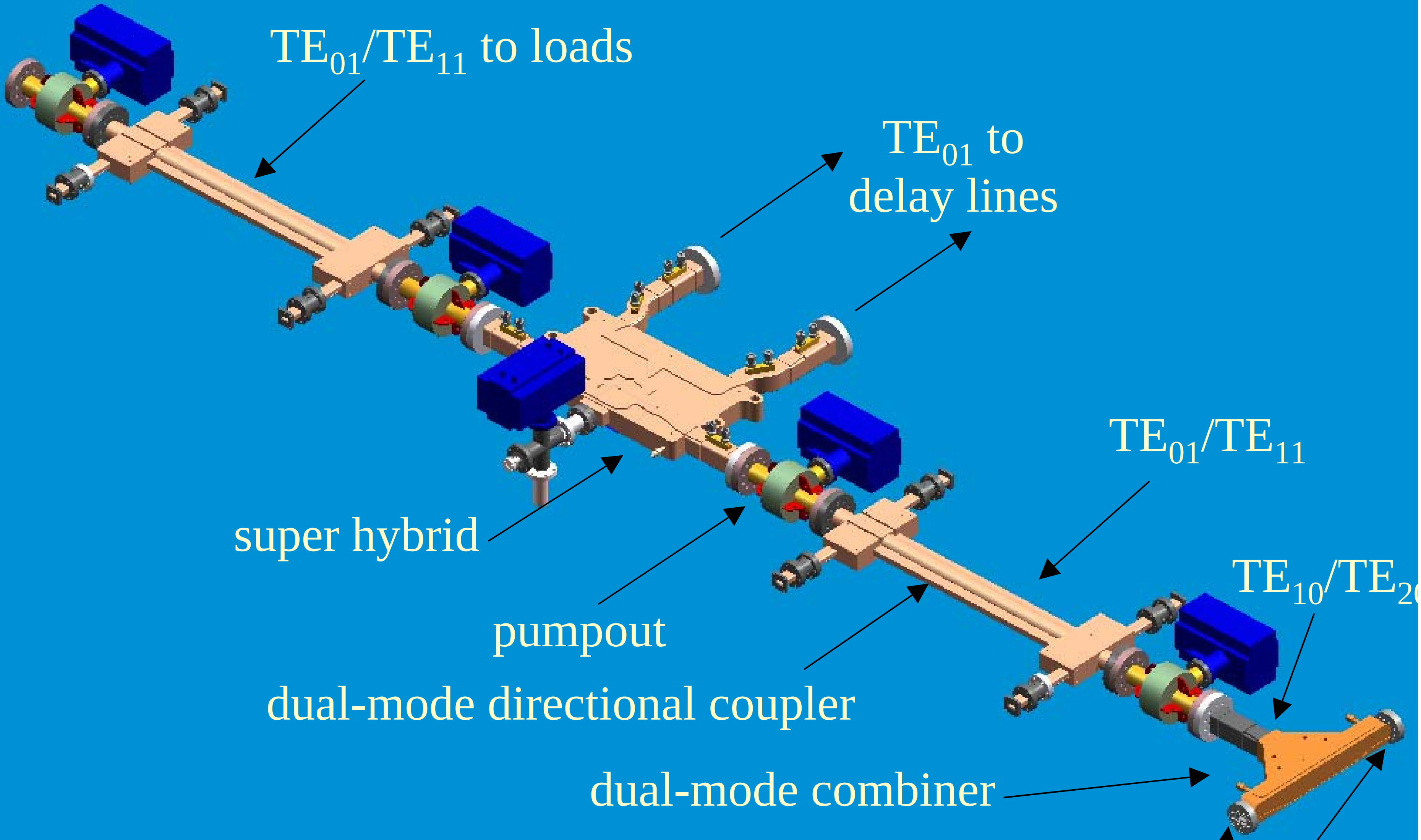
dual-mode
waveguide
carrying
~200 MW

dual-moded resonant
delay lines ~30m
$Q_{int}=10^6$
$Q_{ext}=2 \times 10^4$

single mode waveguide input to
the pulse compression system;
~100 MW/line for 1.6 μs

RF inputs to the
four 50 MW
klystrons

# The Heart of the Pulse Compression System



TE$_{01}$/TE$_{11}$ to loads

TE$_{01}$ to
delay lines

TE$_{01}$/TE$_{11}$

TE$_{10}$/TE$_{2}$

super hybrid

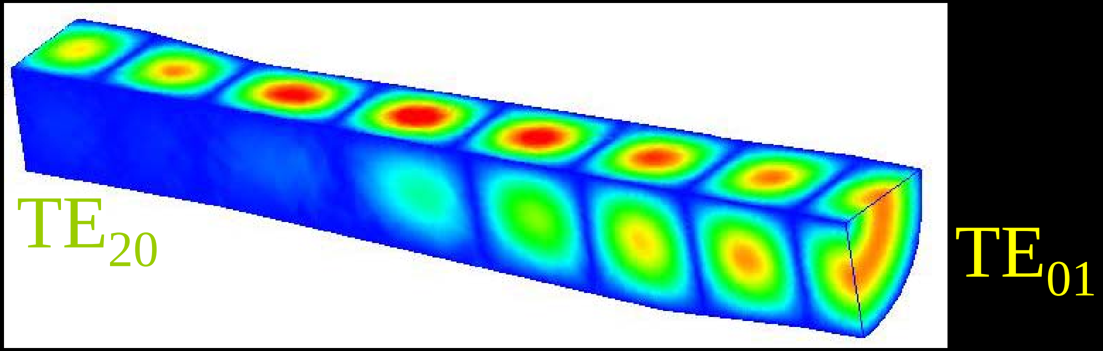
pumpout

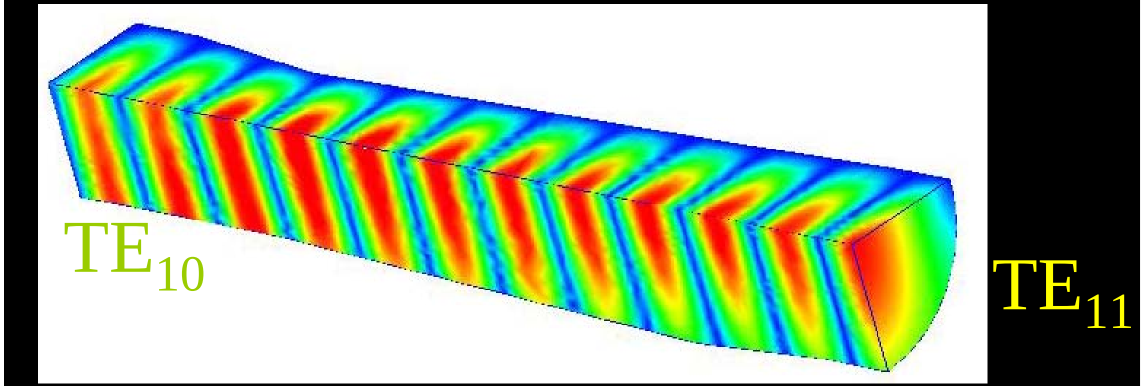
dual-mode directional coupler

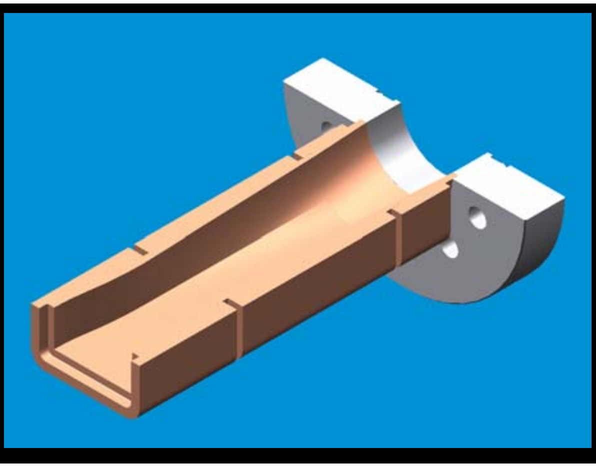
dual-mode combiner

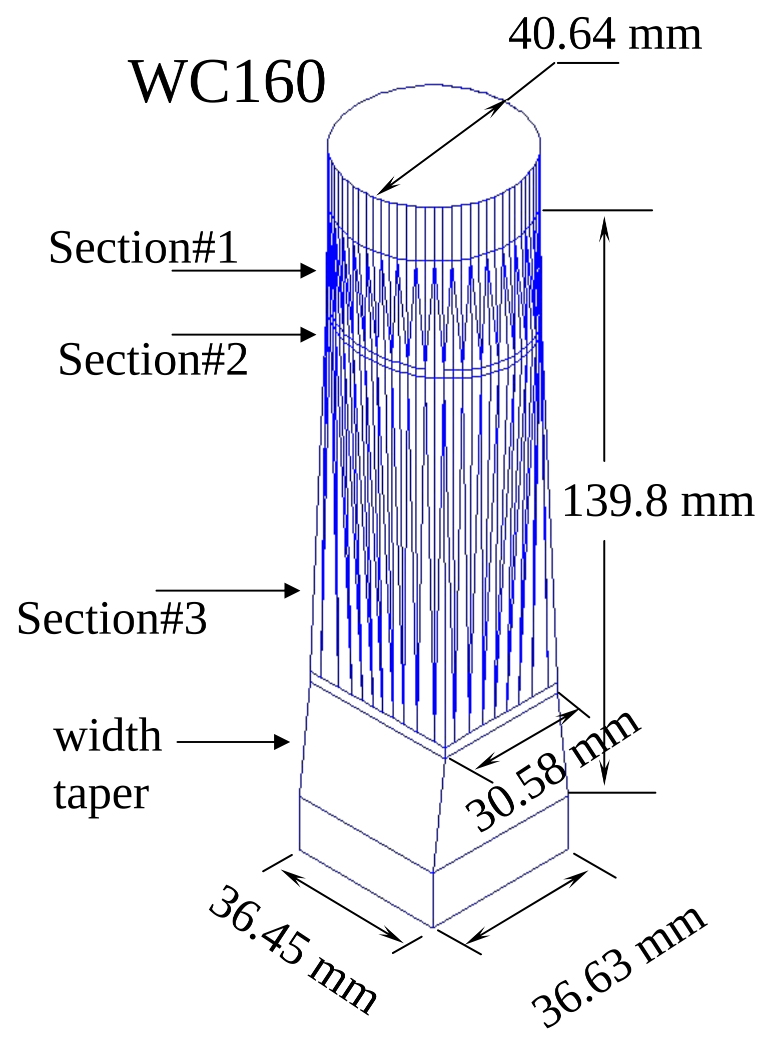
two fundamental mode inputs

# Dual-Mode Rectangular-to-Circular Taper Mode Converter

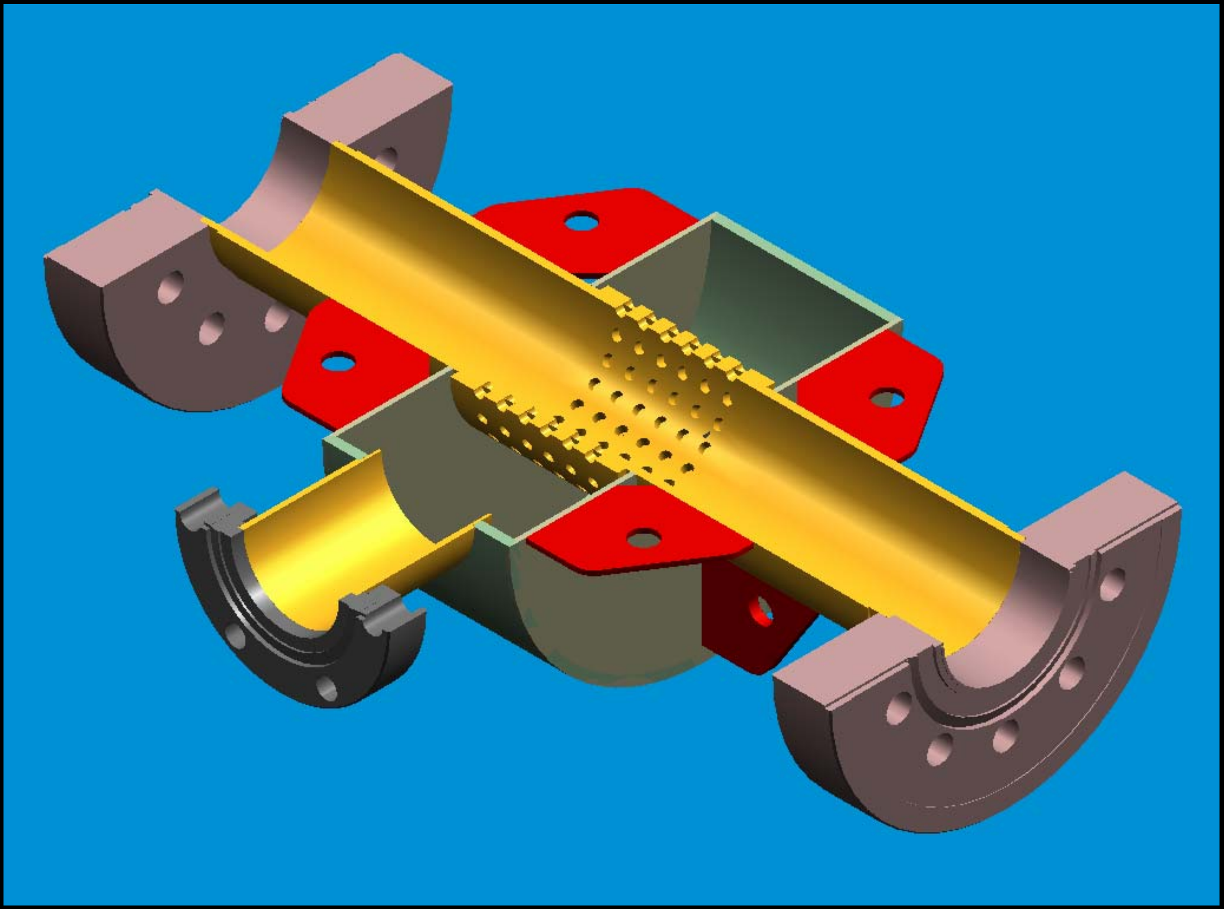






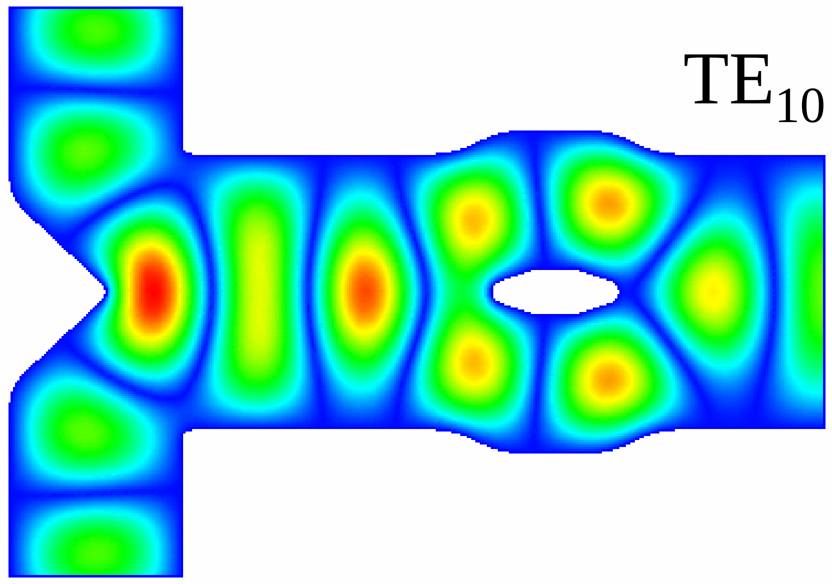


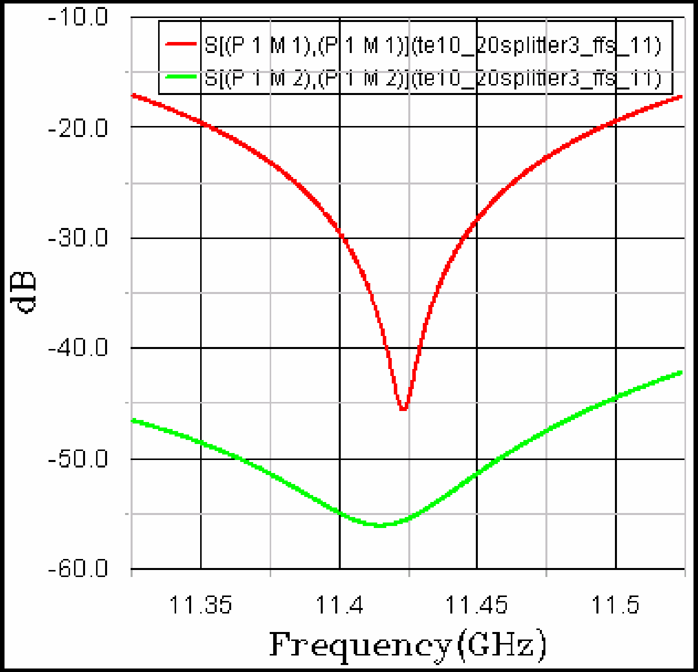
# Dual-Mode Vacuum Pumpout

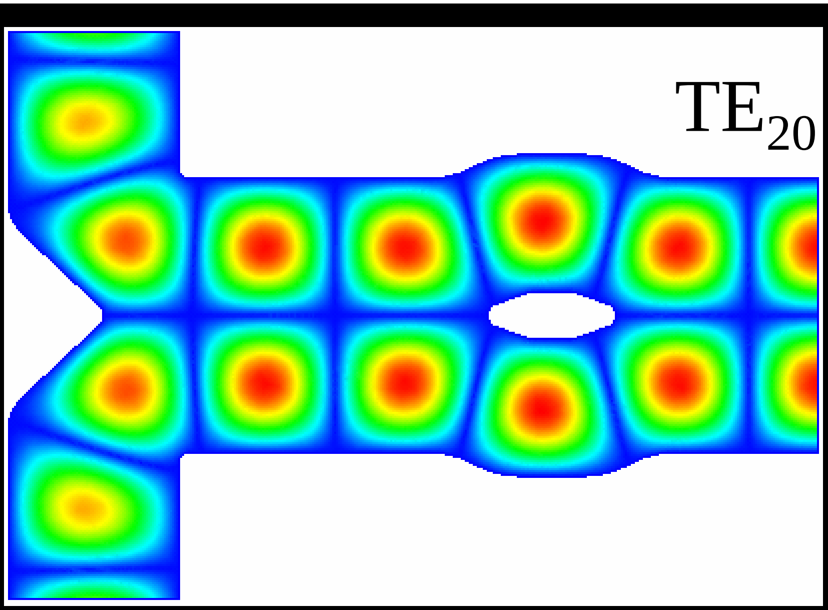


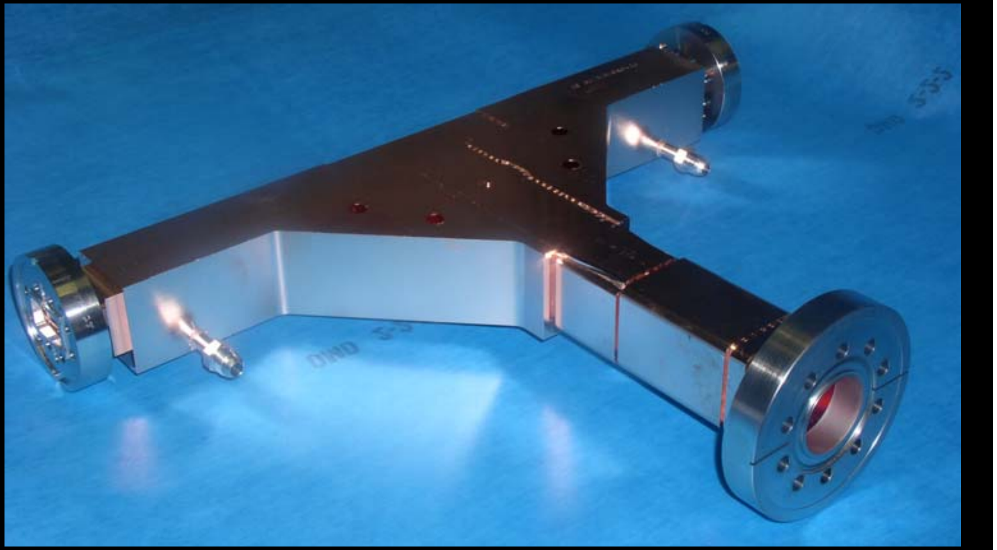
The hole pattern is designed to cancel any coupling or reflection for the $TE_{01}$ and $TE_{11}$ modes.

# Dual-Mode Combiner



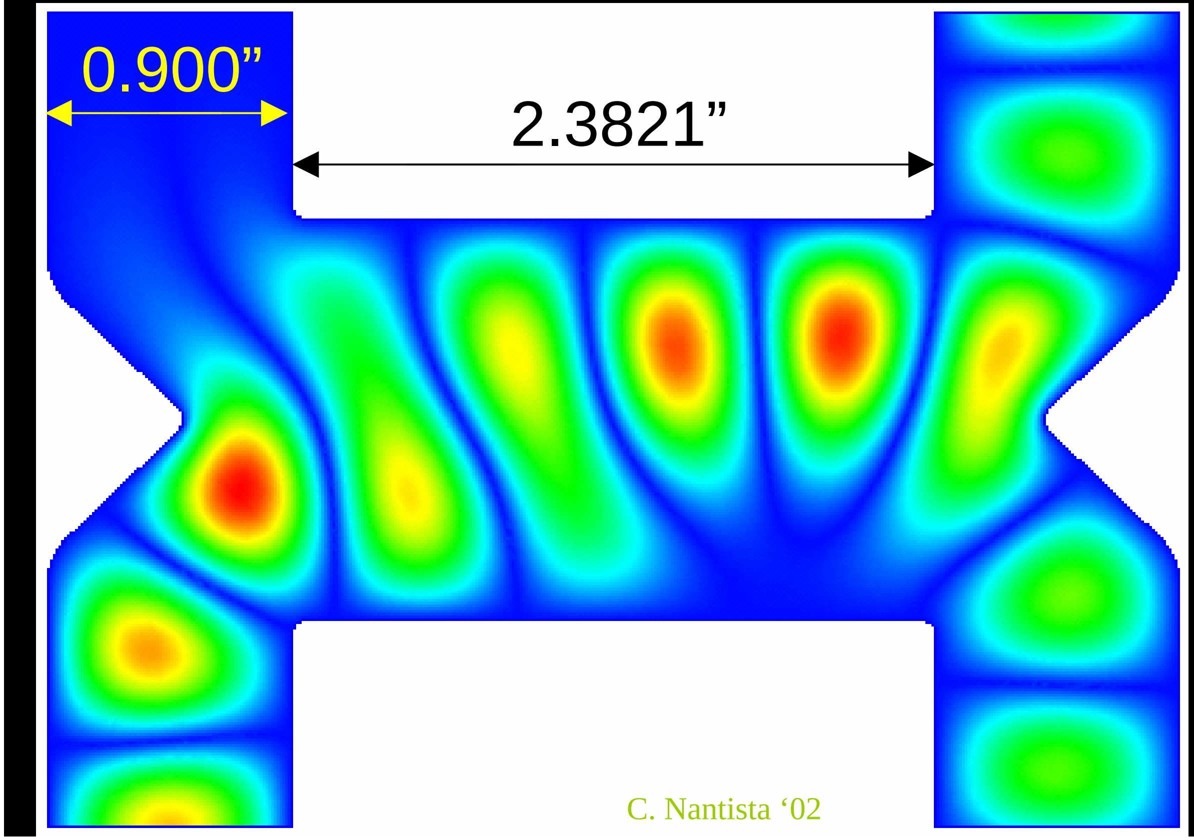




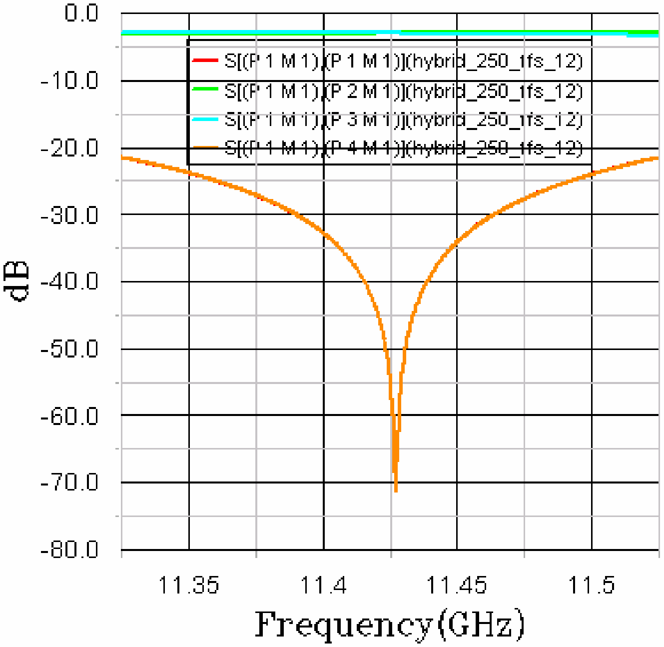


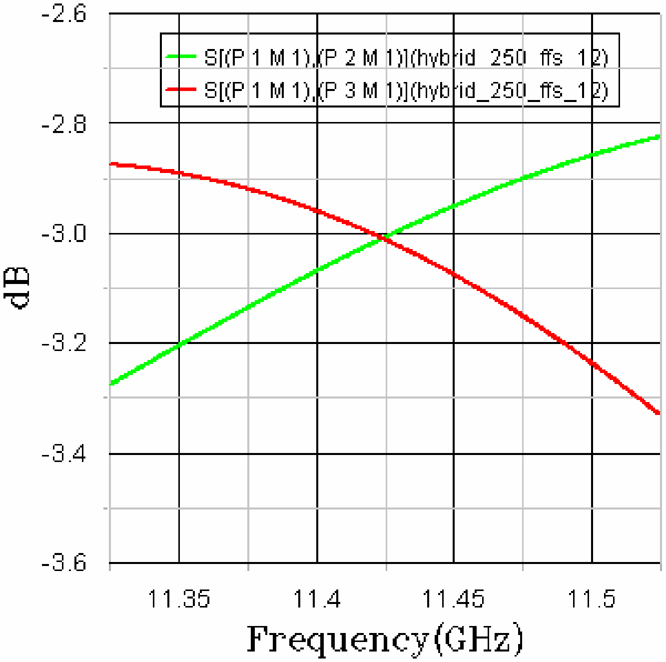
# Magic H Hybrid

| | (P 1 M 1) | (P 2 M 1) | (P 3 M 1) | (P 4 M 1) |
|---|---|---|---|---|
| (P 1 M 1) | 0.0028 | 0.7071 | 0.7071 | 0.0028 |
| (P 2 M 1) | 0.7071 | 0.0028 | 0.0028 | 0.7071 |
| (P 3 M 1) | 0.7071 | 0.0028 | 0.0028 | 0.7071 |
| (P 4 M 1) | 0.0028 | 0.7071 | 0.7071 | 0.0028 |

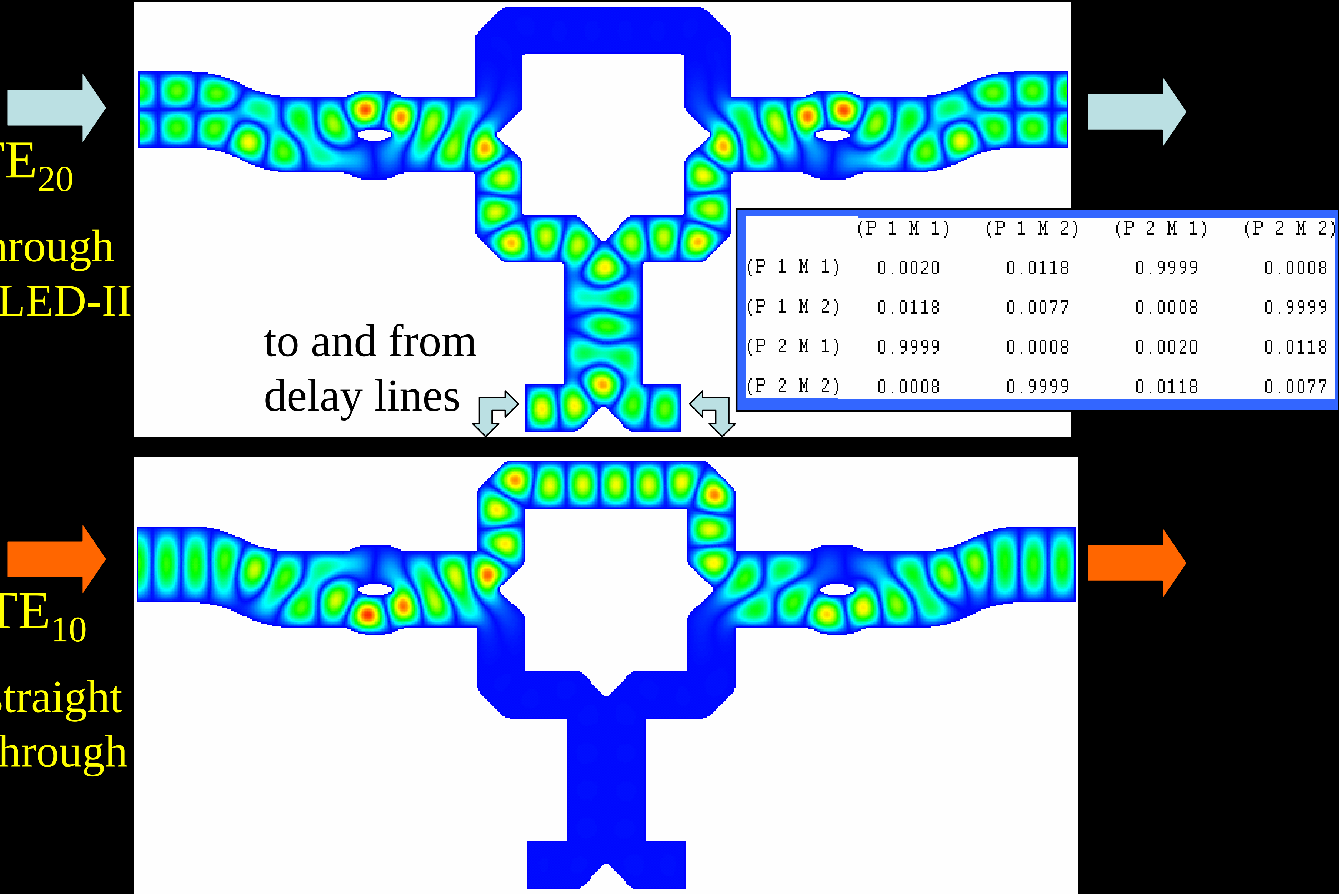


C. Nantista ‘02





# Head



TE$_{20}$

through

SLED-II

to and from

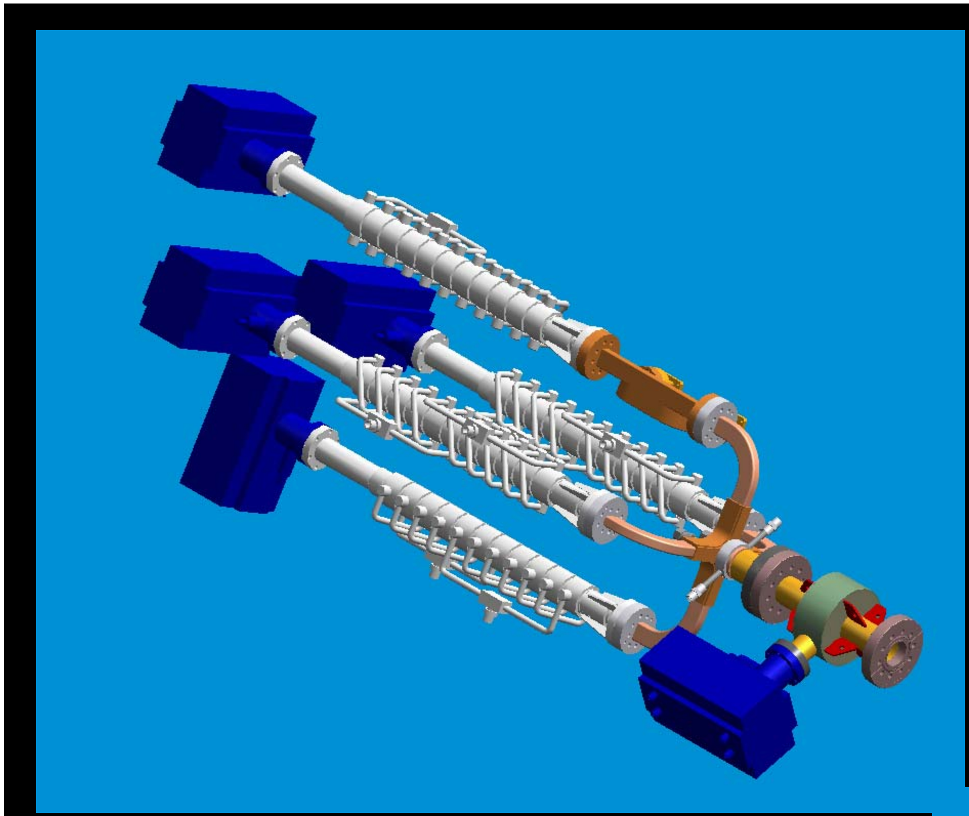
delay lines

|  | (P 1 M 1) | (P 1 M 2) | (P 2 M 1) | (P 2 M 2) |
|---|---|---|---|---|
| (P 1 M 1) | 0.0020 | 0.0118 | 0.9999 | 0.0008 |
| (P 1 M 2) | 0.0118 | 0.0077 | 0.0008 | 0.9999 |
| (P 2 M 1) | 0.9999 | 0.0008 | 0.0020 | 0.0118 |
| (P 2 M 2) | 0.0008 | 0.9999 | 0.0118 | 0.0077 |

TE$_{10}$

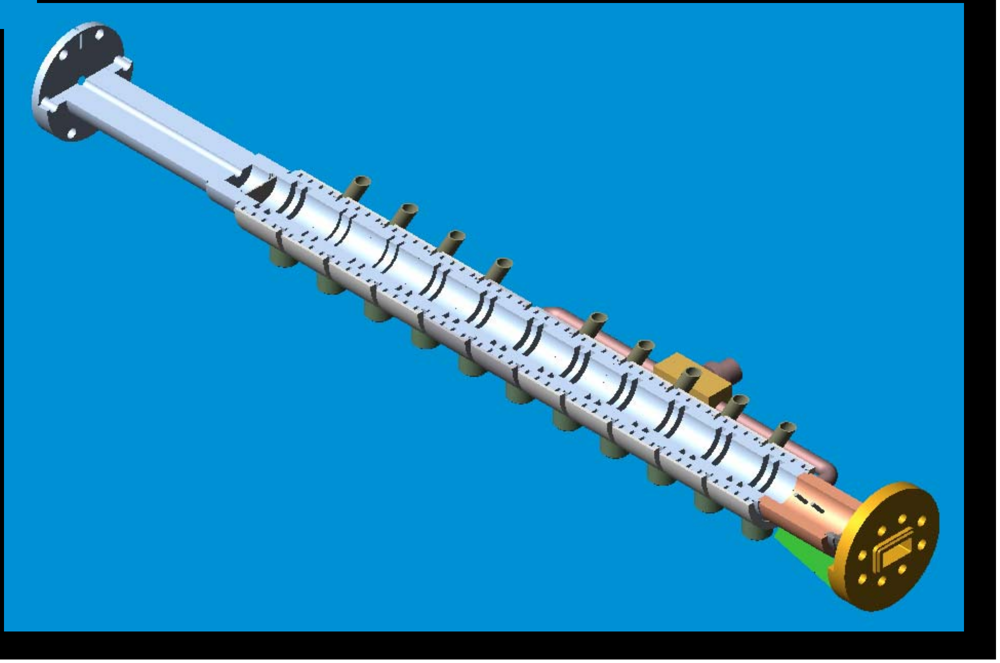
straight

through



# Load Tree

The input power, carried by the $TE_{01}$ mode, is split 4 ways to be absorbed at the loads



# High-Power Load

Magnetic stainless steel carrying circularly polarized $TE_{11}$ past matched pairs of partial choke grooves.

# Dual-Moded Delay Line

Dual-moding the delay lines cuts their required length approximately in half.

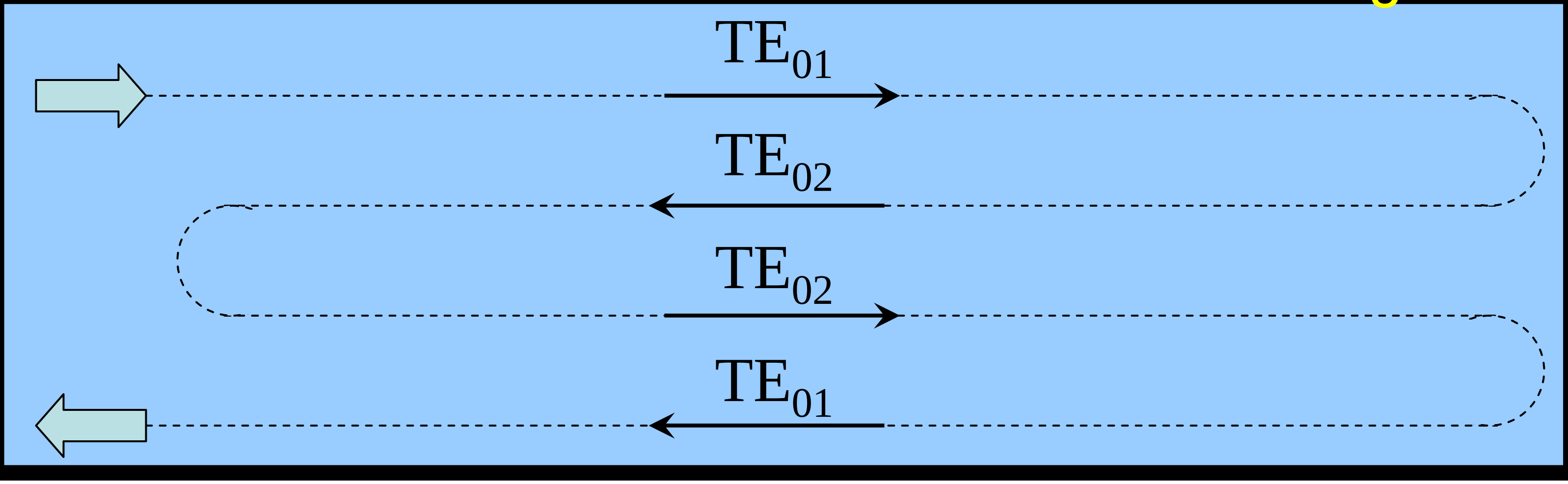
$$L = \frac{T}{2}\frac{v_{g1}v_{g2}}{}$$

input taper

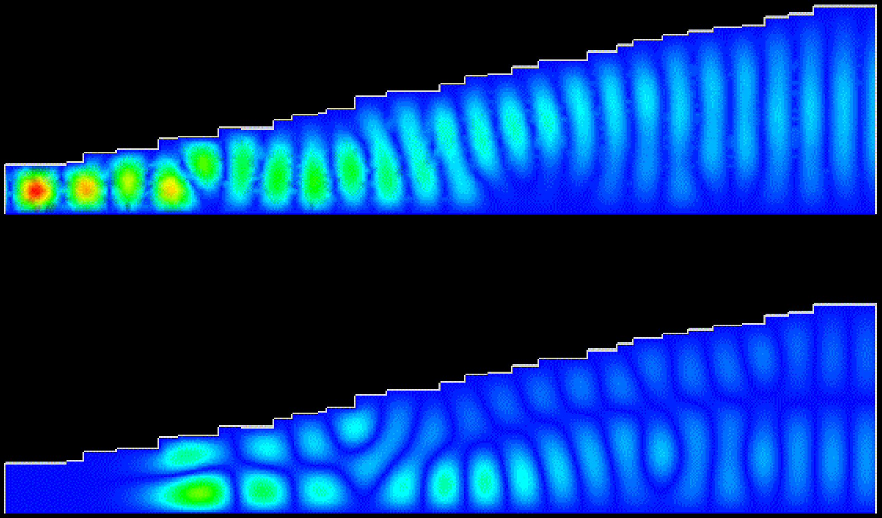
17.08 cm delay line ~29 m long

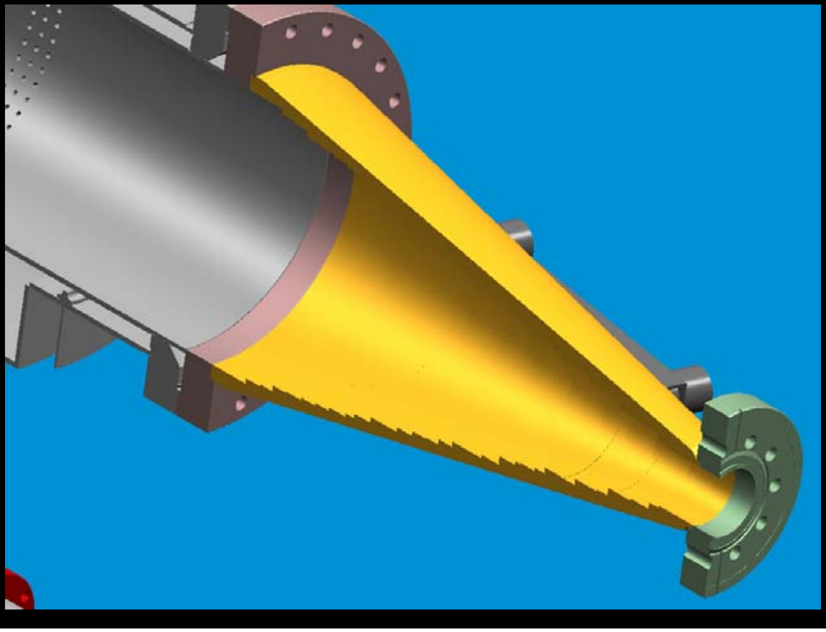
end taper

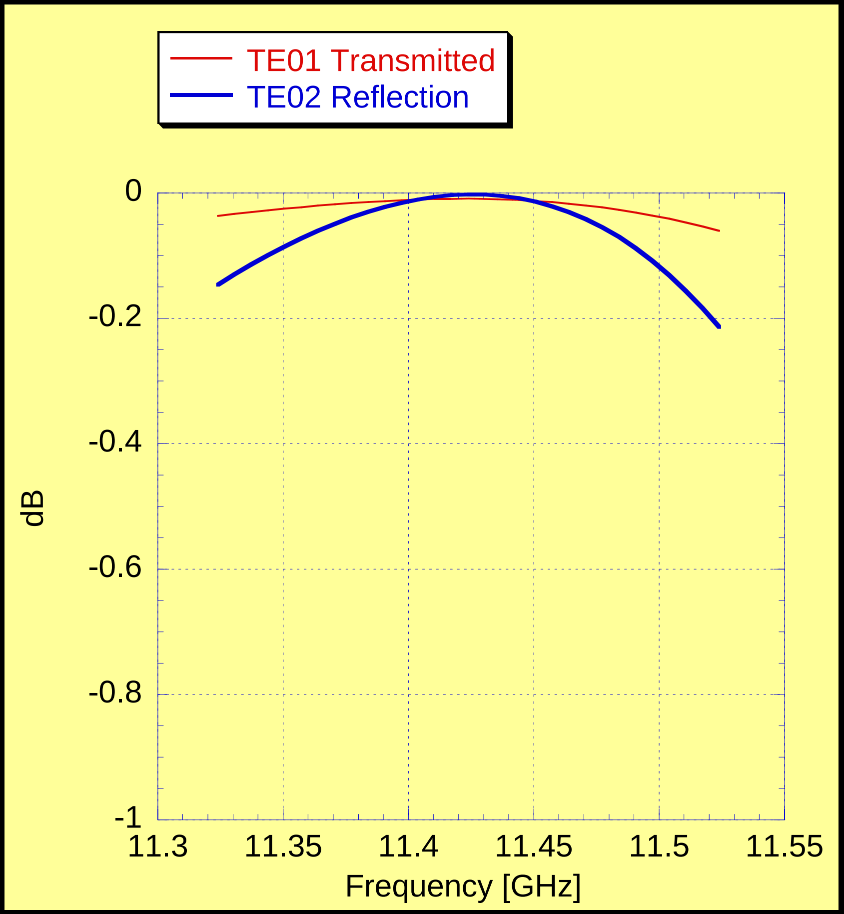
mode converter / tuning short



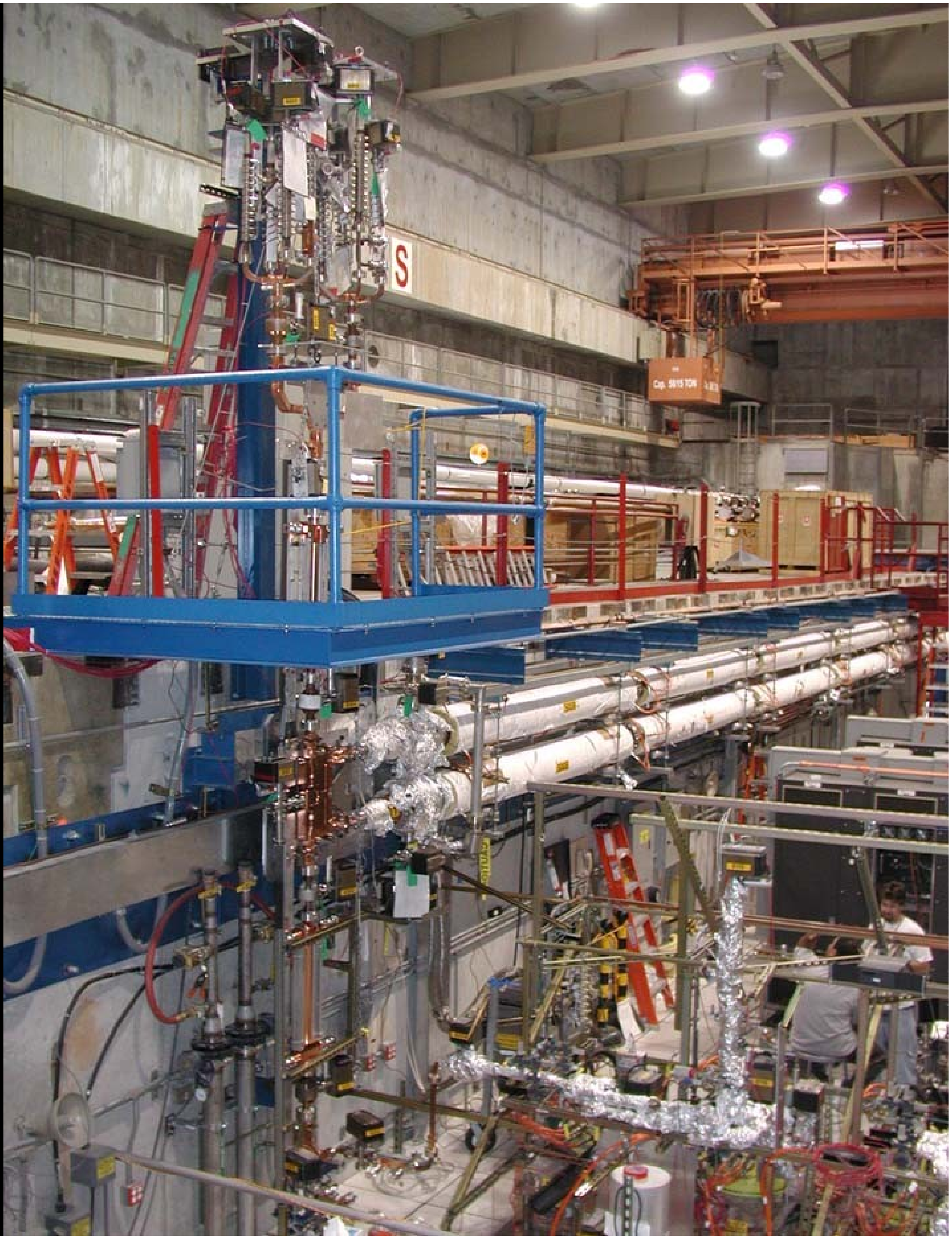
# Input Taper



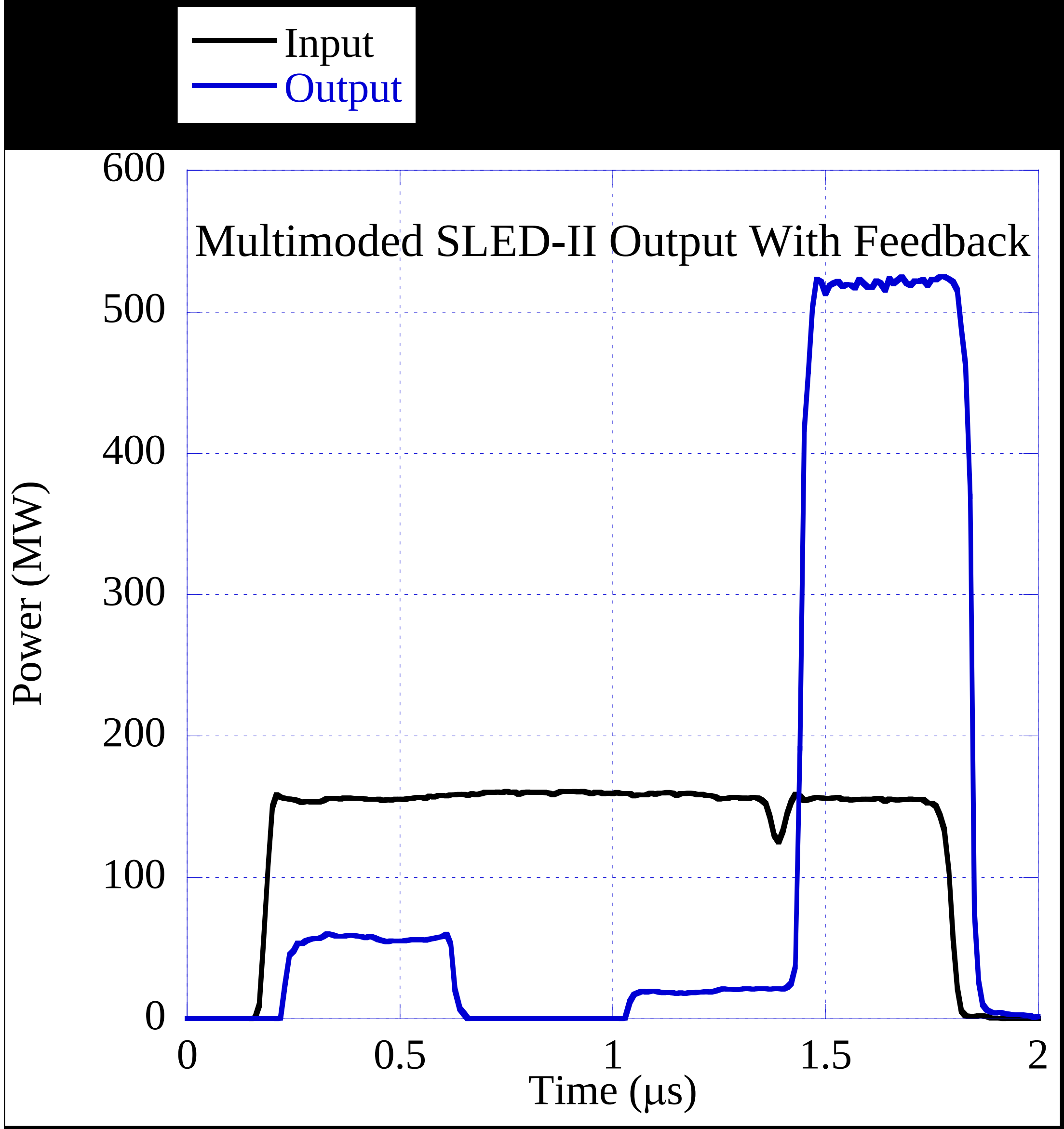


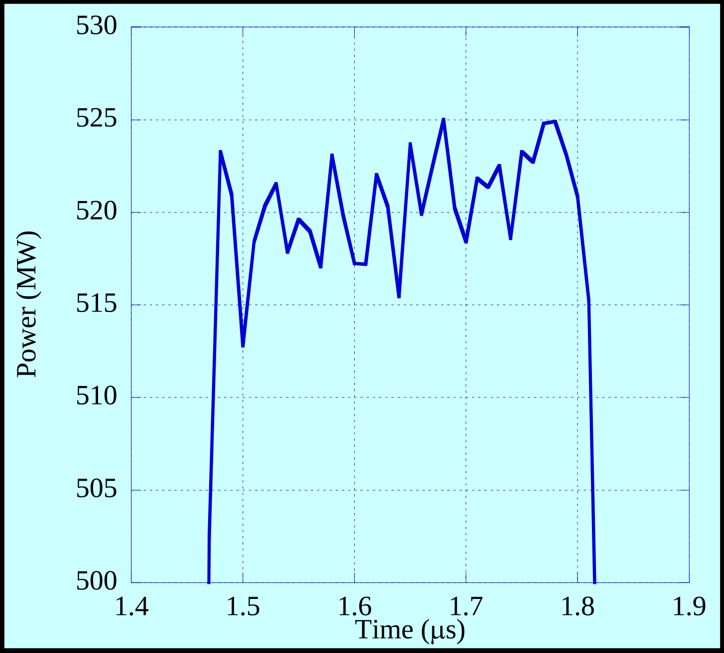

TE01 Transmitted
TE02 Reflection
0
-0.2
-0.4
-0.6
-0.8
-1
dB
11.3
11.35
11.4
11.45
11.5
11.55
Frequency [GHz]

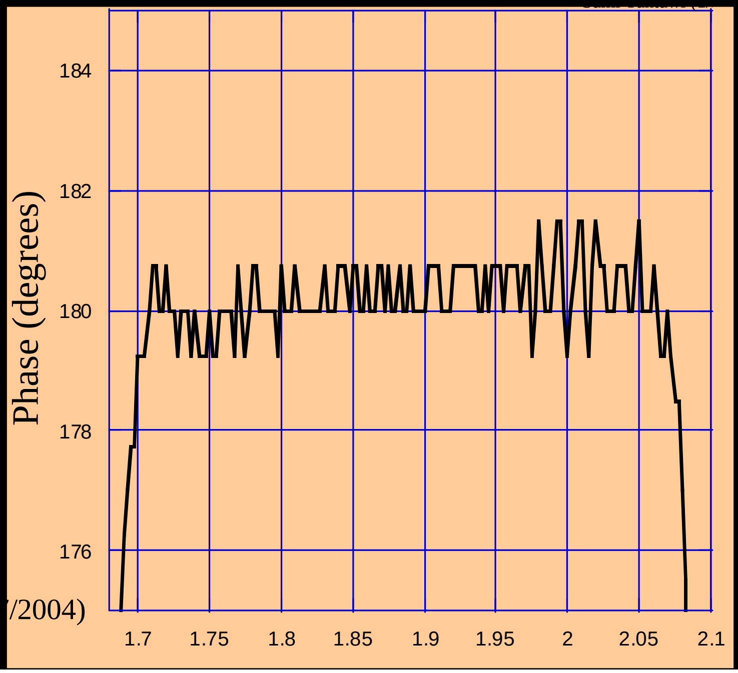
# System Layout



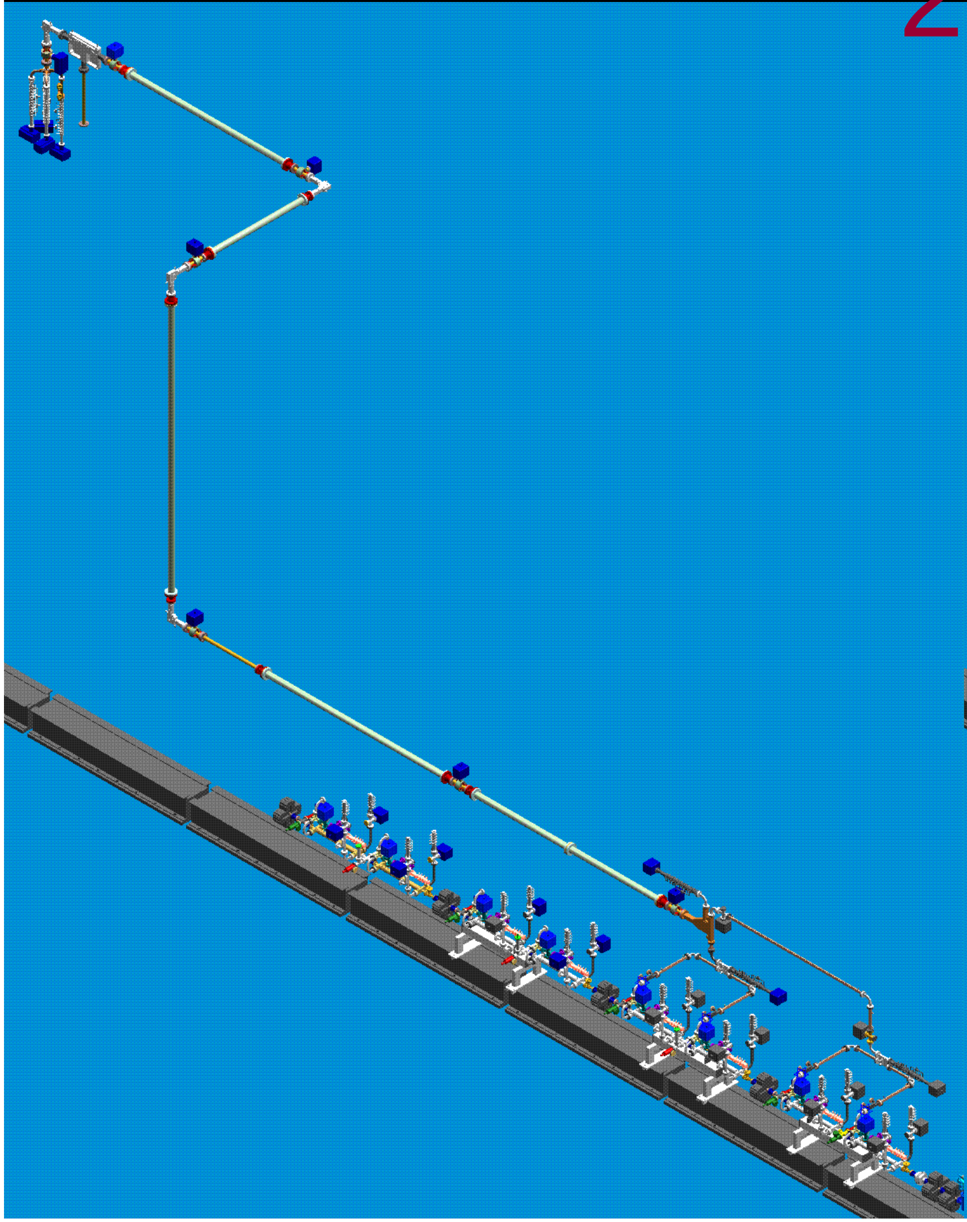
# Flattened Pulse

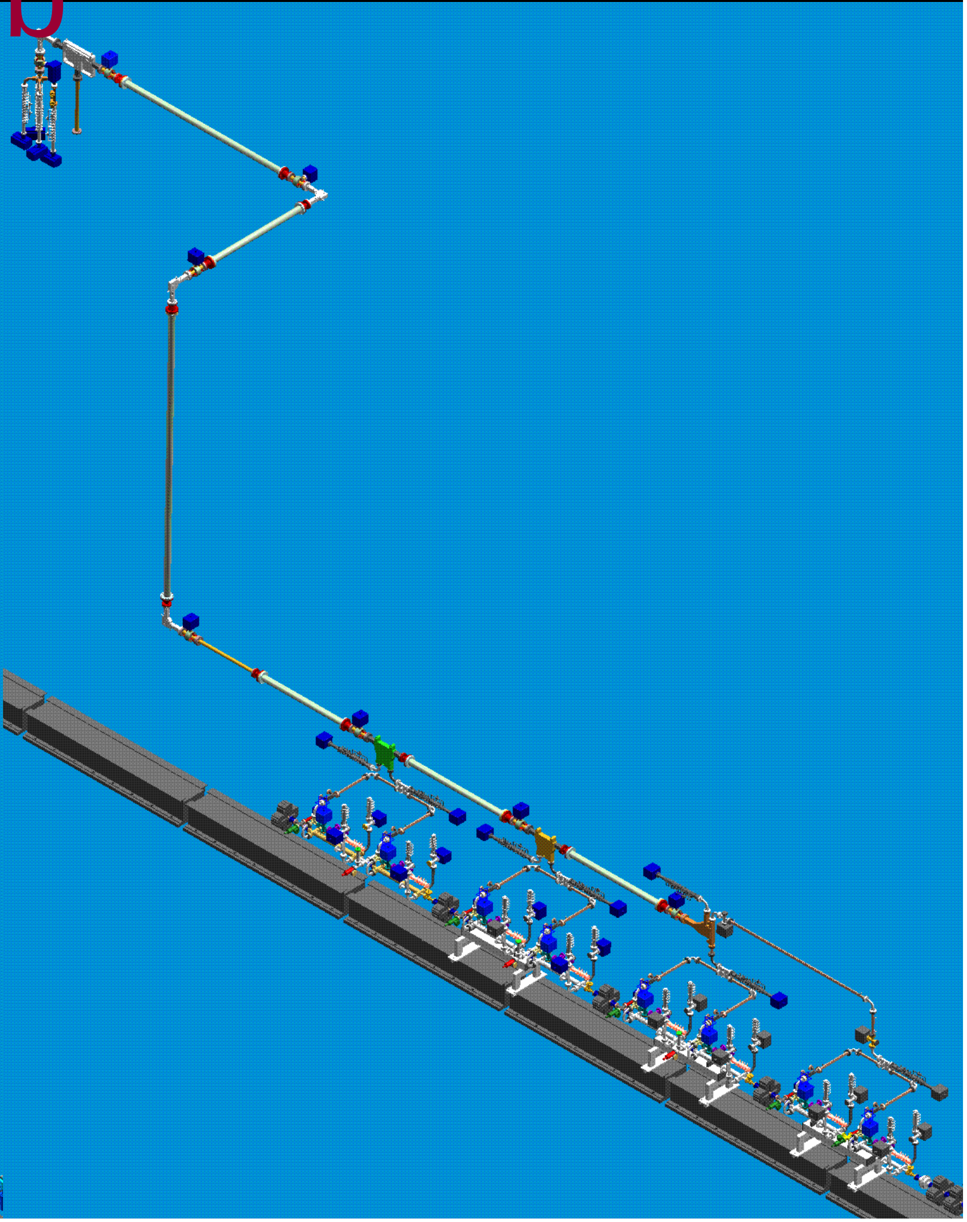




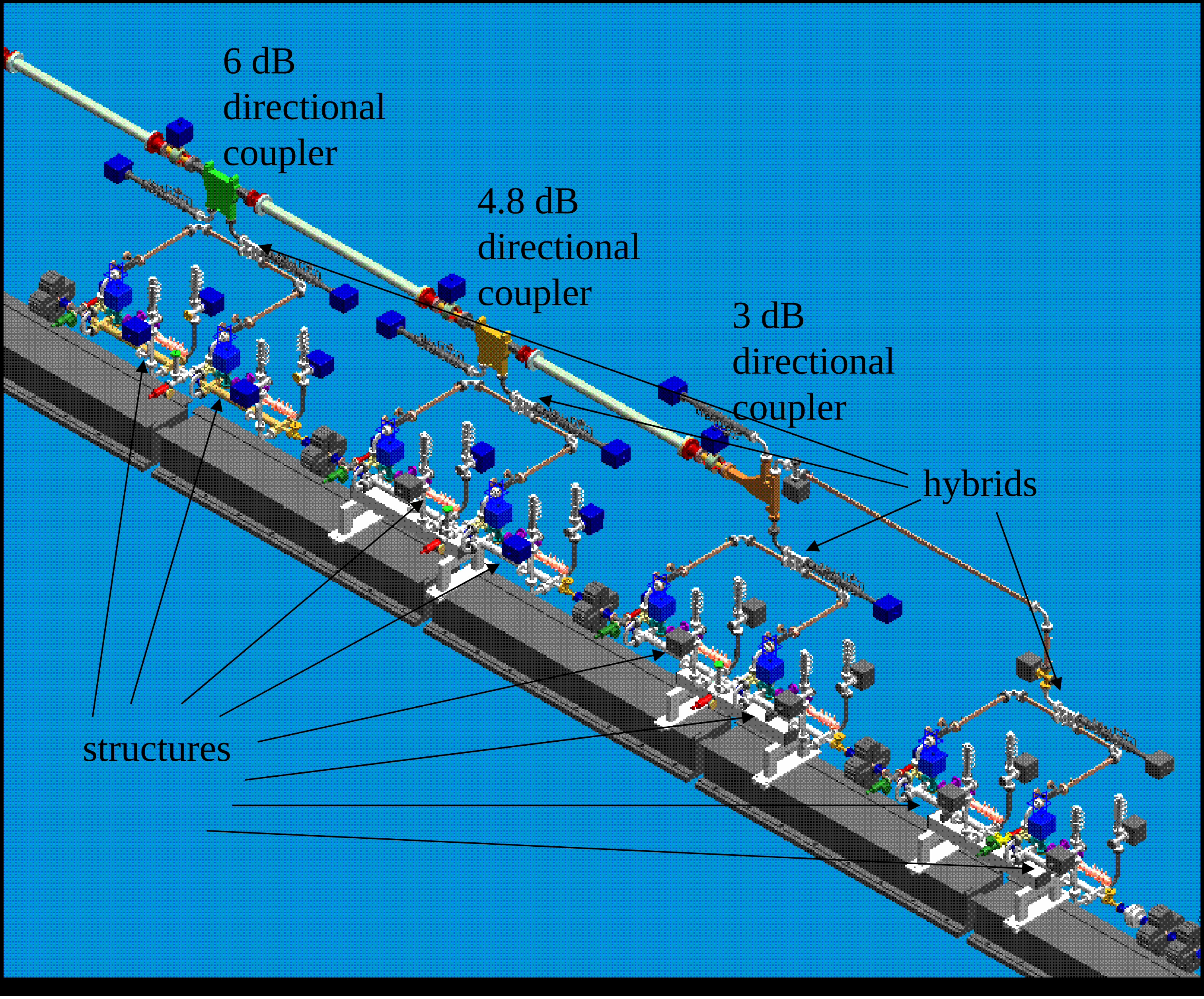


# 8-Pack Phase 2a 8-Pack Phase 2b





# Power Distribution



6 dB directional coupler

4.8 dB directional coupler

3 dB directional coupler

hybrids

structures

# Highlights from the X-Band System

- We have reliably produced and manipulated flat 400 ns rf pulses carrying over 500 MW.
- We have developed waveguide components capable of manipulating hundreds of megawatts.
- We have utilized dual-moding, both for power direction and for shortening delay lines.
- The circular $TE_{01}$ mode is a *miracle* mode solves all problems
- The charging and discharging of the delay lines could be improved with active elements
- We could not relay on circulators, *they do not exist at these power levels.*

# TESLA TDR RF DISTRIBUTION

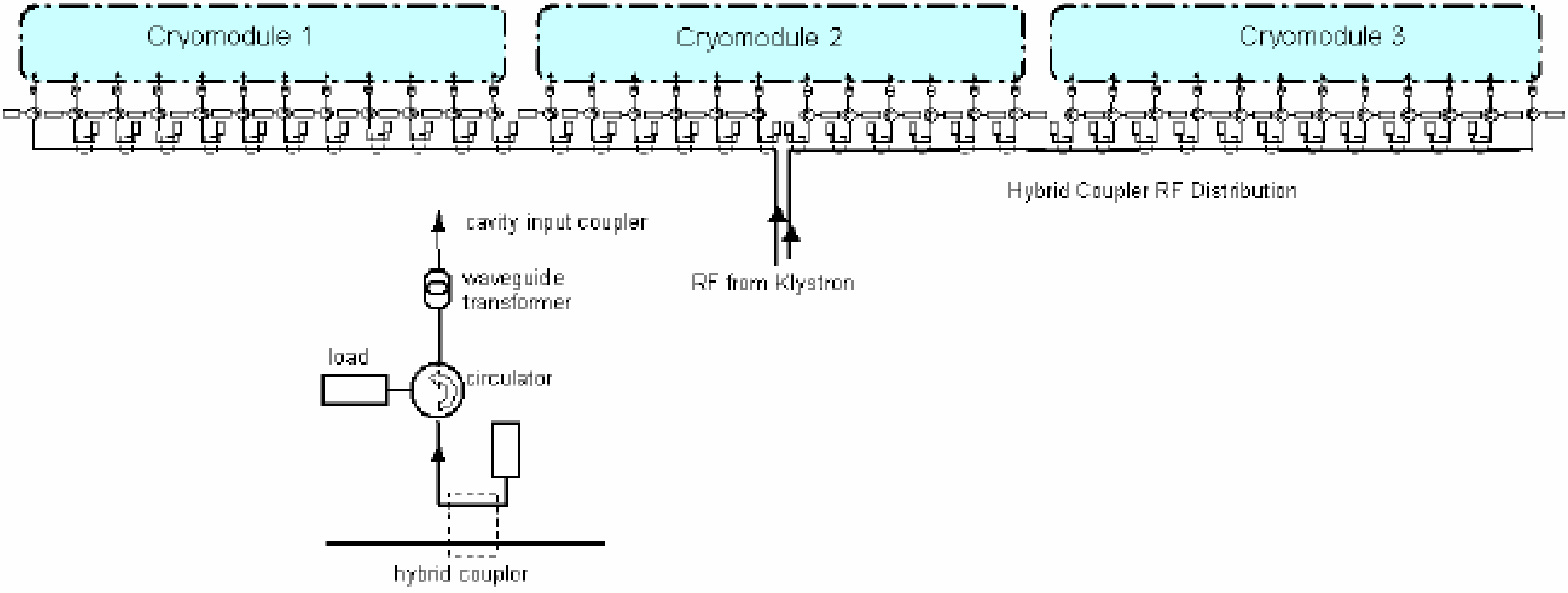


Figure 3.3.5: *RF waveguide distribution of one RF station.*

## TESLA Design:

17 different directional couplers

Less waveguide. More compact.

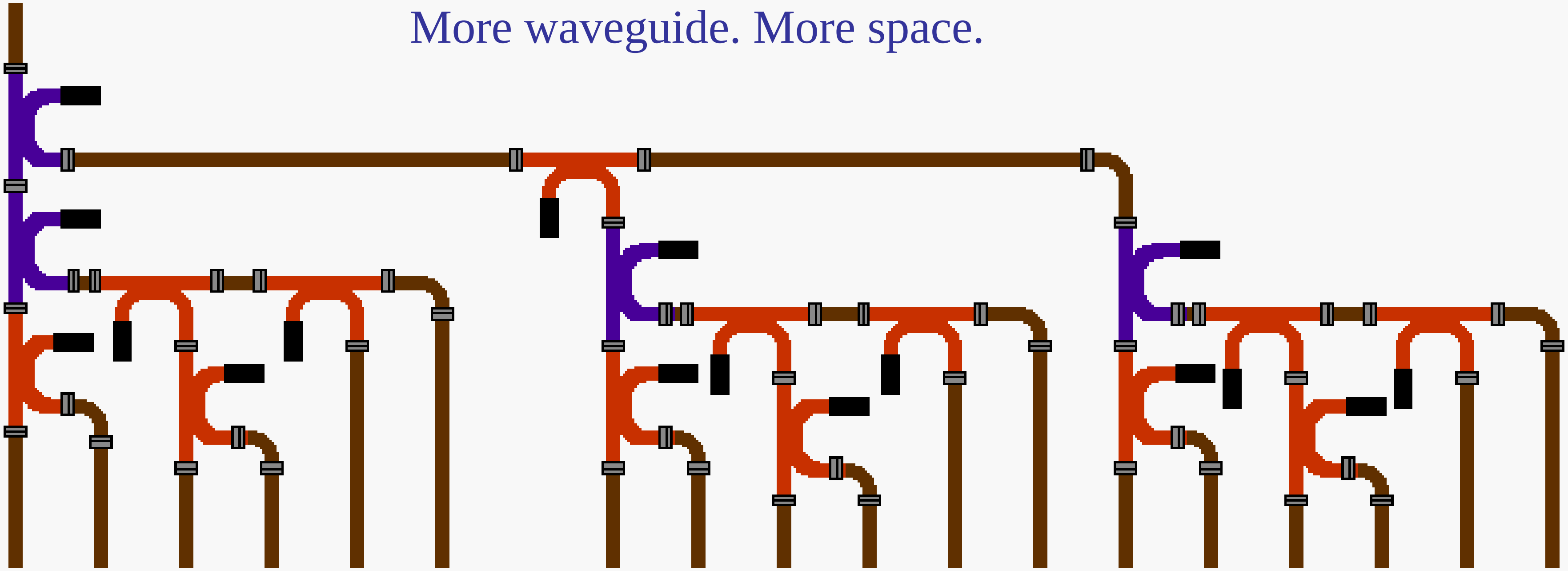
Fitting may be difficult where klystron feeds meet.

## Alternate Scheme:

Only 2 different dir. couplers (-1.76 dB and -3.01 dB)

Same path lengths as above.

Power traverses on avg. 4.33 rather than 9.44 dir. couplers
(fewer flanges and coupling regions → less loss)



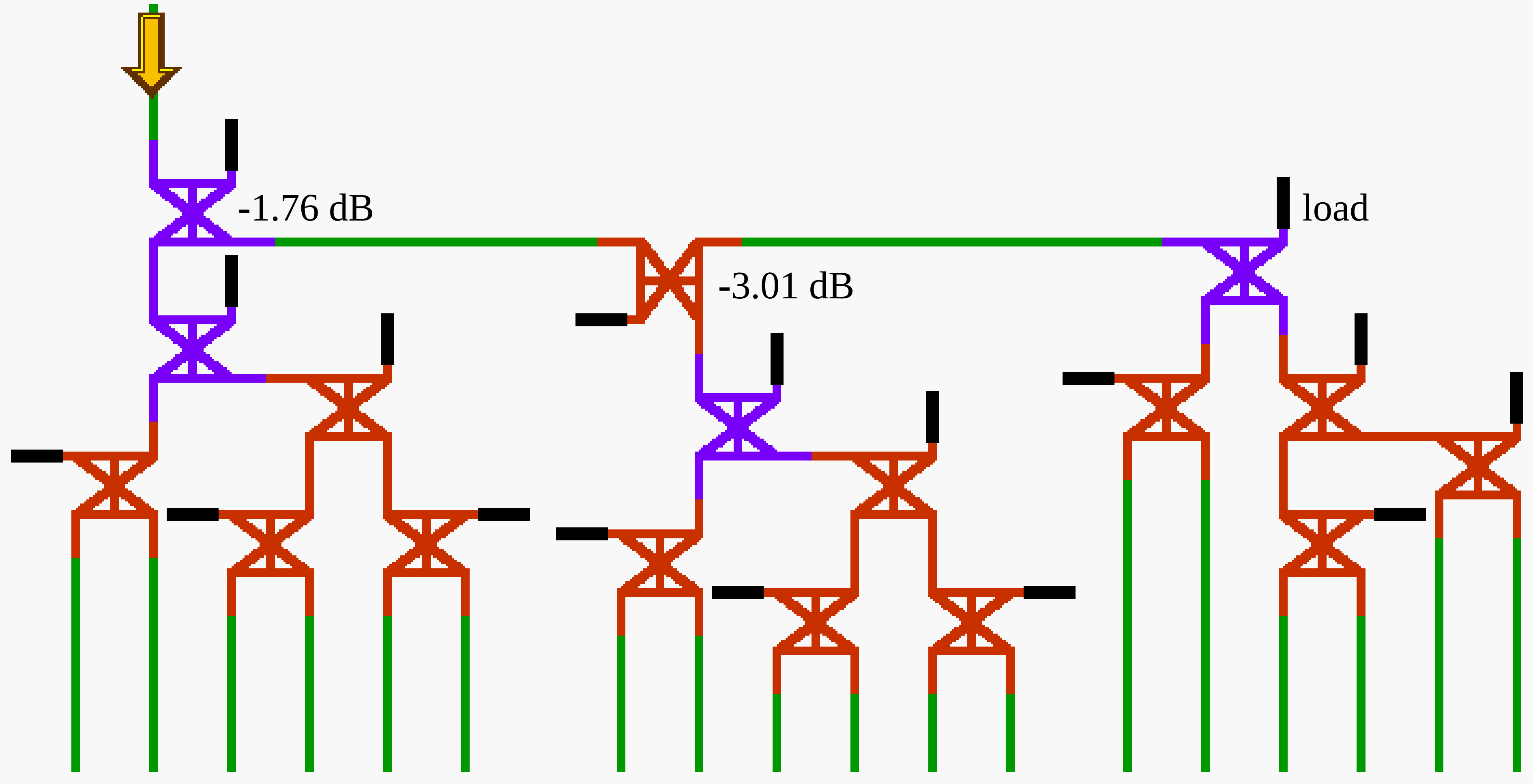
More waveguide. More space.

# BRANCHING DISTRIBUTION

With the proper choice of directional coupler port orientations and spacing (same for all), all 90° bends can be eliminated.

This configuration requires no more pieces of waveguide than the TESLA scheme.

Circulators could be eliminated by cancellation of reflections from each pair.

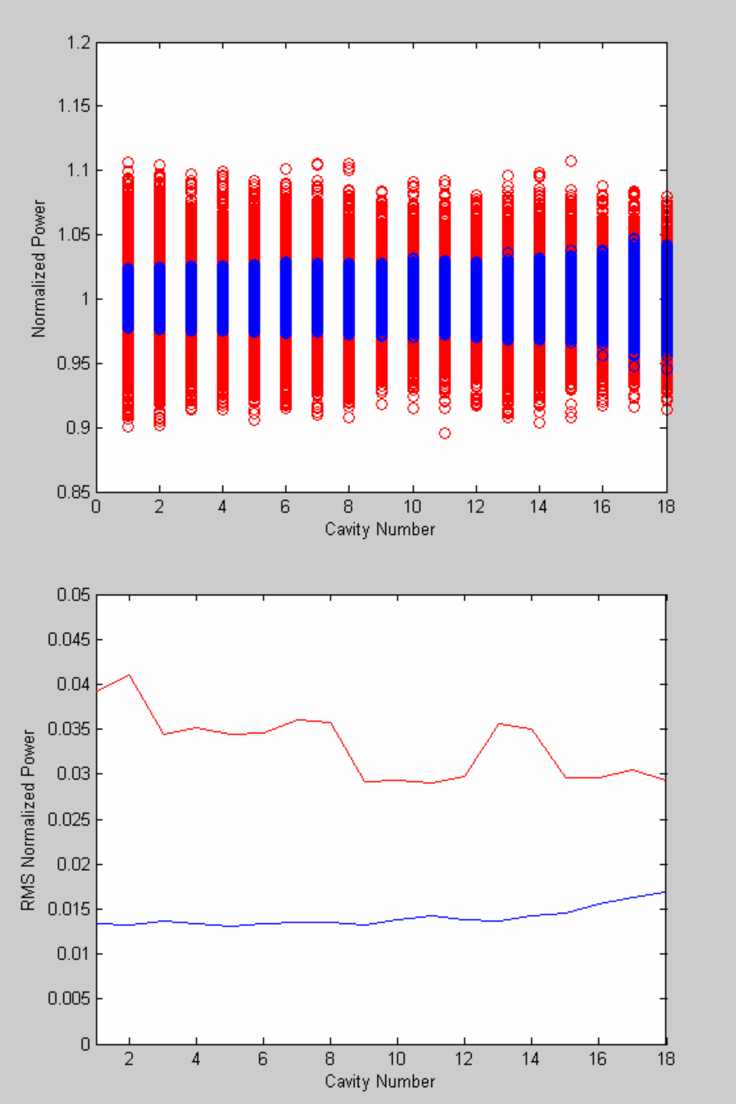


# Effect of Random Hybrid Coupling Errors

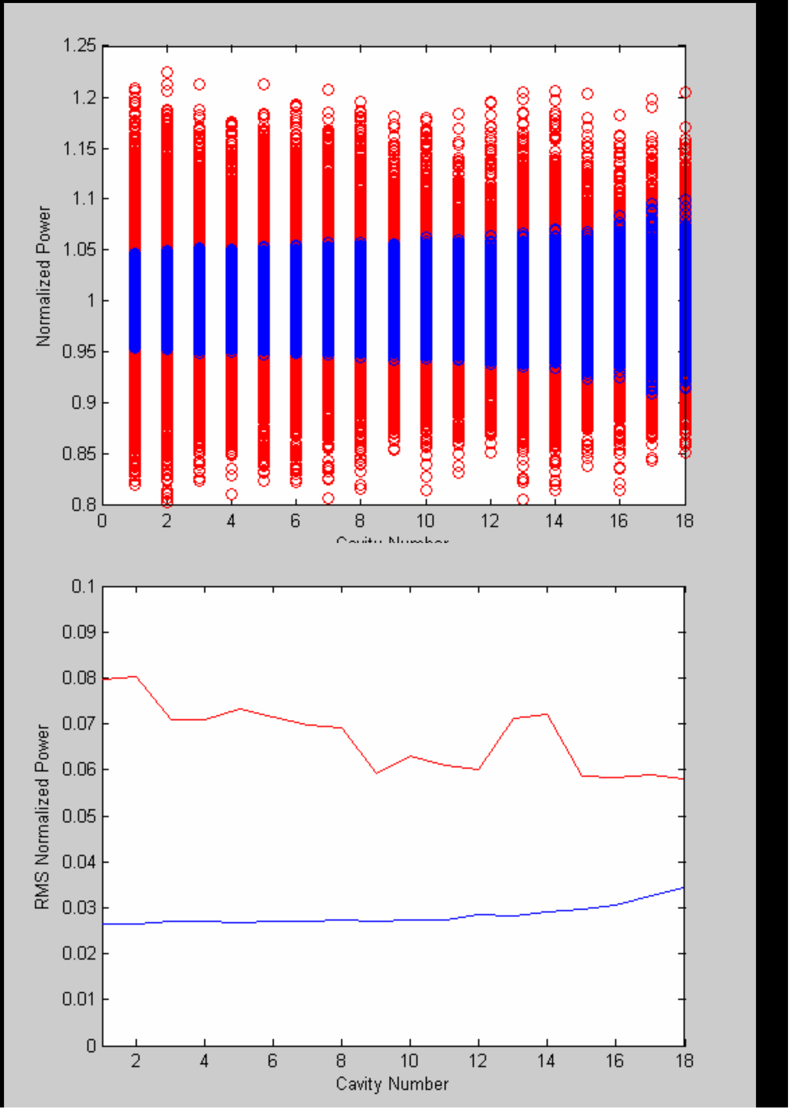
Red: branching distribution

Blue: series distribution

± 0.1 dB



± 0.2 dB



# Binary Branching

**RF POWER DISTRIBUTING WAVEGUIDE SYSTEMS FOR TESLA**

***V. Katalev*** IHEP, Protvino; ***S. Choroba*** DESY, Hamburg

RUPAC ’02

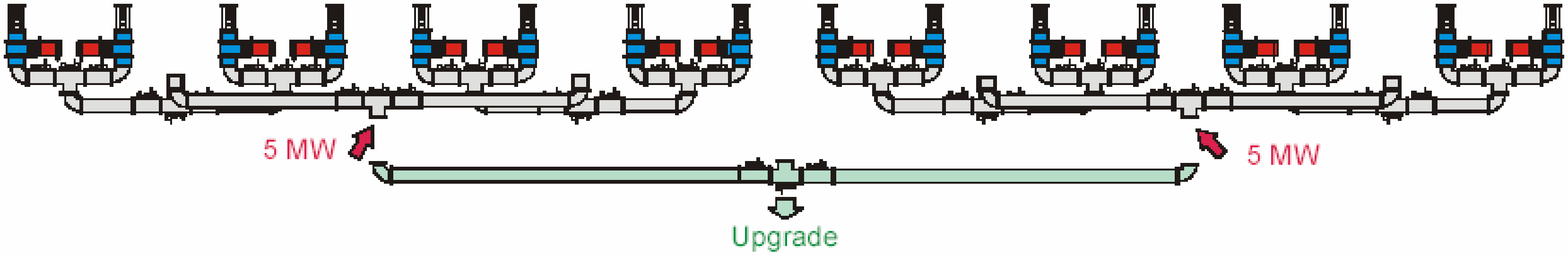
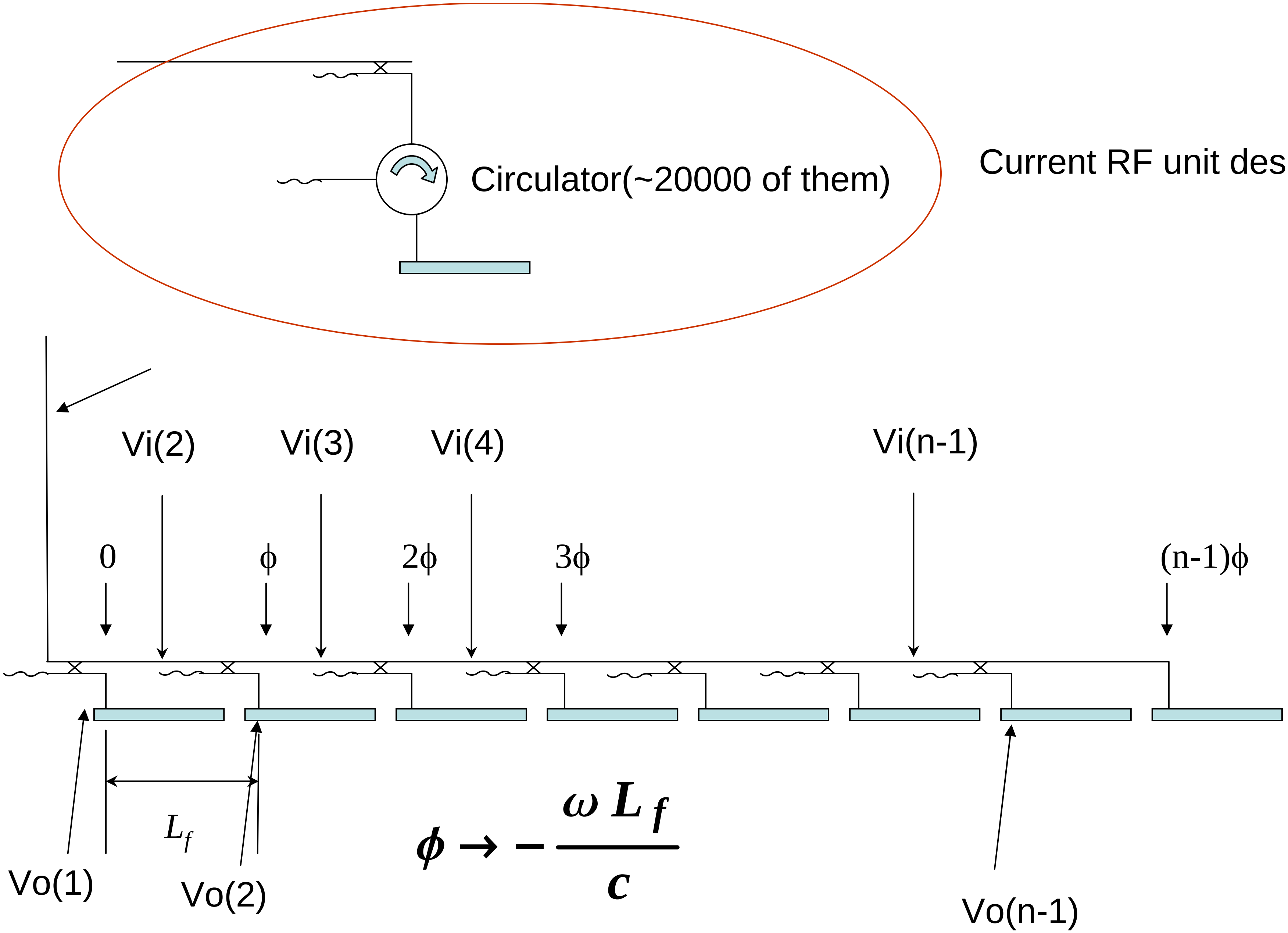


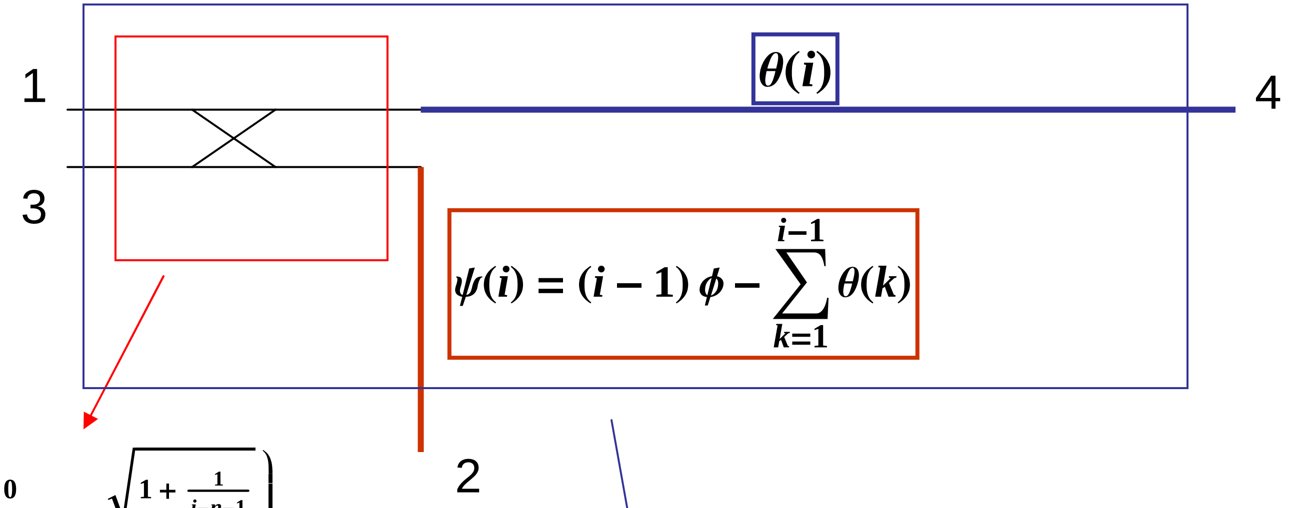
Figure 7: The flexible treelike RF power distributing system

- one splitter design
- same path lengths → same thermal phase change

Current RF unit design



$$\phi \rightarrow -\frac{\omega L_f}{c}$$



$$\boxed{\theta(i)}$$

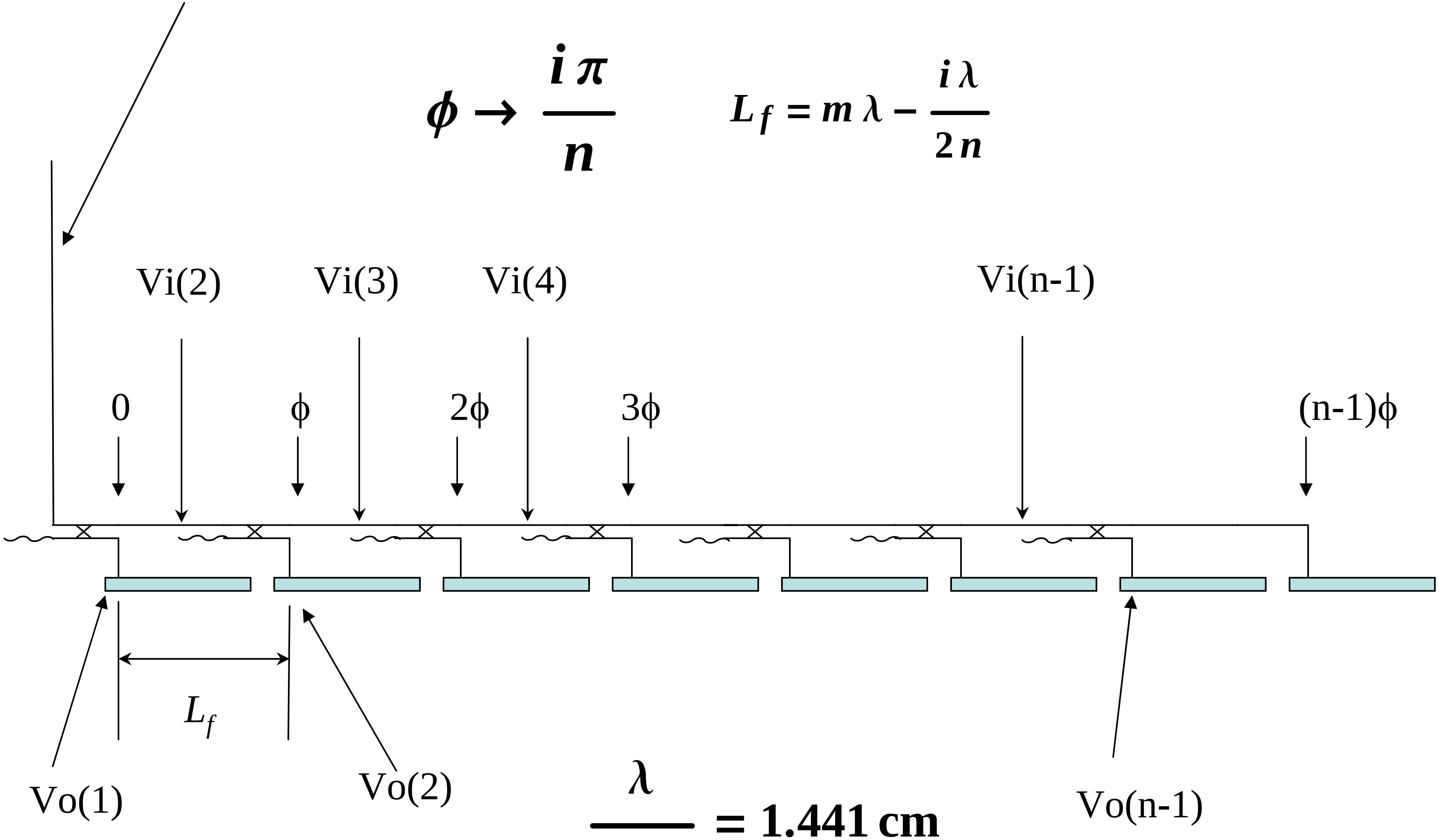
$$\psi(i) = (i-1)\,\phi - \sum_{k=1}^{i-1} \theta(k)$$

$$s_i = \begin{pmatrix} 0 & \frac{1}{\sqrt{-i+n+1}} & 0 & \sqrt{1+\frac{1}{i-n-1}} \\ \frac{1}{\sqrt{-i+n+1}} & 0 & \sqrt{1+\frac{1}{i-n-1}} & 0 \\ 0 & \sqrt{1+\frac{1}{i-n-1}} & 0 & -\frac{1}{\sqrt{-i+n+1}} \\ \sqrt{1+\frac{1}{i-n-1}} & 0 & -\frac{1}{\sqrt{-i+n+1}} & 0 \end{pmatrix}$$

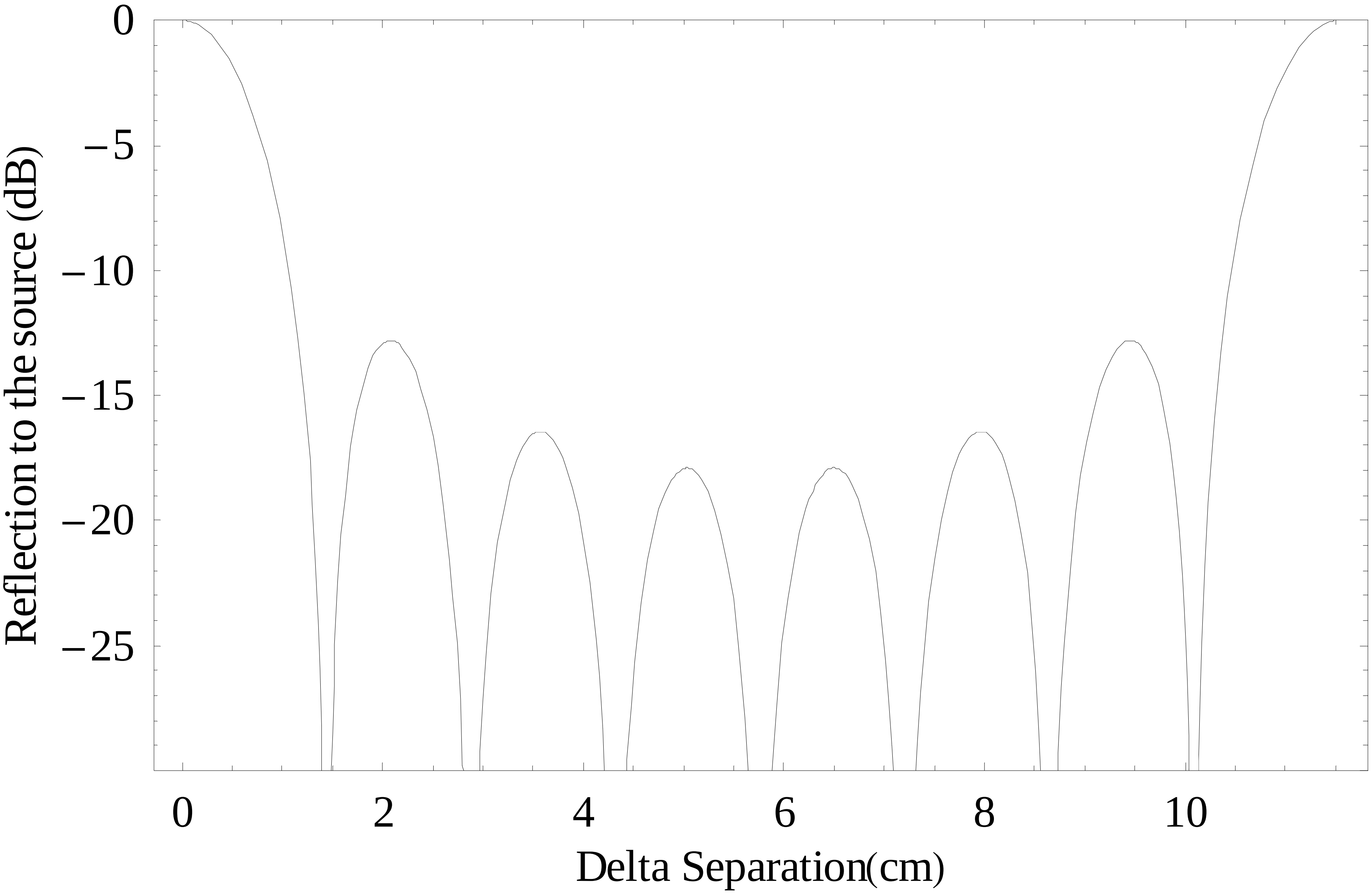
$$\begin{pmatrix} 0 & \frac{e^{i\left((i-1)\,\phi-\sum_{k=1}^{i-1}\theta(k)\right)}}{\sqrt{-i+n+1}} & 0 & e^{i\,\theta(i)}\sqrt{1+\frac{1}{i-n-1}} \\ \frac{e^{i\left((i-1)\,\phi-\sum_{k=1}^{i-1}\theta(k)\right)}}{\sqrt{-i+n+1}} & 0 & e^{i\left((i-1)\,\phi-\sum_{k=1}^{i-1}\theta(k)\right)}\sqrt{1+\frac{1}{i-n-1}} & 0 \\ 0 & e^{i\left((i-1)\,\phi-\sum_{k=1}^{i-1}\theta(k)\right)}\sqrt{1+\frac{1}{i-n-1}} & 0 & -\frac{e^{i\,\theta(i)}}{\sqrt{-i+n+1}} \\ e^{i\,\theta(i)}\sqrt{1+\frac{1}{i-n-1}} & 0 & -\frac{e^{i\,\theta(i)}}{\sqrt{-i+n+1}} & 0 \end{pmatrix}$$

$$R = \frac{1}{n}\, e^{i\,(n-1)\,\phi} \sum_{i=1}^{n} \cos((-2\,i+n+1)\,\phi) \quad = \frac{\sin(n\,\phi)\, e^{i\,(n-1)\,\phi}}{n\sin(\phi)}$$

$$\phi \rightarrow \frac{i\,\pi}{n} \qquad L_f = m\,\lambda - \frac{i\,\lambda}{2\,n}$$



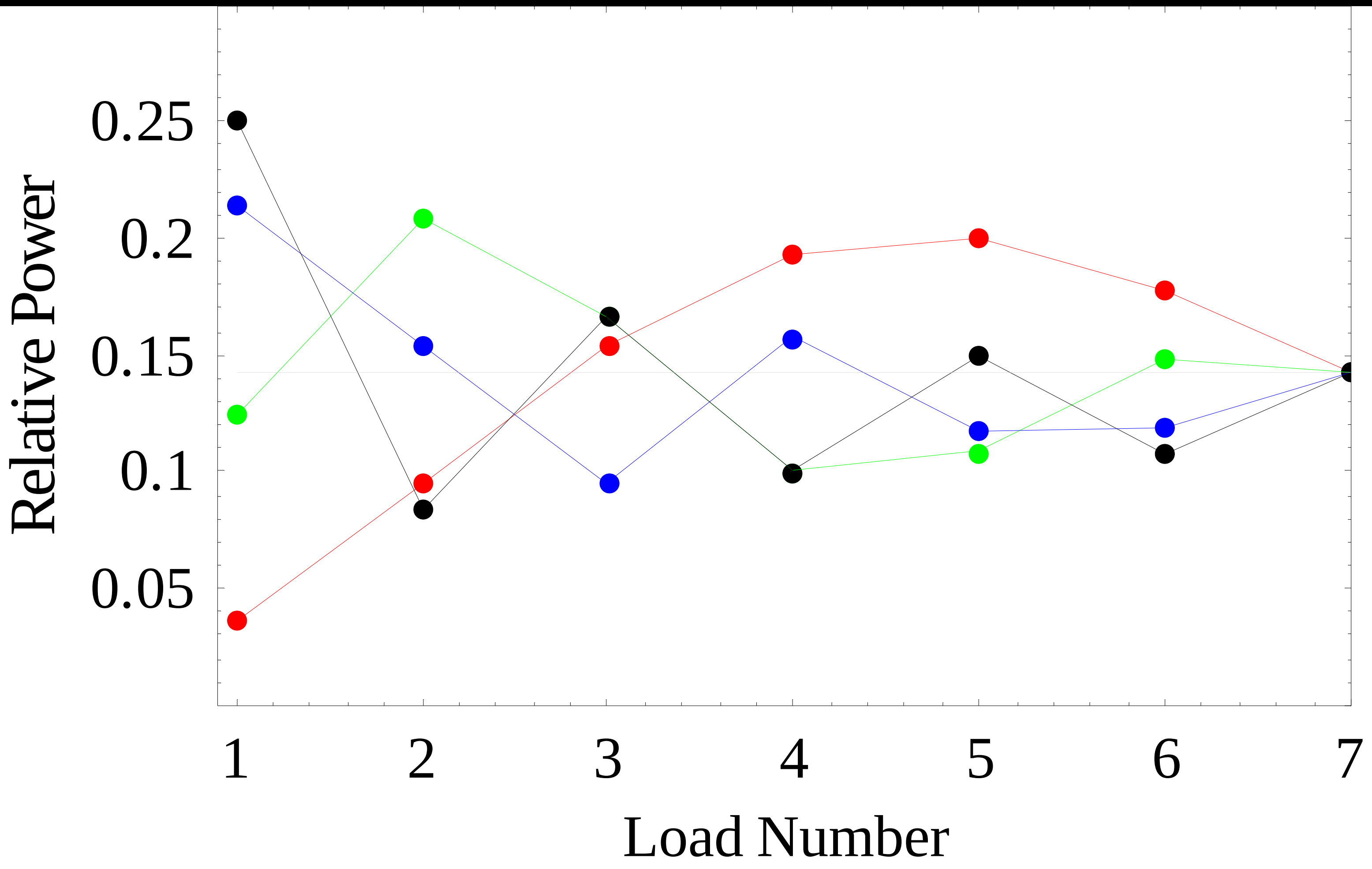
$$\frac{\lambda}{2\,x\,8} = 1.441\,\mathrm{cm}$$



Reflection to the source (dB)
0
−5
−10
−15
−20
−25
0
2
4
6
8
10
Delta Separation(cm)

For a solution $i$ of an $n$ structure problem the amplitude of the signal at load $j$ is given by

$$\frac{\sum_{k=1}^{j} e^{\frac{2\,\mathbb{i}\,i\,k\,\pi}{n}} - j}{\sqrt{2\sum_{k=1}^{j} k}\,\sqrt{n}}$$

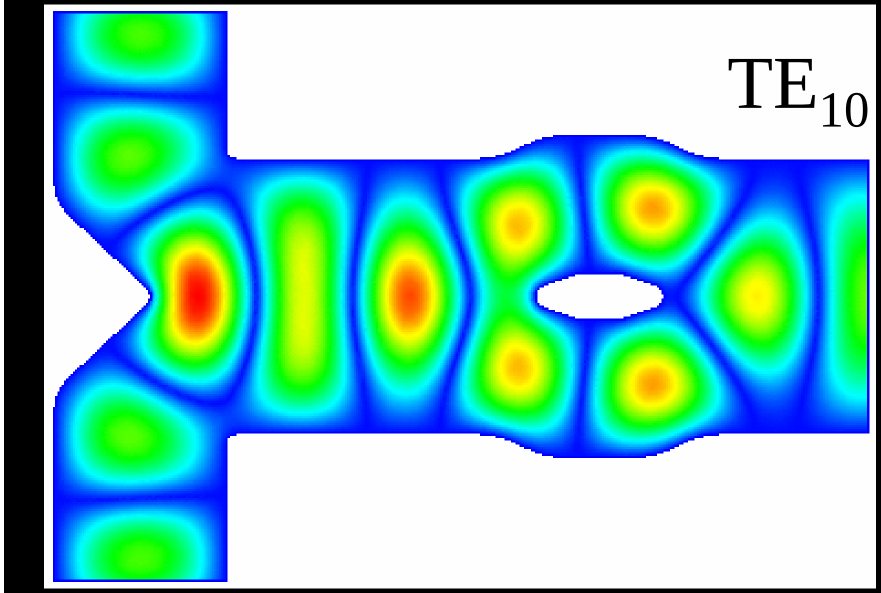

0.25
0.2
0.15
0.1
0.05
Relative Power
1
2
3
4
5
6
7
Load Number

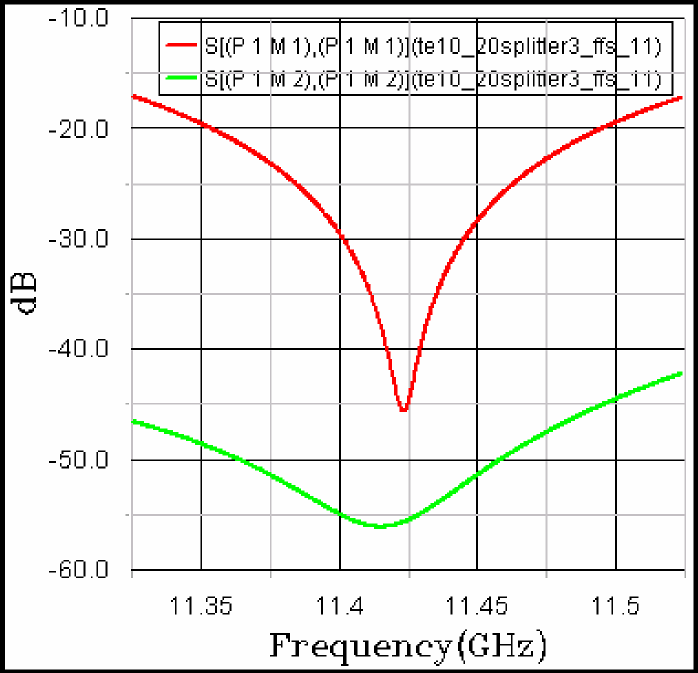
# HYBRID COUPLERS

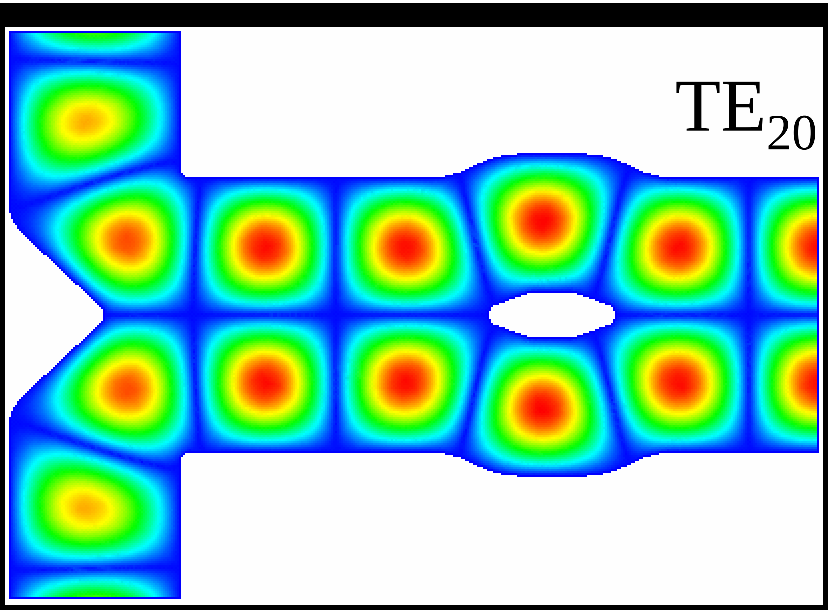
TESLA Baseline:

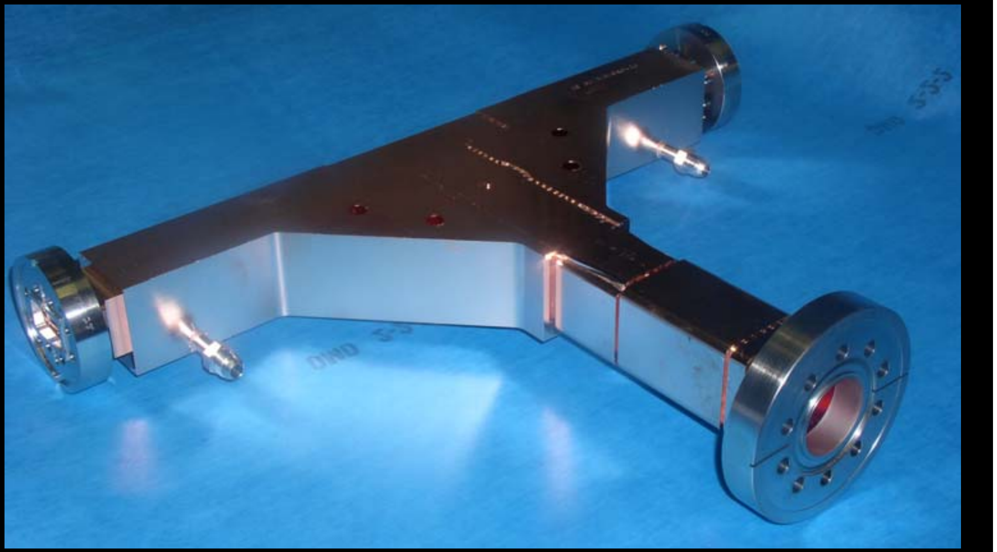
Improvement:

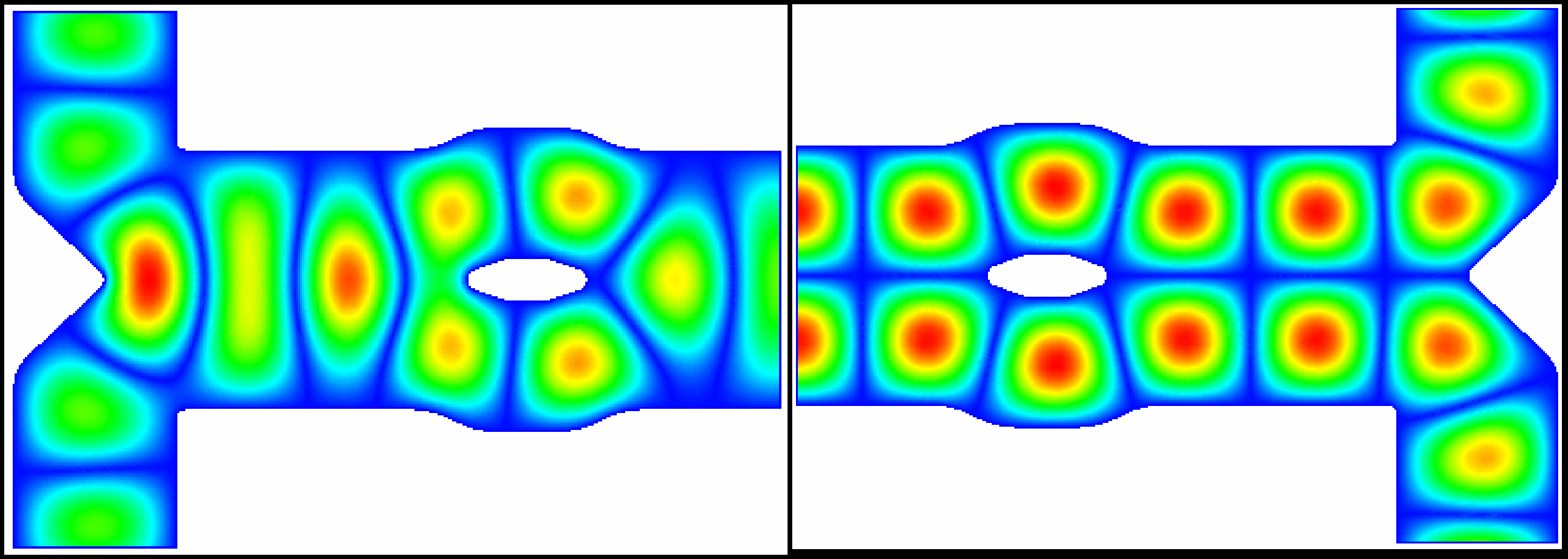
# Dual-Mode Combiner



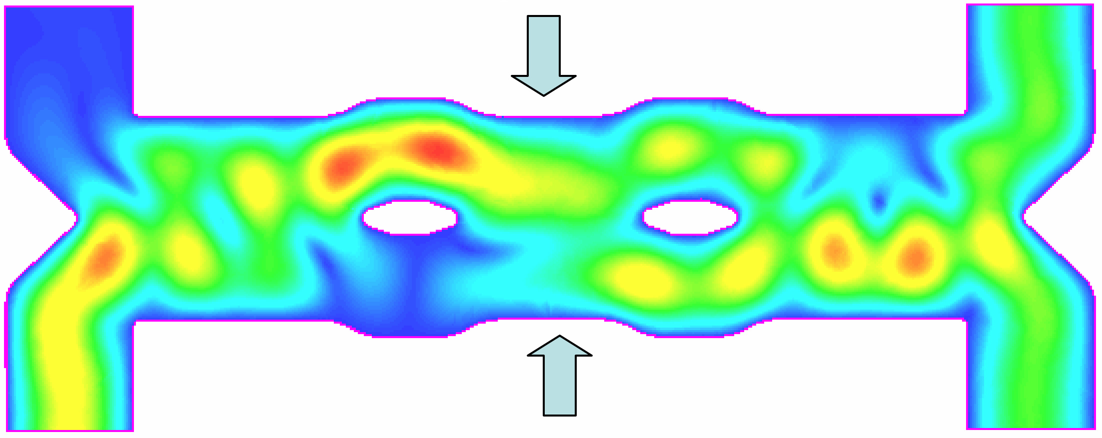




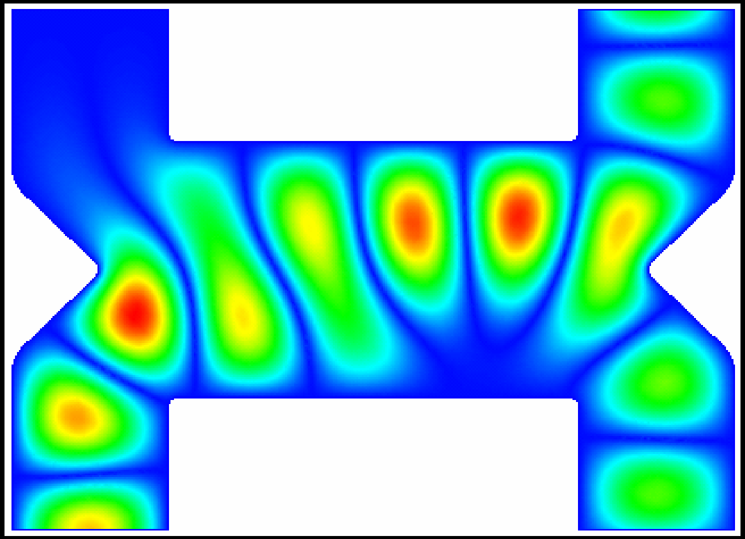




# Adjustable Coupling?



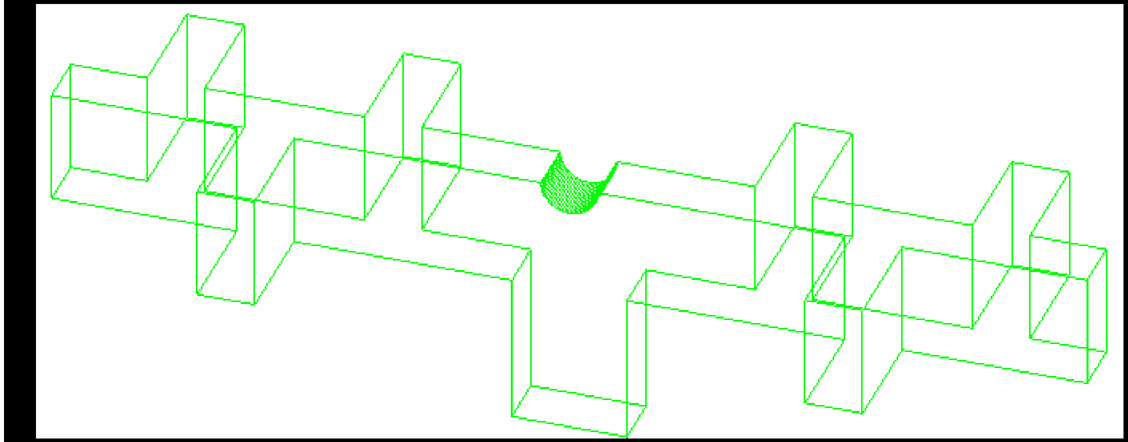
squeeze

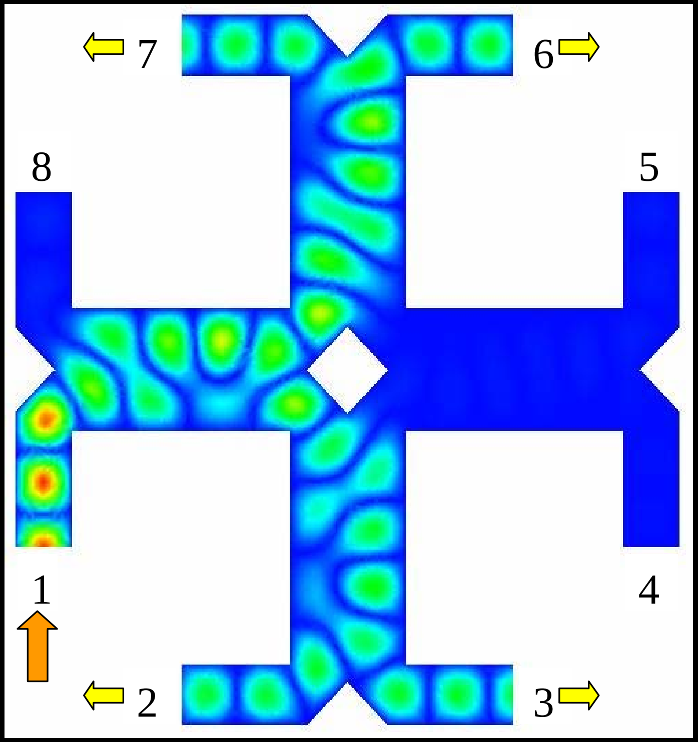


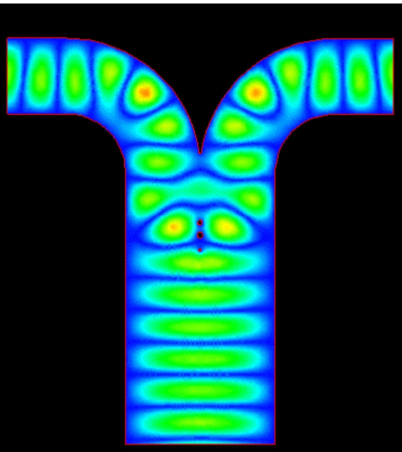
# Distribution Without Directional Couplers

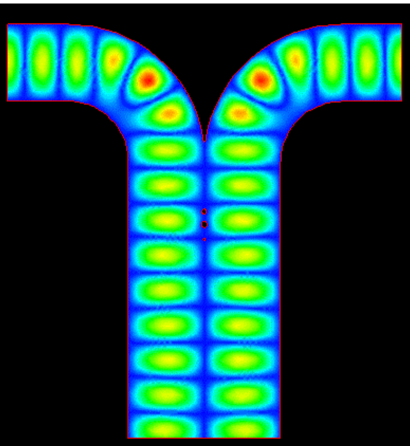
With a circulator at each cavity, are directional couplers necessary?

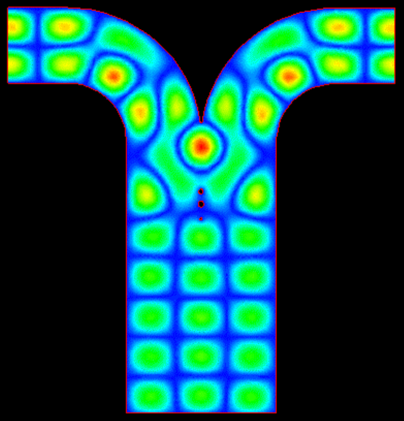
What about 3-port tap-offs or multi-port dividers?

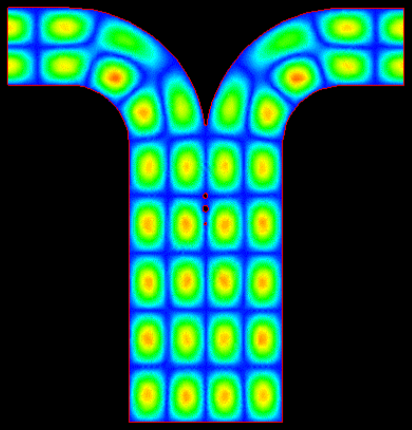





TE$_{10}$


TE$_{20}$


TE$_{30}$


TE$_{40}$

With This we can construct a 16-port *precise* directional divider; one input, 8-output and 7 loads

# Basic Equations

$$V(t) = V_{rf}(t) - V_b(t)$$

$$= \sqrt{4P\frac{R}{Q_0}Q_L}\left(1-e^{-\frac{\omega t}{2Q_L}}\right) - I_b\frac{R}{Q_0}Q_L\left(1-e^{-\frac{\omega(t-t_i)}{2Q_L}}\right)$$

For optimal coupling of power to beam:

$$\mathrm{Given: E_{acc}, L, I_b, R/Q_0}$$

$$V = E_{acc}L$$

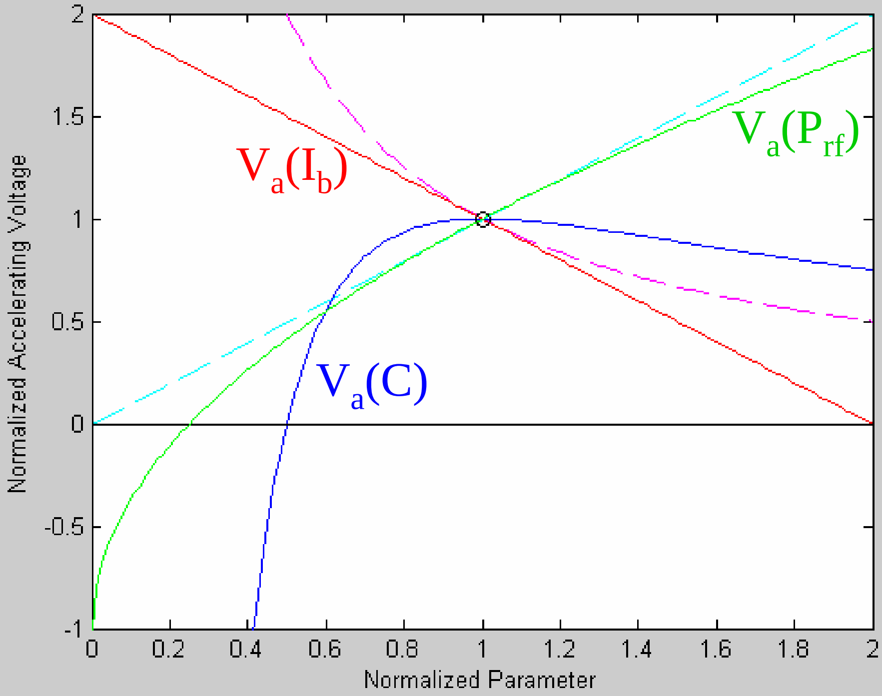
$$P = I_b V$$

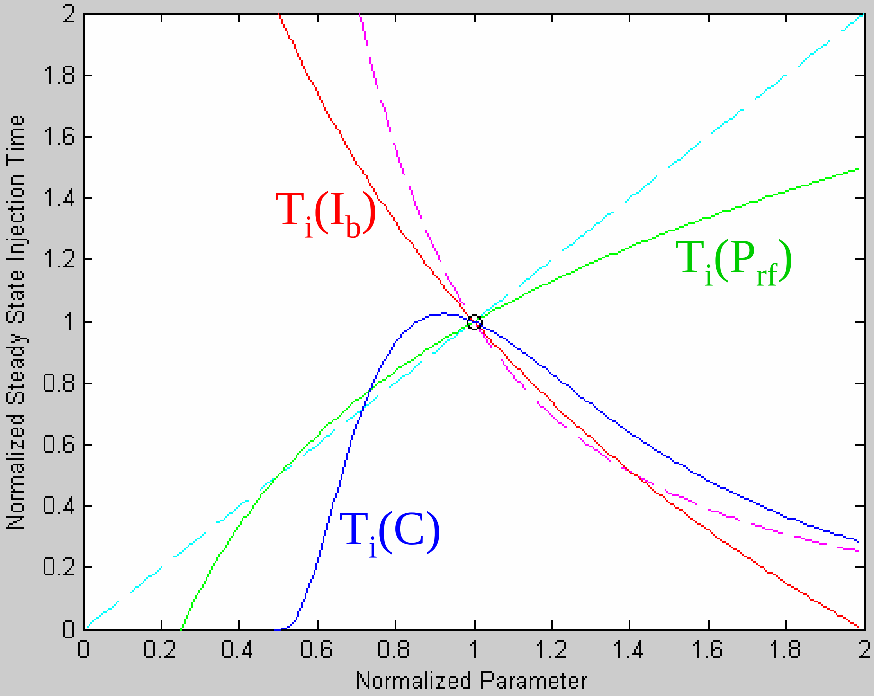
$$Q_L = \frac{P}{I_b^2\frac{R}{Q_0}}$$

$$t_i = \tau_c \ln 2 = \frac{2Q_L}{\omega}\ln 2$$

# Superconducting Cavity Behavior*

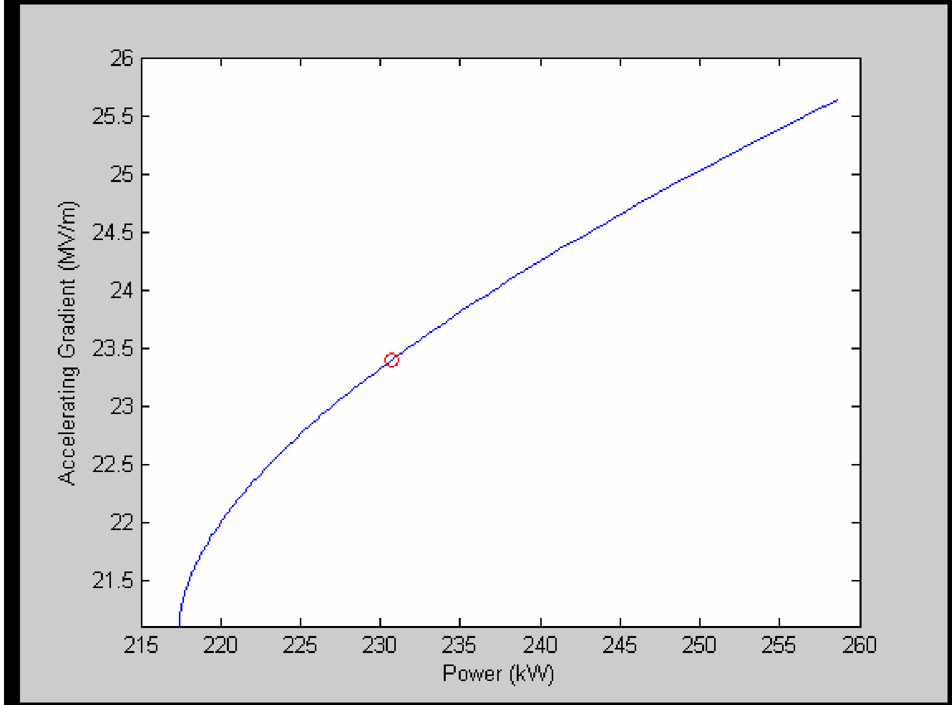
Dashed lines are for continually optimized coupling.

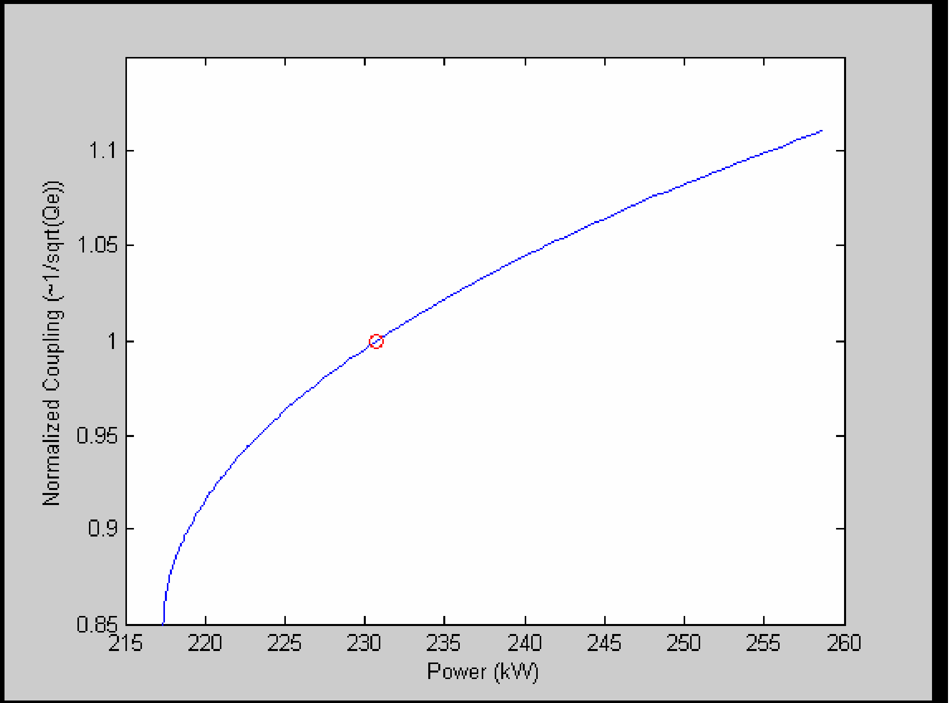




*Infinite $Q_0$ assumed.

$C \propto E_e/V_a \propto Q_e^{-1/2}$ assumed large enough that $Q_e \ll Q_0$ but small enough that the initial reflection ≅ 1.





For more than -0.26 dB (5.8%) below nominal power, steady state cannot be achieved at nominal injection time.

$I_b = 9.5$ mA

$E_{acc} = 23.4$ MV/m

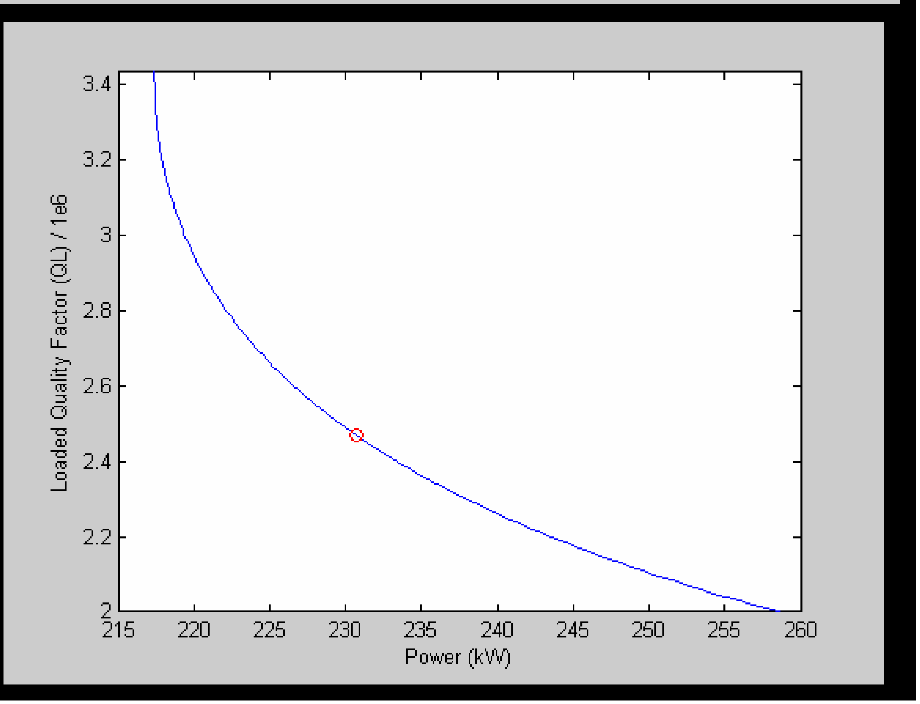
$L = 1.038$ m

$V_0 = 24.29$ MV

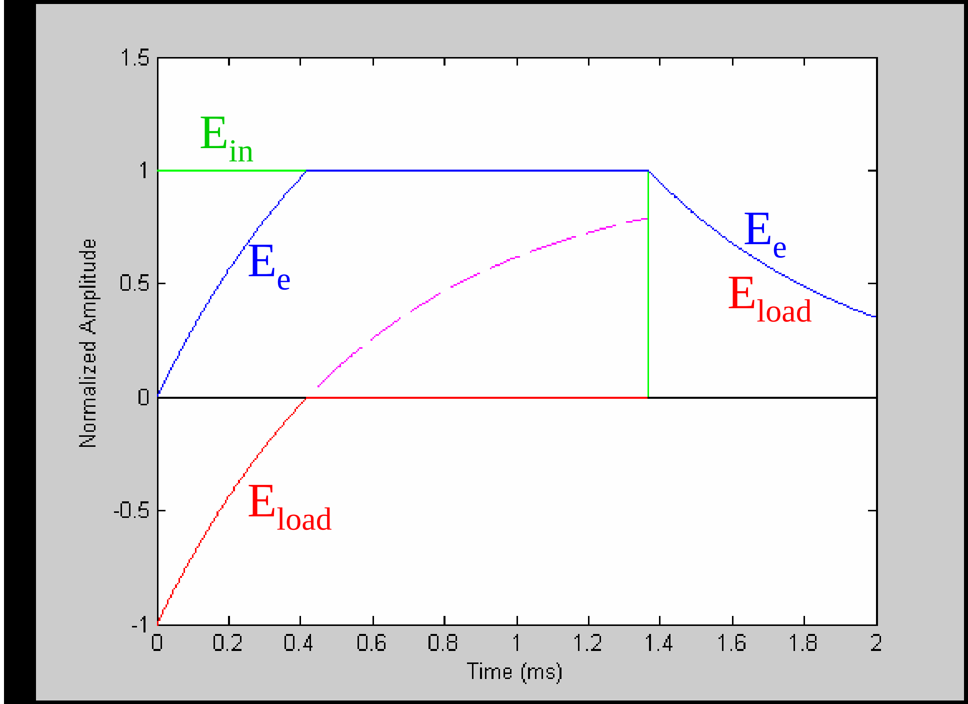
$P_0 = 230.8$ kW

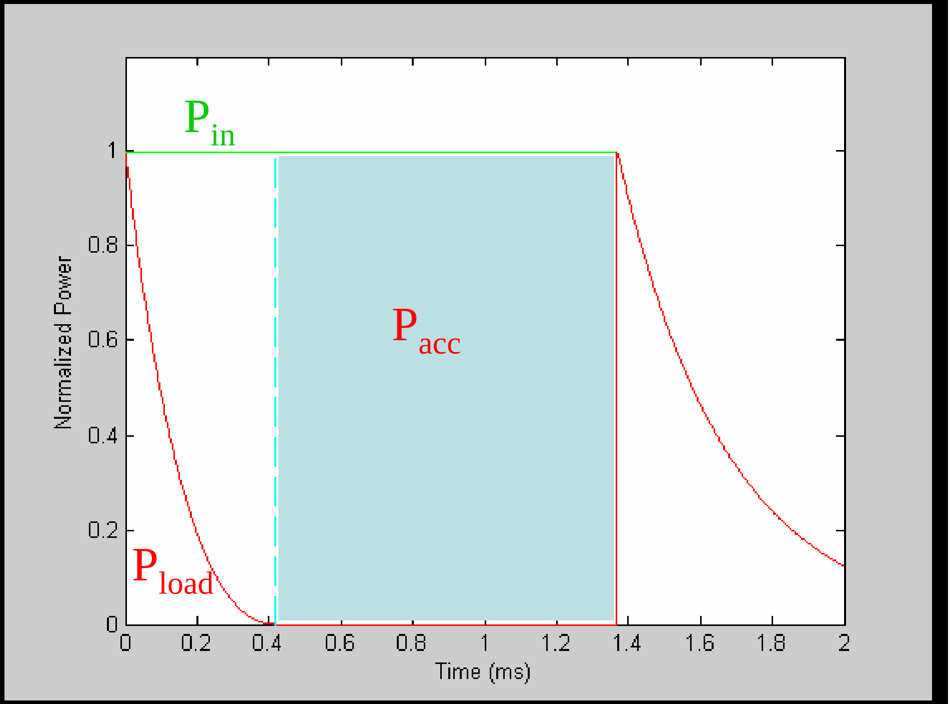
$Q_{L0} = 2.47 \times 10^6$

$t_i = 418.9\ \mu s$



# Field and Power Waveforms





~<u>69%</u> of rf power (at cavity) goes into the beam.

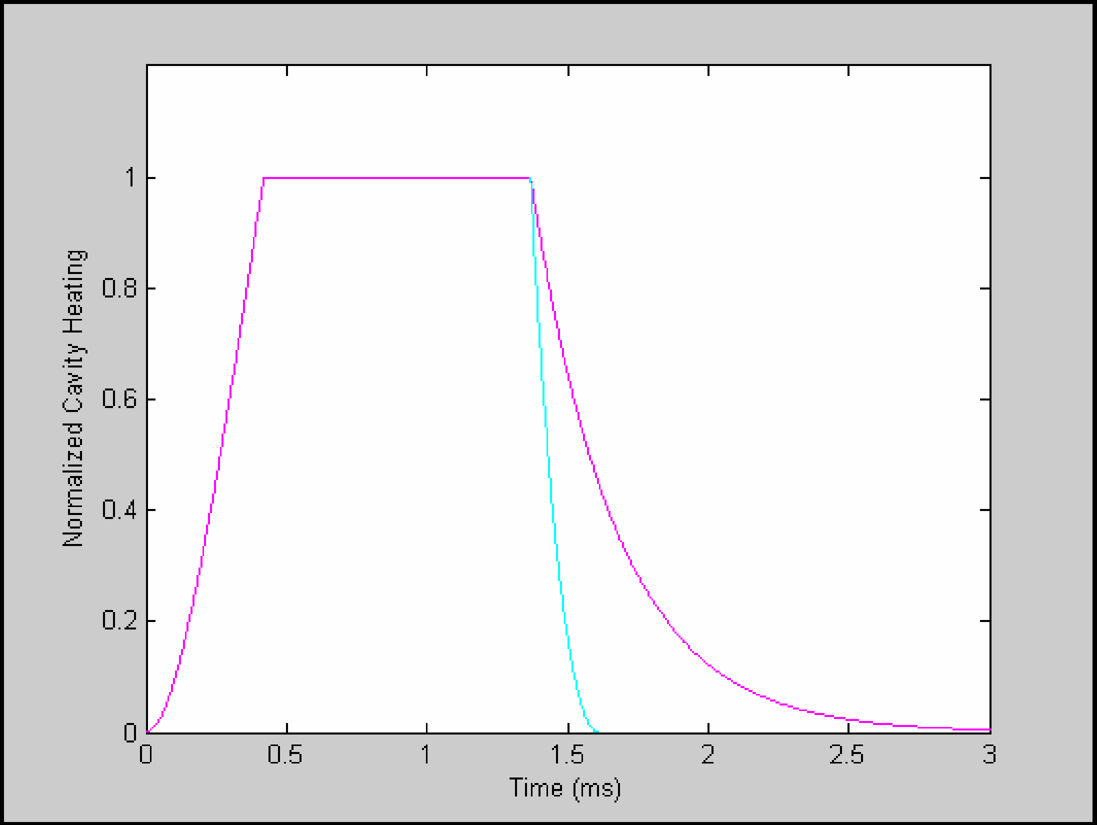
31% of rf wasted: 22% filling cavity

9% to load during fill

# RF CAVITY HEATING

Q: Should we use rf phase flip to empty cavity faster?

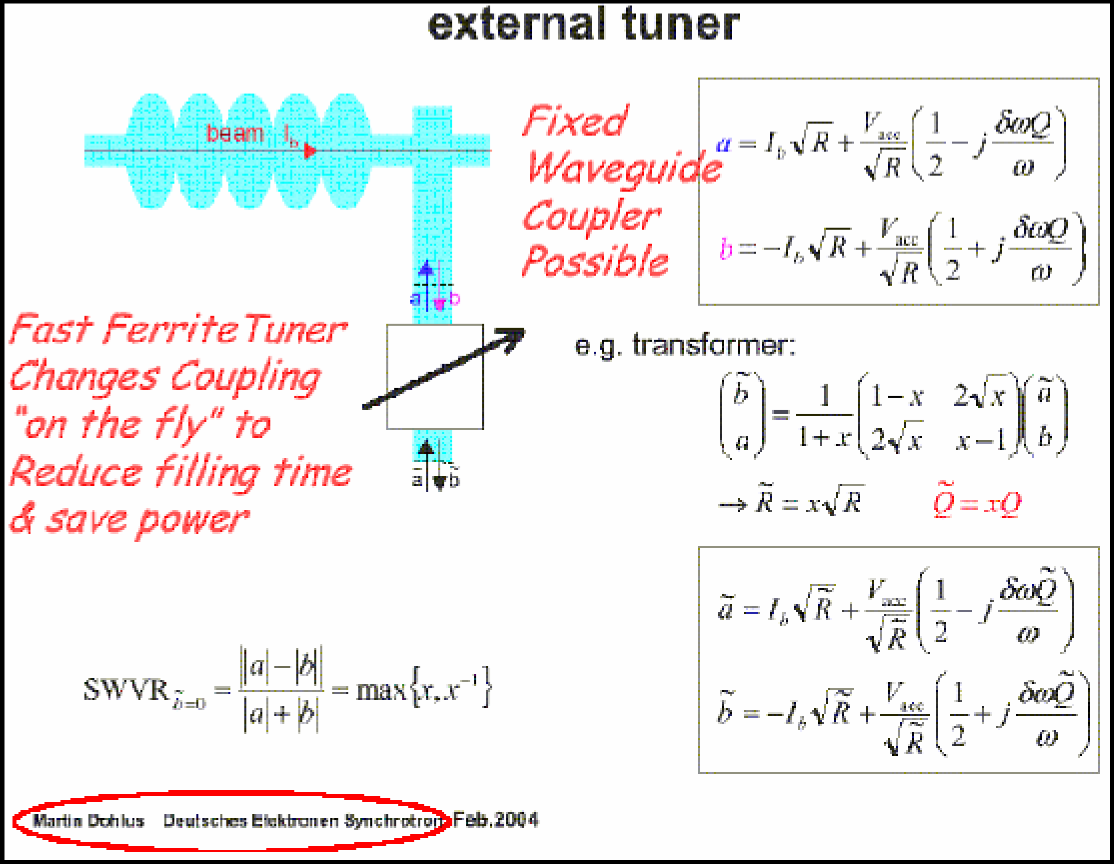
Cavity heating: ~11.6% during fill
~67.1% during beam
~21.3% after beam



By reversing the rf phase after the beam and extending the pulse to 1.61ms, we can save 16.2% of cavity heating, but at a cost of 17.5% more rf power.

A: No. But if we have switchable coupling, we could drop $Q_L$ to dump the energy faster.

With agile coupling control, some or all of the 9% lost during filling can be saved, reducing the fill time from 419 μs to $\tau_c/2 = t_i/(2\ln 2) = 302$ μs.



## external tuner

Fixed Waveguide Coupler Possible

$$a = I_b\sqrt{R} + \frac{V_{acc}}{\sqrt{R}}\left(\frac{1}{2} - j\frac{\delta\omega Q}{\omega}\right)$$

$$b = -I_b\sqrt{R} + \frac{V_{acc}}{\sqrt{R}}\left(\frac{1}{2} + j\frac{\delta\omega Q}{\omega}\right)$$

Fast Ferrite Tuner Changes Coupling "on the fly" to Reduce filling time & save power

e.g. transformer:

$$\begin{pmatrix}\tilde{b}\\ a\end{pmatrix} = \frac{1}{1+x}\begin{pmatrix}1-x & 2\sqrt{x}\\ 2\sqrt{x} & x-1\end{pmatrix}\begin{pmatrix}\tilde{a}\\ b\end{pmatrix}$$

$$\rightarrow \tilde{R} = x\sqrt{R} \qquad \tilde{Q} = xQ$$

$$\tilde{a} = I_b\sqrt{\tilde{R}} + \frac{V_{acc}}{\sqrt{\tilde{R}}}\left(\frac{1}{2} - j\frac{\delta\omega \tilde{Q}}{\omega}\right)$$

$$\tilde{b} = -I_b\sqrt{\tilde{R}} + \frac{V_{acc}}{\sqrt{\tilde{R}}}\left(\frac{1}{2} + j\frac{\delta\omega \tilde{Q}}{\omega}\right)$$

$$\mathrm{SWVR}_{\tilde{b}=0} = \frac{|a|-|b|}{|a|+|b|} = \max\{x, x^{-1}\}$$

Martin Dohlus Deutsches Elektronen Synchrotron Feb.2004

- Switch Array
  - Targeted for the implementation of sub-gigawatt level X-band active pulse compression system for the Next Linear Collider (NLC)
  - Working under $TE_{01}$ mode in circular waveguide
  - Implemented with array of silicon PIN diodes
  - Required switch time: ~10ns

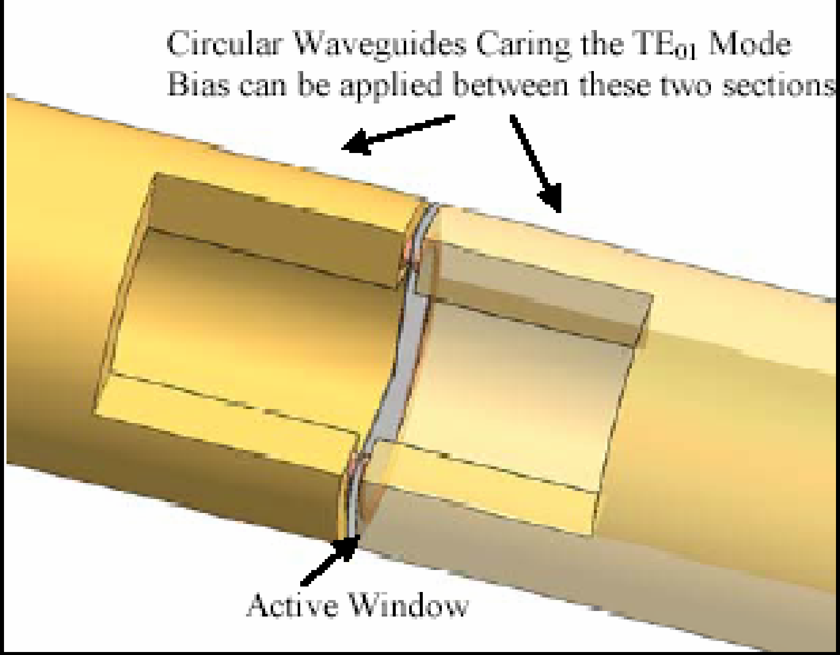
# Design of the switch arrays (cont.)

- Low loss
  - Use high purity silicon wafer
  - When diodes are off
    - 3% loss from HFSS simulation
  - High carrier density when diodes are on
    - 3% loss for carrier density of $5\times10^{17}/\text{cm}^3$
    - 10% loss for carrier density of $5\times10^{16}/\text{cm}^3$
    - carrier layer thickness 50µm.

- Amplifier array
  - Potential megawatt level pulsed RF source
  - Similar configuration as the switch array
  - Implemented with silicon IMPATT diodes
  - Output of diodes are spatially combined
  - Other device/material options

# Design of the switch arrays

- Working at $TE_{01}$ mode in circular waveguide



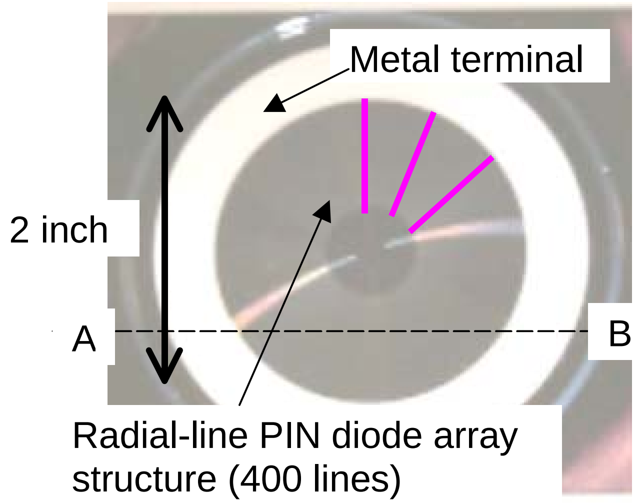
- Fabricated on one 4 inch floatzone silicon wafer
- Hundreds of PIN diodes integrated
- Two configurations with different number of diodes (960 and 576)

# Design and Implementation of PIN/NIP Diode Array Active Window

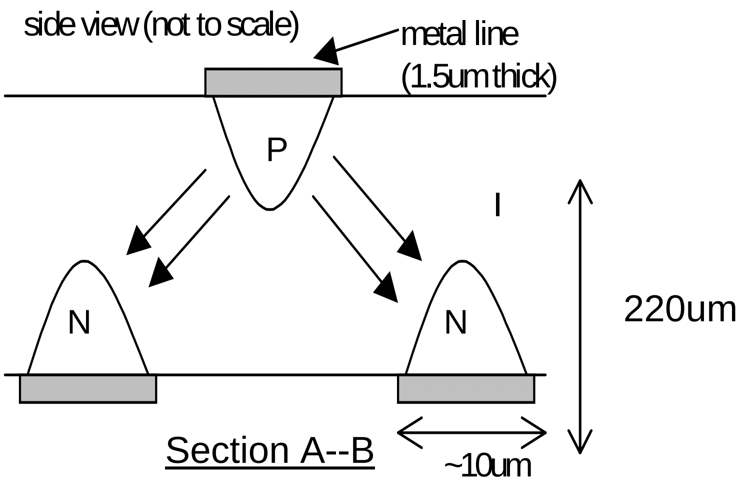
## PIN diode array Active Window

- All doping profile and metallic terminals on the window are radial, i.e. perpendicular to electric field of the $TE_{01}$ mode. → Effect of doping and metal lines on RF signal is small when the diode is reverse biased.

- With forward bias, carriers are injected into I region and I region becomes conductor → RF signal is reflected.



Radial-line PIN diode array structure (400 lines)

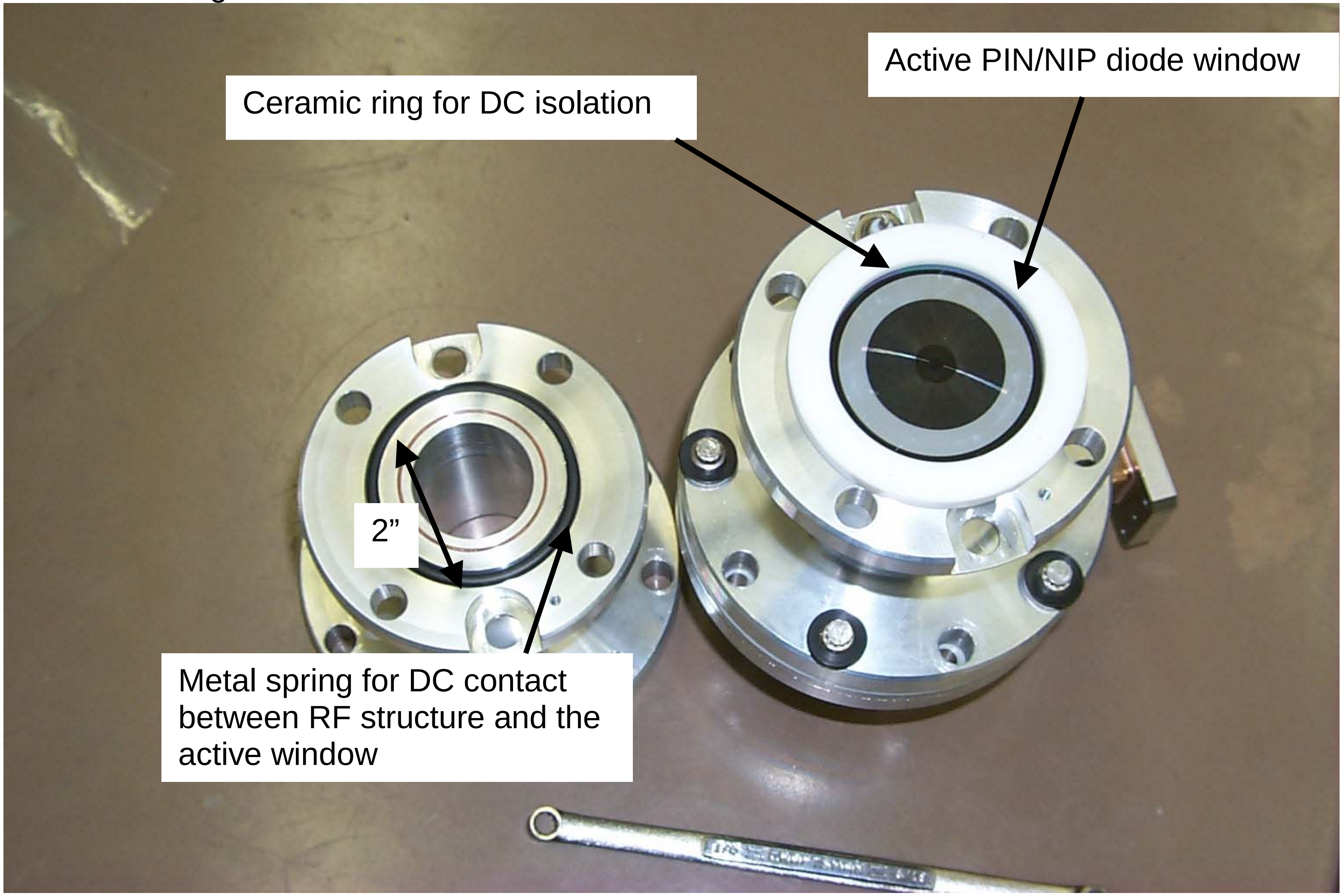


Section A--B

- Base material: high resistivity (pure) silicon, <5000ohm-cm, n-type
- Diameter of active region: 1.3 inch
- Thickness: **220um**
- Coverage (metal/doping line on the surface): ~10%

## RF structure

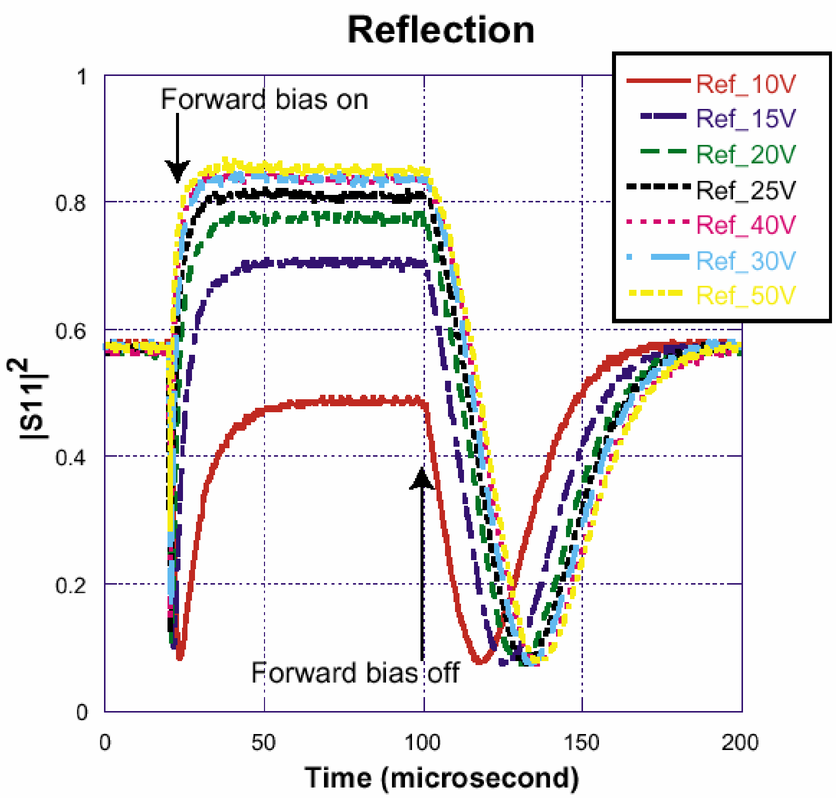
- DC isolation by $Al_2O_3$ ceramic ring
- No RF choke is needed ($TE_{01}$ mode)
- Higher impedance (Zg / Z0 ~4, close to cutoff) for this experiment
    - Enhance the effect of window switching status
    - Lower loss at the window during forward bias
    - Huge mismatch without bias

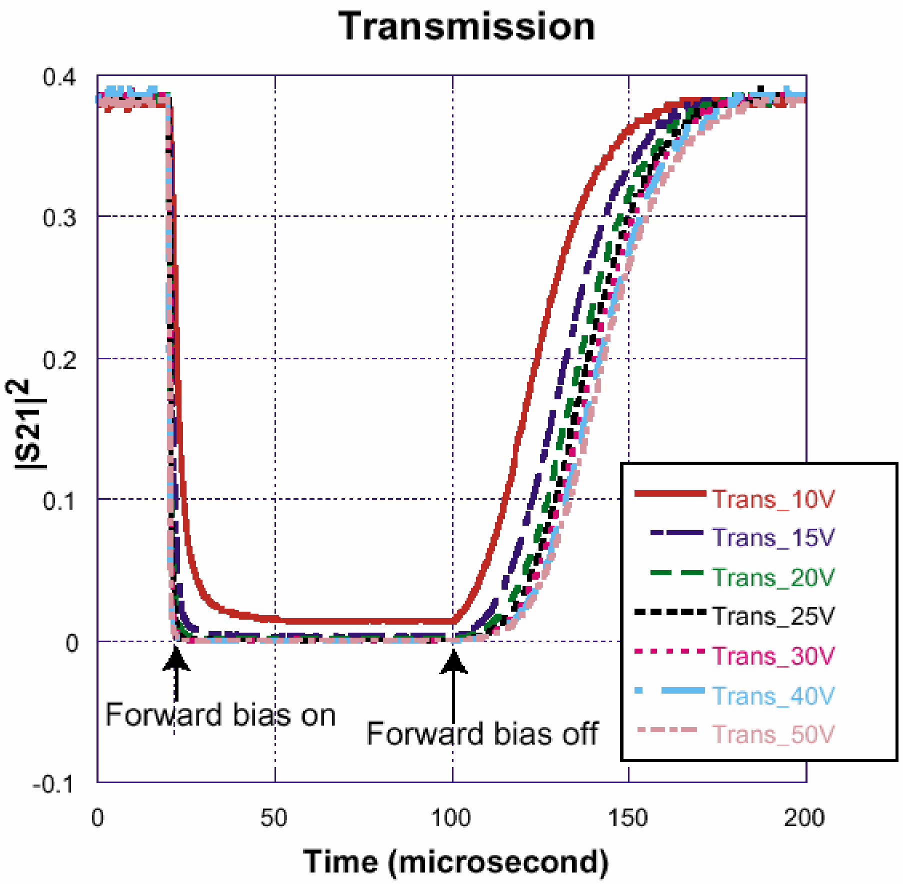


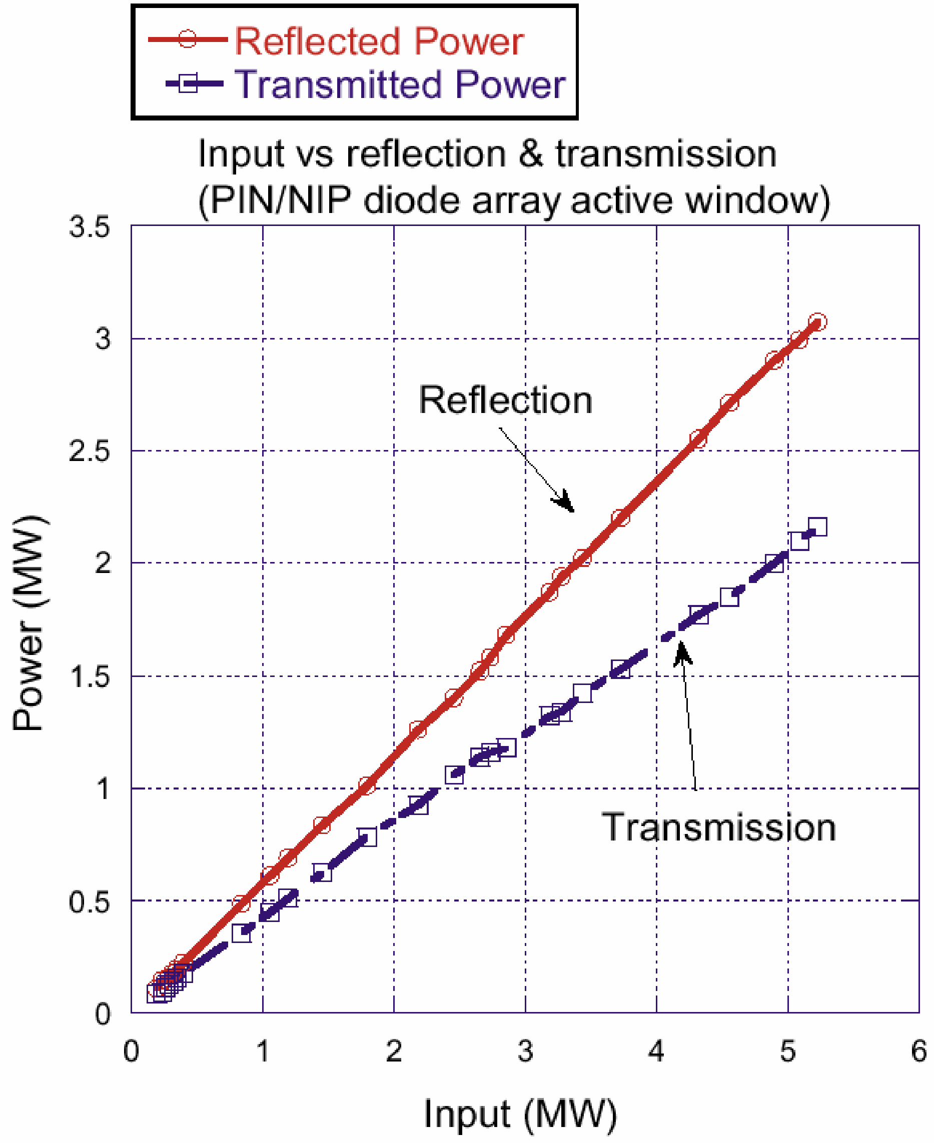
Active PIN/NIP diode window

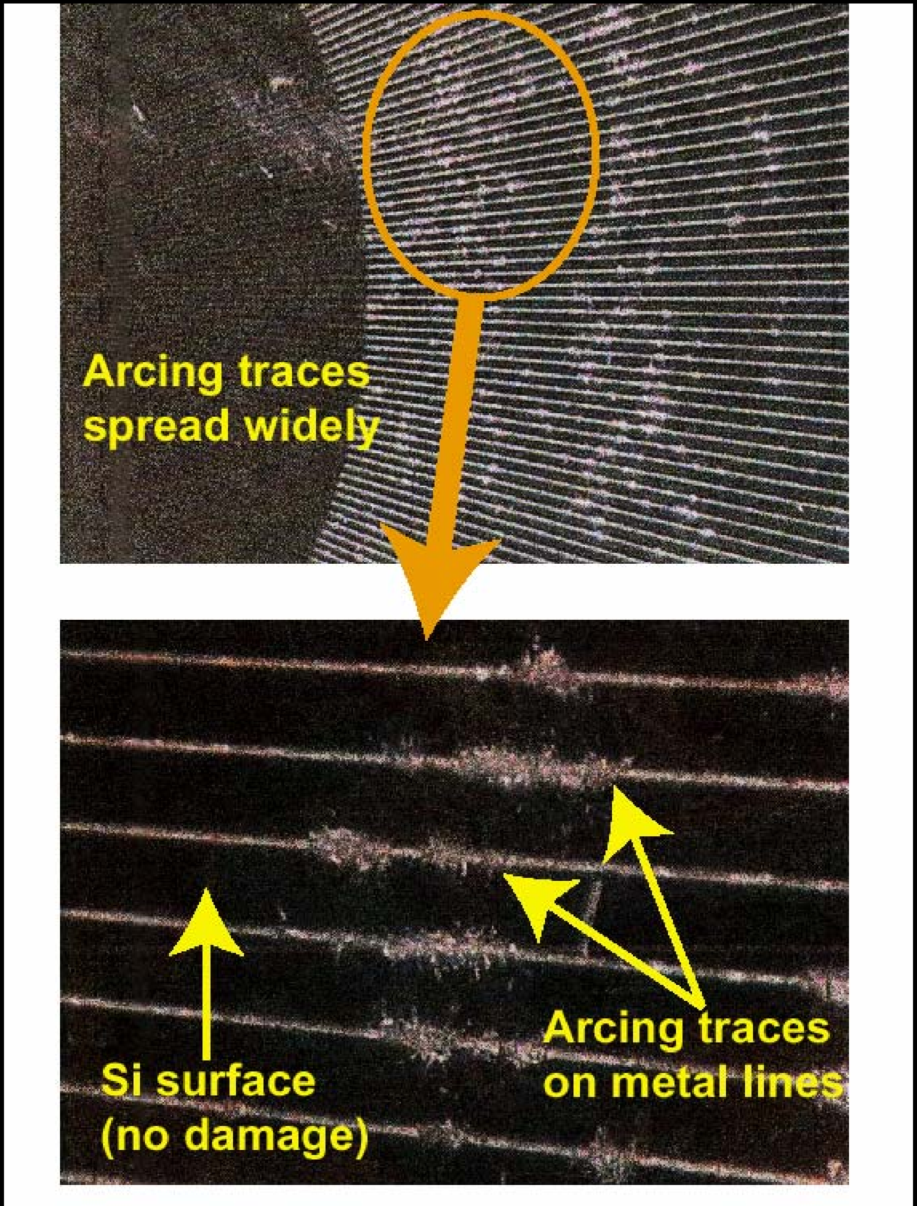
Ceramic ring for DC isolation

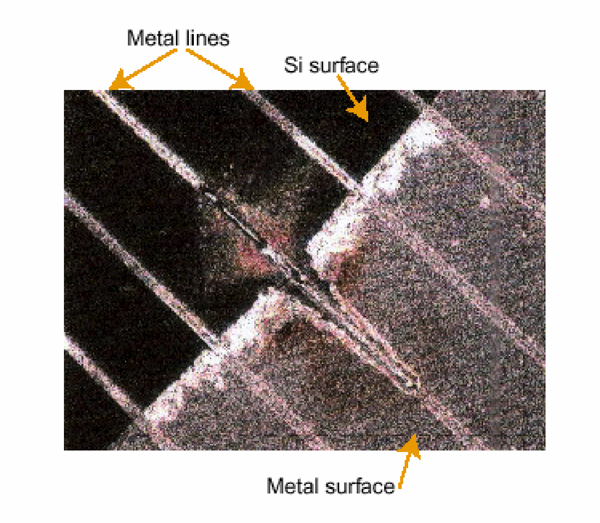
Metal spring for DC contact between RF structure and the active window


Reflection
Forward bias on
Forward bias off
|S11|^2
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
Time (microsecond)
Ref_10V
Ref_15V
Ref_20V
Ref_25V
Ref_40V
Ref_30V
Ref_50V

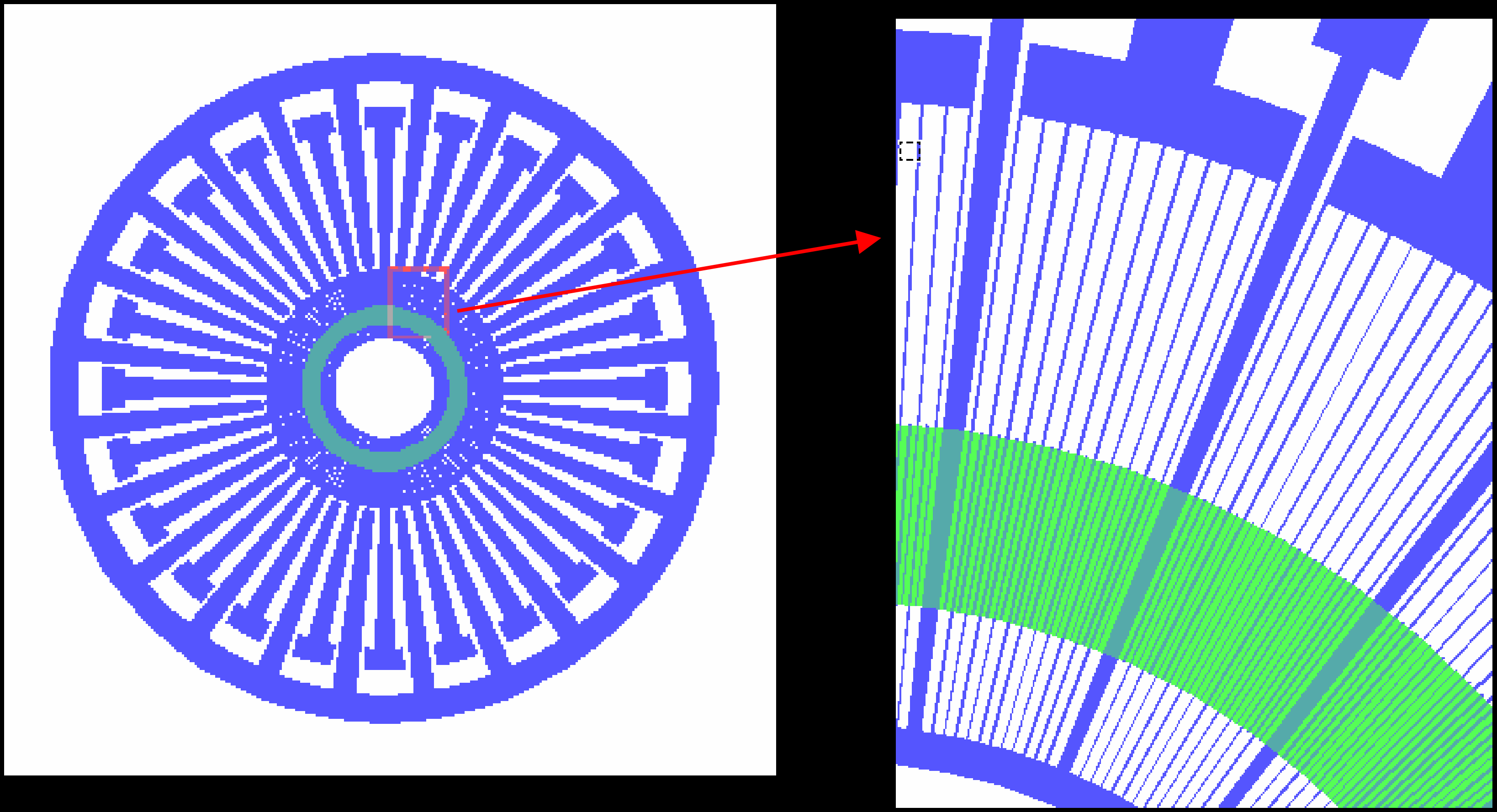

Transmission
|S21|^2
0.4
0.3
0.2
0.1
0
-0.1
0
50
100
150
200
Time (microsecond)
Forward bias on
Forward bias off
Trans_10V
Trans_15V
Trans_20V
Trans_25V
Trans_30V
Trans_40V
Trans_50V


Reflected Power
Transmitted Power
Input vs reflection & transmission
(PIN/NIP diode array active window)
Reflection
Transmission
Power (MW)
Input (MW)
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
4
5
6


Arcing traces
spread widely
Si surface
(no damage)
Arcing traces
on metal lines

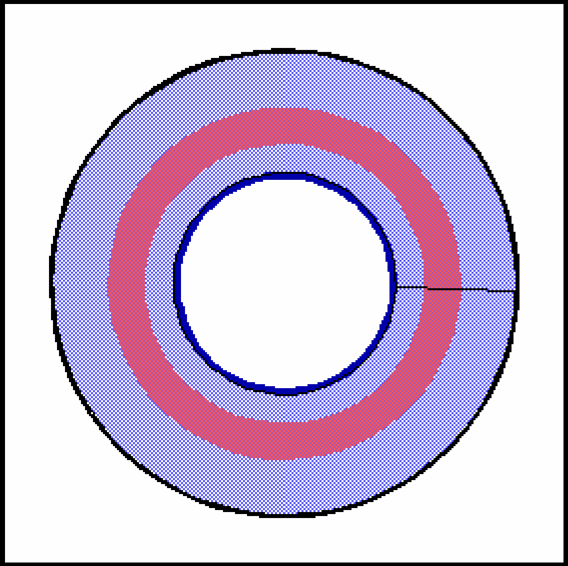

Metal lines
Si surface
Metal surface

# Layout of the switch arrays



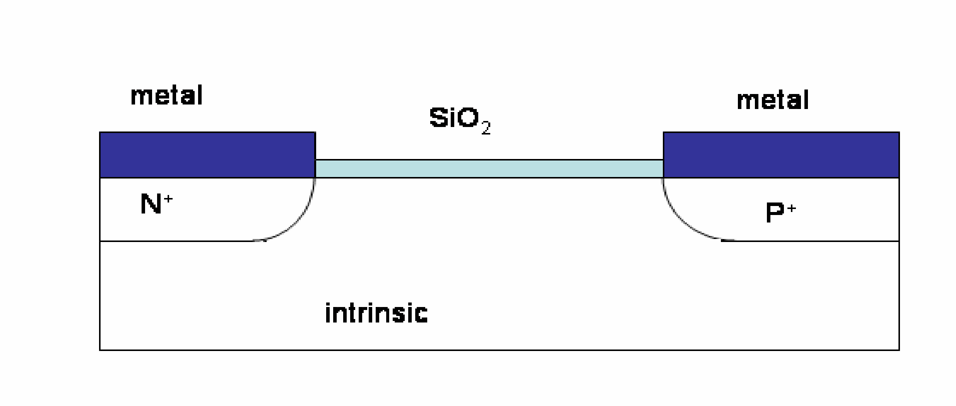
# Design of the switch arrays (cont.)

- High contrast between on and off states
  - Self matched ($S_{11}<0.1$) when diodes are off.
  - Full reflection ($S_{12}<0.1$) when diodes turn on.



# Design of the PIN diode

- 2-D structure compatible with CMOS process
- Diodes length 60-120micron
  - Generate$10^{16}$~$10^{17}$/$cm^3$ carrier density with moderate current
  - With proper bias, on time <20ns, off time<200ns.



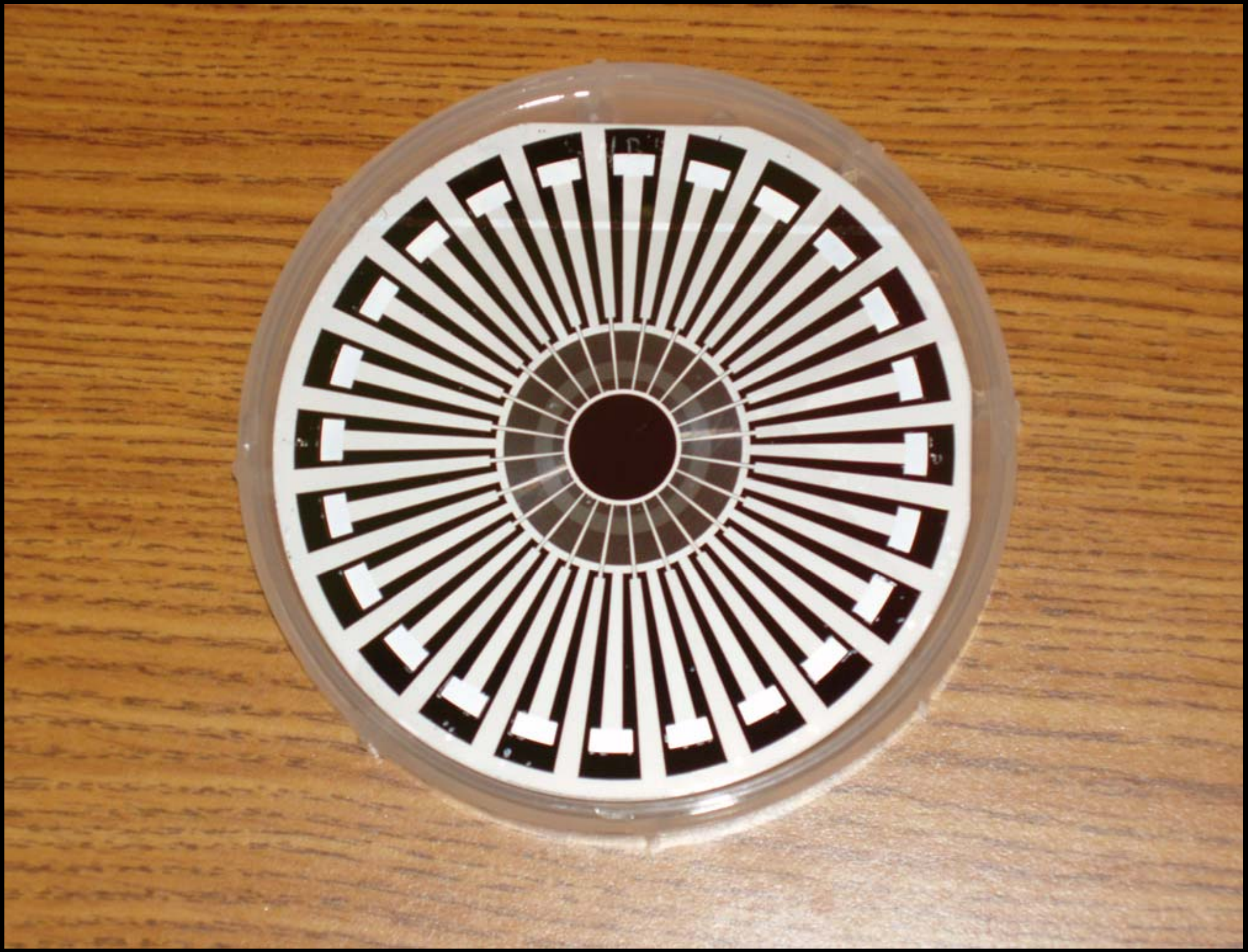
# Factors limiting diode speed

- Need high voltage to compensate space charge field.
- Need inject/draw big charge (~50µC) in short time
- Non-uniformity in diodes:
  - Some diodes response faster than the others, will draw more current, lower the voltage over other diodes, and burn themselves.
- Problem for turn off speed:
  - Local breakdown caused by high voltage

# Fabrication of the diode array

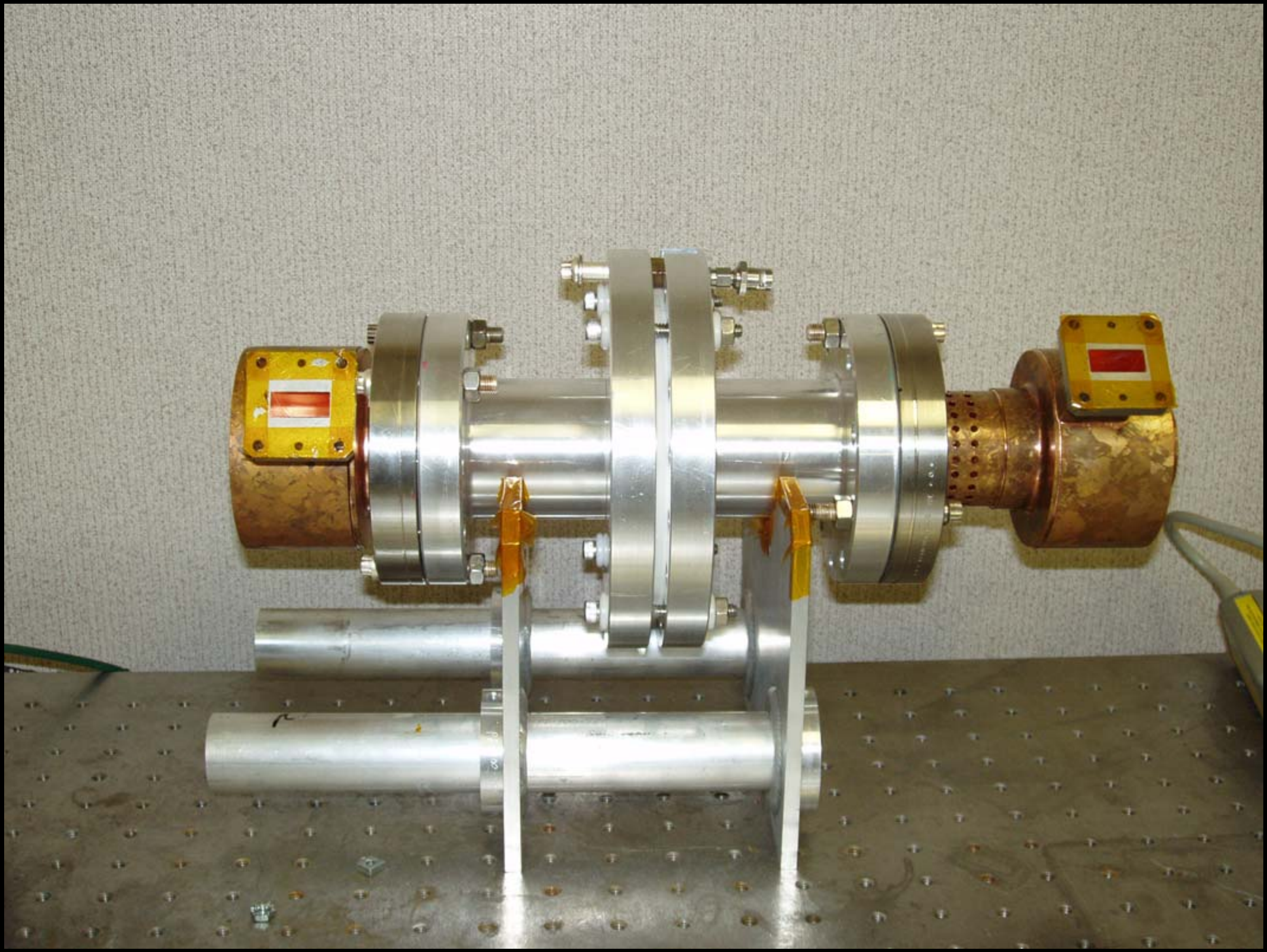
- Fabricated at Stanford Nanofabrication Facility
- Using CMOS compatible technology

# Diode array

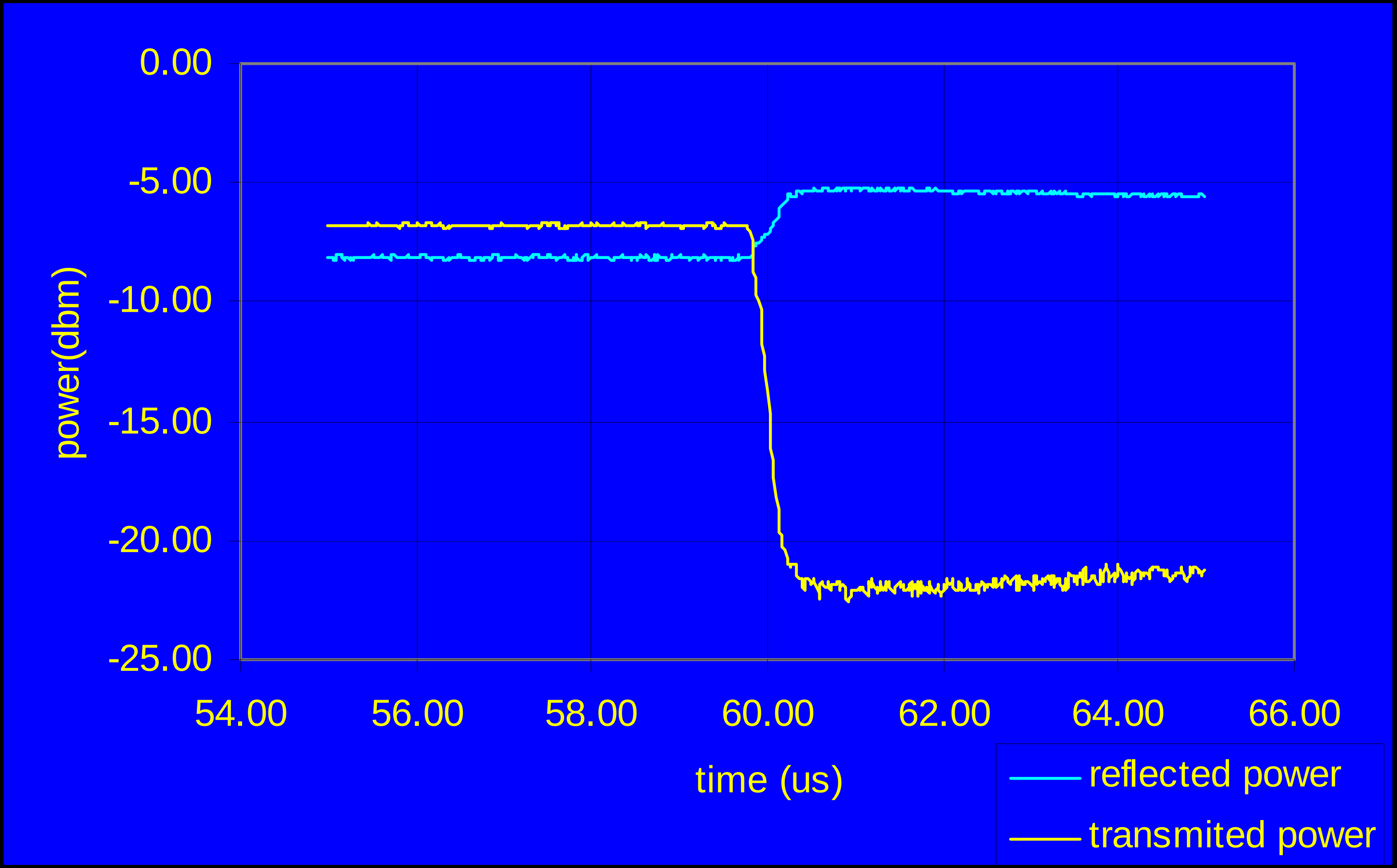


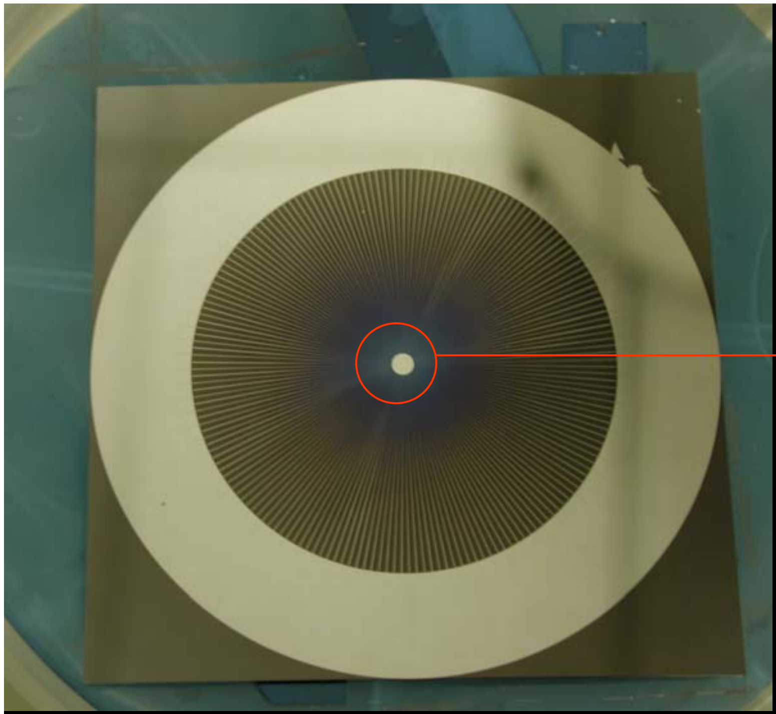
# Testing structure

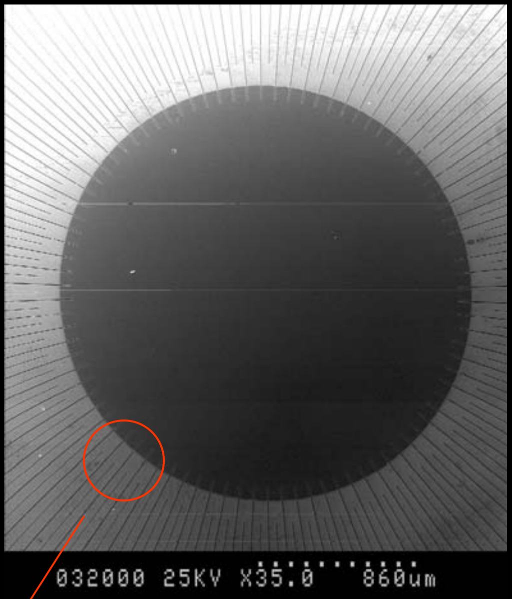
# Testing setup



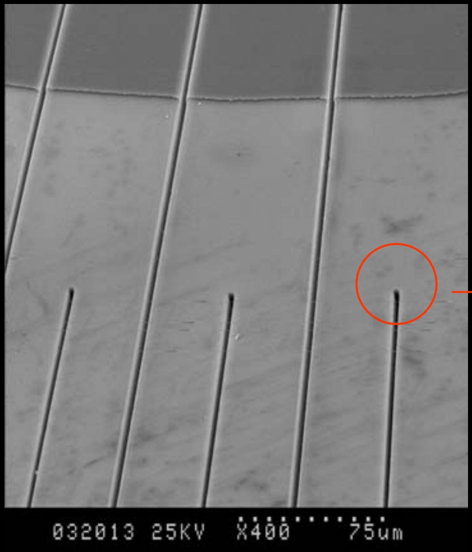
# Switch on time

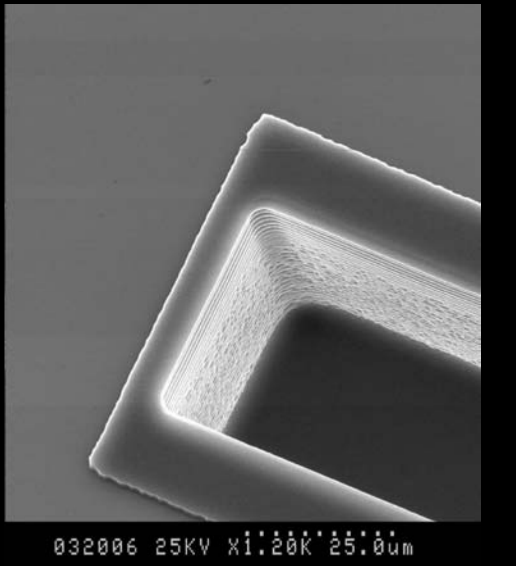


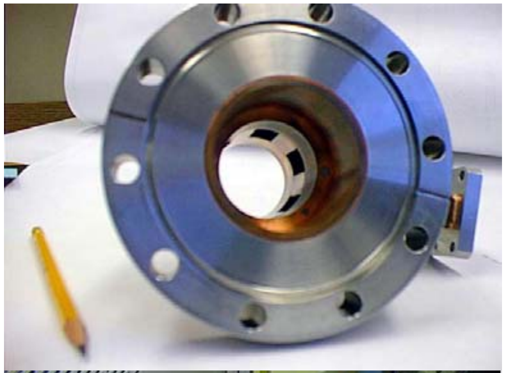


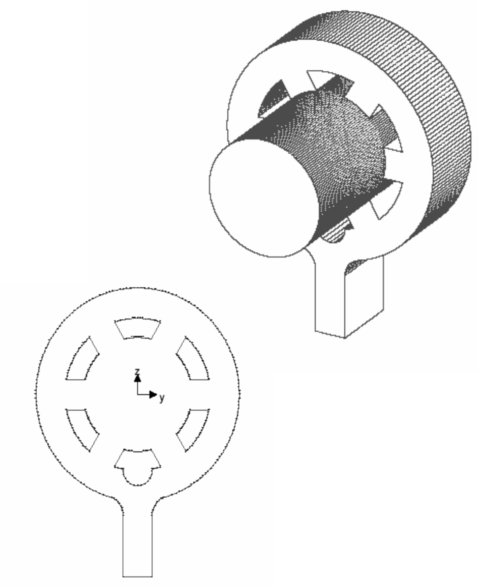


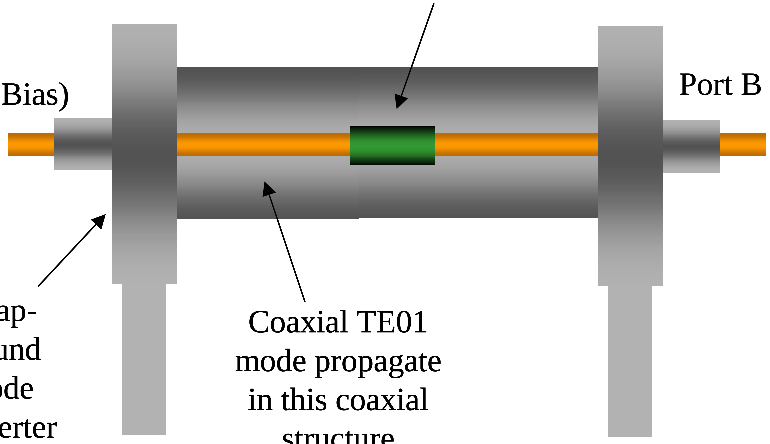
# The structure of the new thin wafer RF Switch











Garnet Material

Port A (Bias)

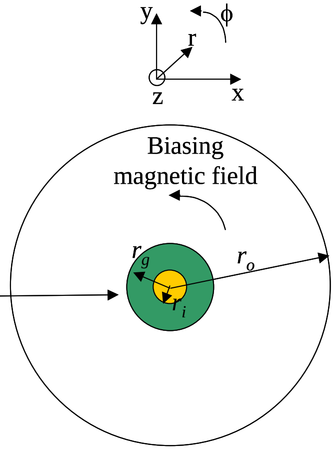
Port B (Bias)

Wrap-around Mode converter

Port 1 (rf)

Coaxial TE01 mode propagate in this coaxial structure

Port 2 (rf)



y

ϕ

r

z

x

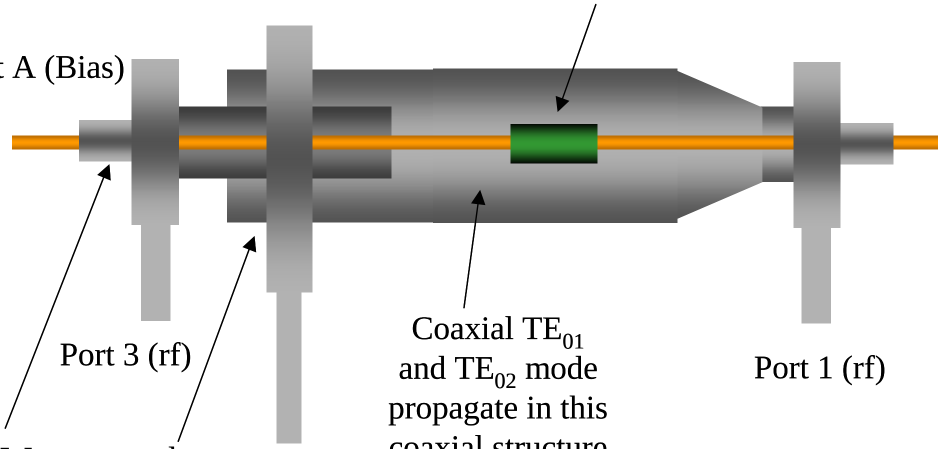
Biasing magnetic field

$r_g$

$r_o$

$r_i$

Garnet Material



Garnet Material

Port A (Bias)

Port 3 (rf)

Coaxial $TE_{01}$ and $TE_{02}$ mode propagate in this coaxial structure

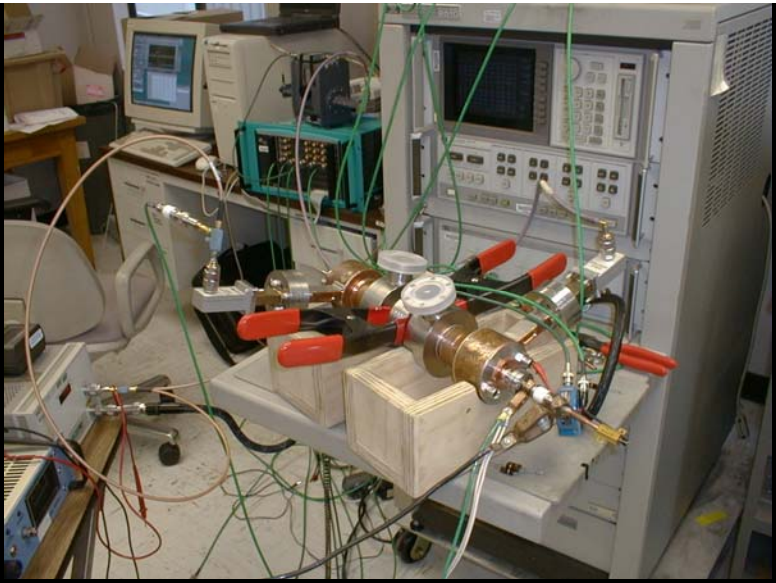
Port 1 (rf)

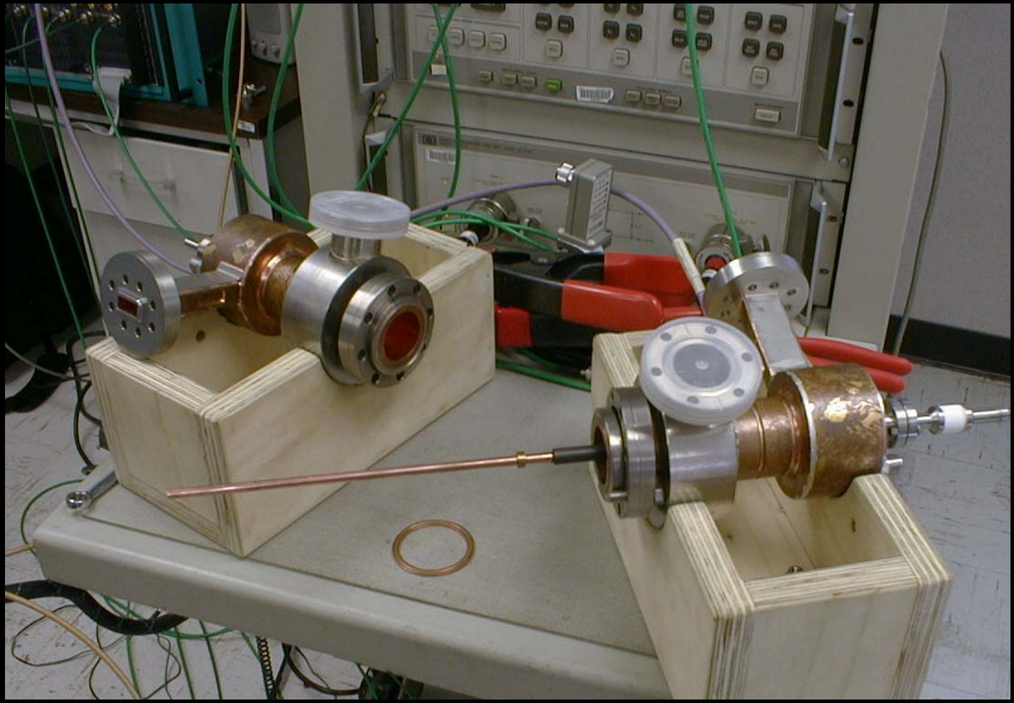
Wrap-around Mode converter

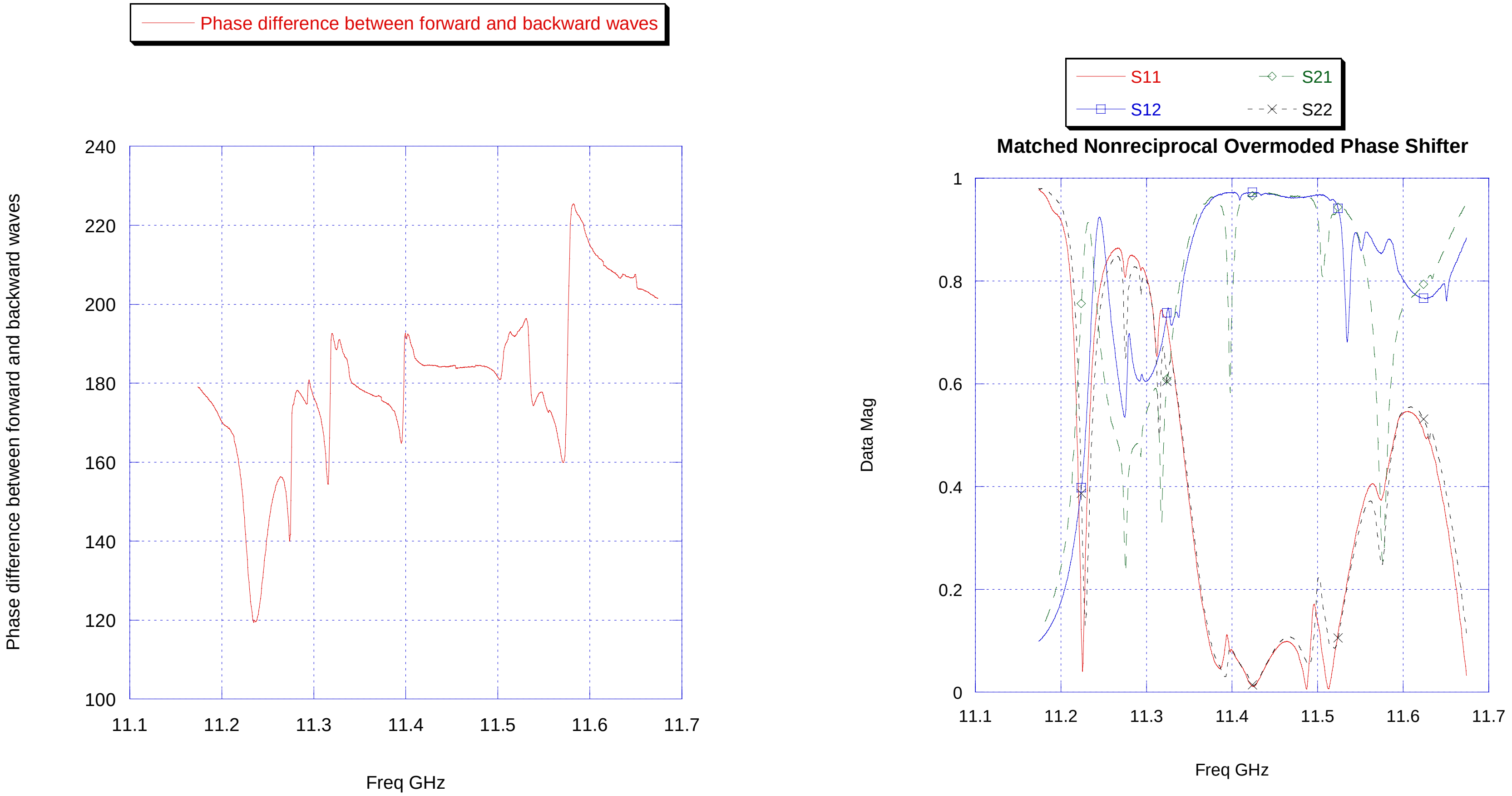
Port 2 (rf)

Wrap-Around Mode Converter for Tap-off, and extraction, tested to 470 MW

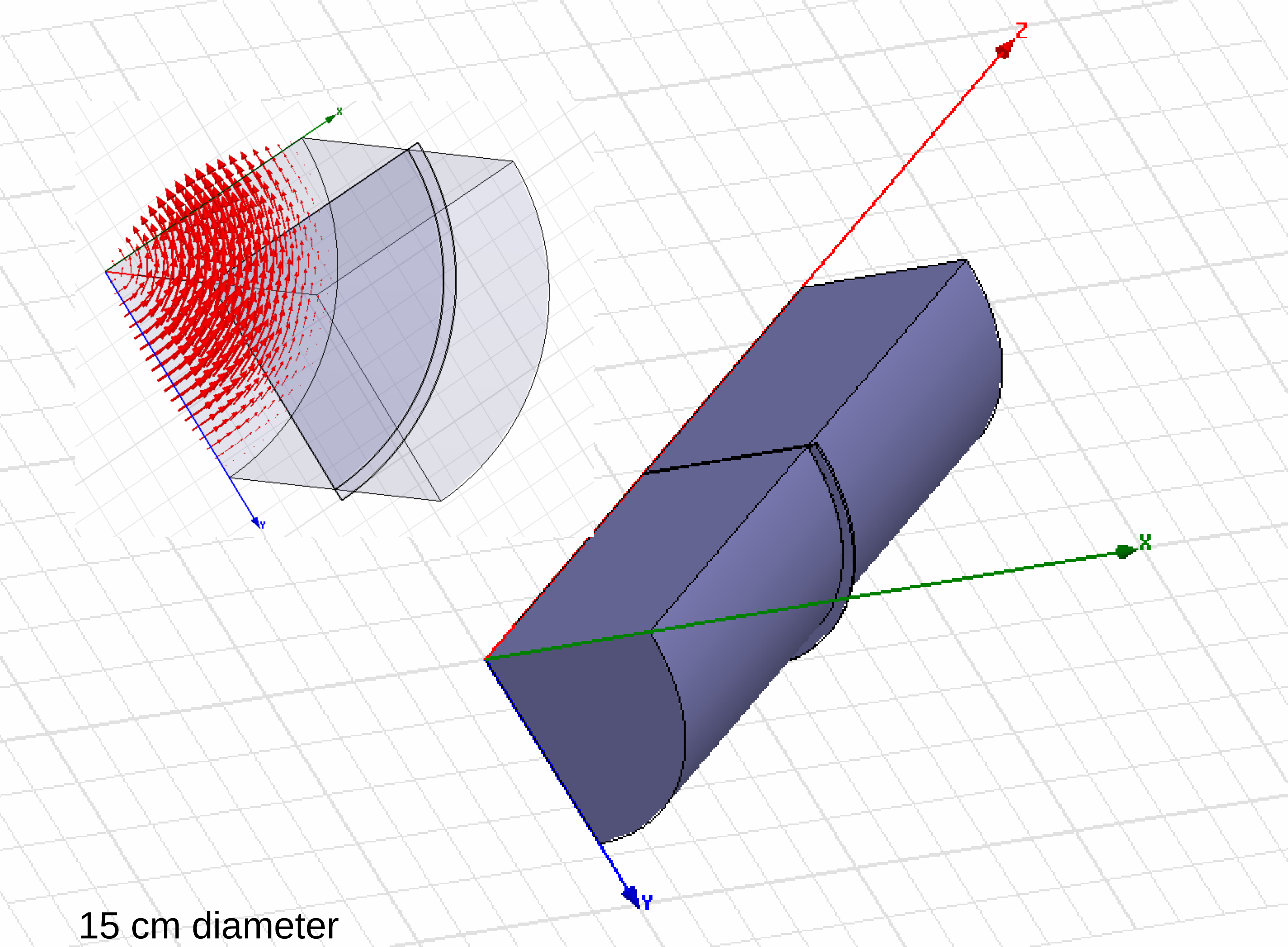
# Active nonreciprocal phase shifter prototype



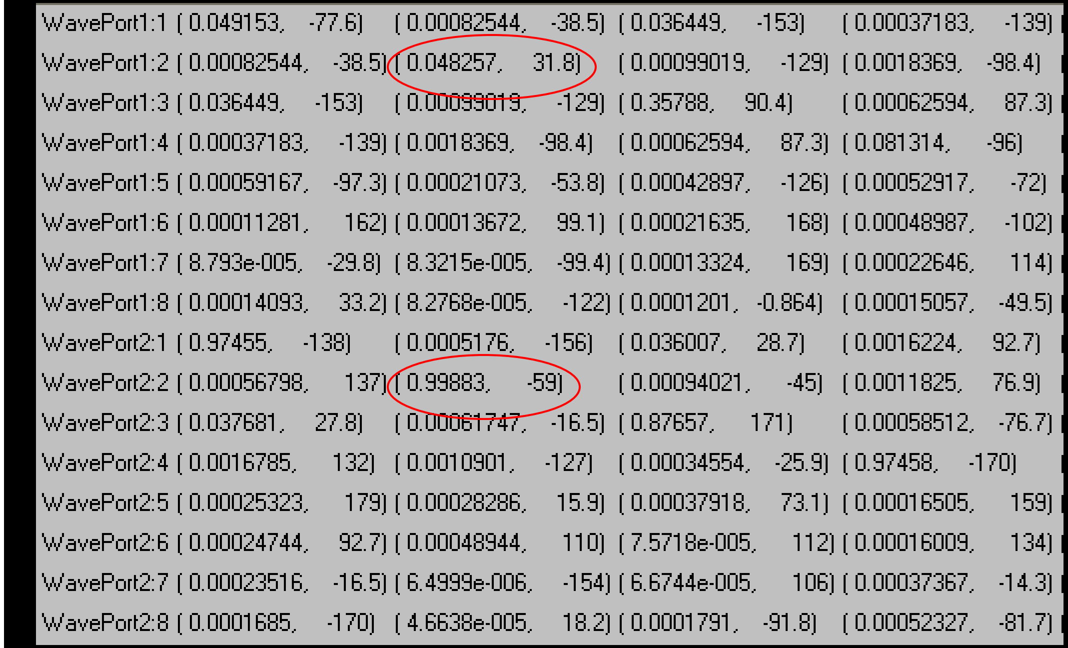




Cold test data for the first prototype of the overmoded nonreciprocal phase shifter. It indicates low losses and good match.  The phase shift between forward and backward waves is approximately 180 degrees

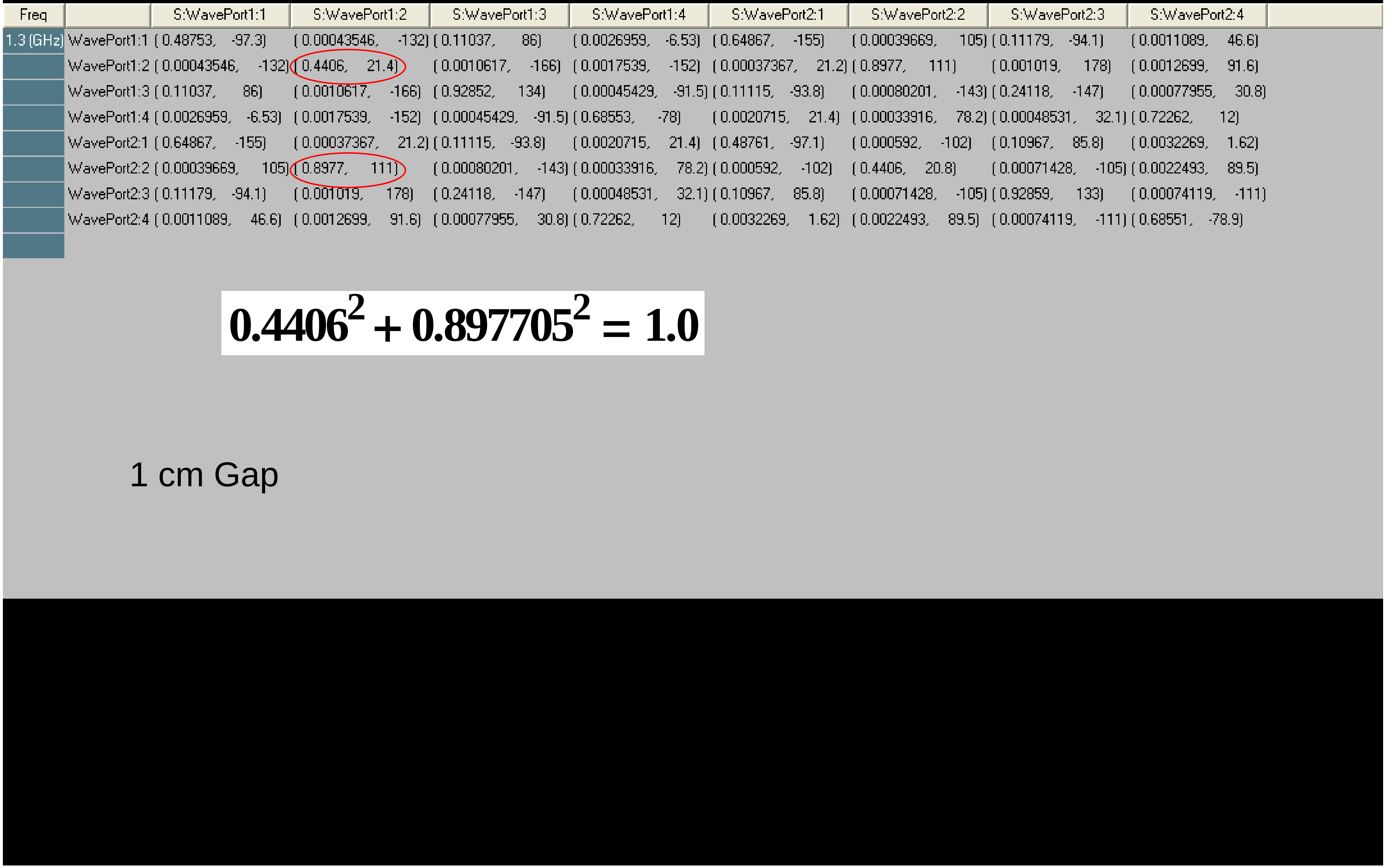


15 cm diameter



```
WavePort1:1 ( 0.049153,    -77.6)    ( 0.00082544,   -38.5) ( 0.036449,     -153)    ( 0.00037183,    -139)
WavePort1:2 ( 0.00082544,   -38.5) ( 0.048257,     31.8)    ( 0.00099019,    -129) ( 0.0018369,   -98.4)
WavePort1:3 ( 0.036449,     -153)    ( 0.00099019,     -129) ( 0.35788,     90.4)     ( 0.00062594,    87.3)
WavePort1:4 ( 0.00037183,    -139) ( 0.0018369,   -98.4)  ( 0.00062594,    87.3) ( 0.081314,      -96)
WavePort1:5 ( 0.00059167,   -97.3) ( 0.00021073,    -53.8) ( 0.00042897,    -126) ( 0.00052917,     -72)
WavePort1:6 ( 0.00011281,     162) ( 0.00013672,    99.1) ( 0.00021635,     168) ( 0.00048987,    -102)
WavePort1:7 ( 8.793e-005,   -29.8)  ( 8.3215e-005,   -99.4) ( 0.00013324,     169) ( 0.00022646,     114)
WavePort1:8 ( 0.00014093,    33.2) ( 8.2768e-005,    -122) ( 0.0001201,   -0.864)  ( 0.00015057,   -49.5)
WavePort2:1 ( 0.97455,    -138)      ( 0.0005176,    -156)  ( 0.036007,    28.7)     ( 0.0016224,    92.7)
WavePort2:2 ( 0.00056798,     137) ( 0.99883,      -59)      ( 0.00094021,     -45) ( 0.0011825,    76.9)
WavePort2:3 ( 0.037681,     27.8)    ( 0.00061747,   -16.5) ( 0.87657,      171)      ( 0.00058512,   -76.7)
WavePort2:4 ( 0.0016785,     132)   ( 0.0010901,    -127)  ( 0.00034554,   -25.9) ( 0.97458,    -170)
WavePort2:5 ( 0.00025323,     179) ( 0.00028286,    15.9)  ( 0.00037918,    73.1) ( 0.00016505,     159)
WavePort2:6 ( 0.00024744,    92.7) ( 0.00048944,     110)  ( 7.5718e-005,     112) ( 0.00016009,     134)
WavePort2:7 ( 0.00023516,   -16.5) ( 6.4999e-006,    -154) ( 6.6744e-005,     106) ( 0.00037367,   -14.3)
WavePort2:8 ( 0.0001685,    -170)   ( 4.6638e-005,    18.2) ( 0.0001791,    -91.8)   ( 0.00052327,   -81.7)
```

$$0.048567^2 + 0.99883^2 = 1.00002$$

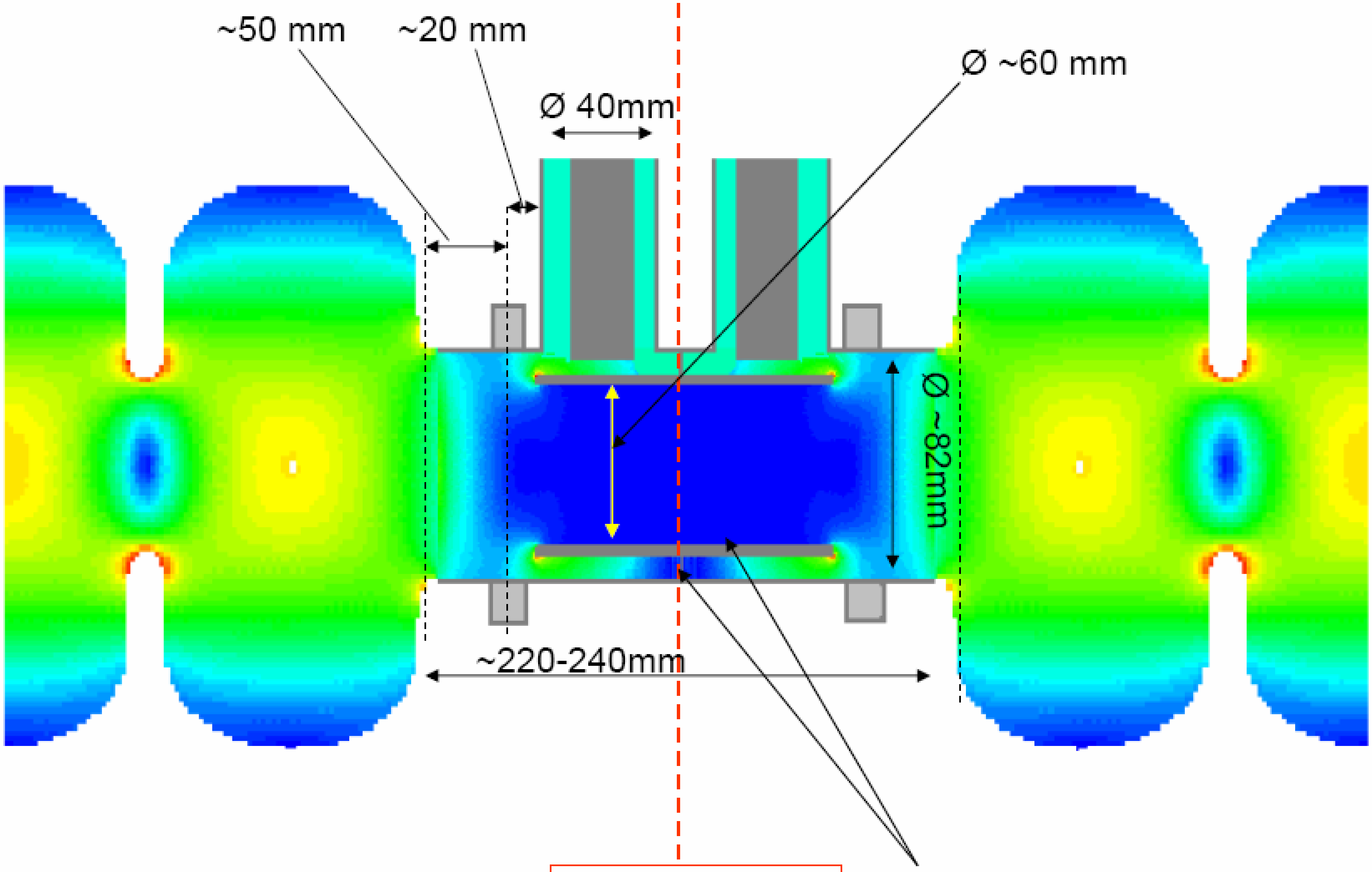


| Freq | | S:WavePort1:1 | S:WavePort1:2 | S:WavePort1:3 | S:WavePort1:4 | S:WavePort2:1 | S:WavePort2:2 | S:WavePort2:3 | S:WavePort2:4 | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.3 (GHz) | WavePort1:1 | ( 0.48753, -97.3) | ( 0.00043546, -132) | ( 0.11037, 86) | ( 0.0026959, -6.53) | ( 0.64867, -155) | ( 0.00039669, 105) | ( 0.11179, -94.1) | ( 0.0011089, 46.6) | |
| | WavePort1:2 | ( 0.00043546, -132) | ( 0.4406, 21.4) | ( 0.0010617, -166) | ( 0.0017539, -152) | ( 0.00037367, 21.2) | ( 0.8977, 111) | ( 0.001019, 178) | ( 0.0012699, 91.6) | |
| | WavePort1:3 | ( 0.11037, 86) | ( 0.0010617, -166) | ( 0.92852, 134) | ( 0.00045429, -91.5) | ( 0.11115, -93.8) | ( 0.00080201, -143) | ( 0.24118, -147) | ( 0.00077955, 30.8) | |
| | WavePort1:4 | ( 0.0026959, -6.53) | ( 0.0017539, -152) | ( 0.00045429, -91.5) | ( 0.68553, -78) | ( 0.0020715, 21.4) | ( 0.00033916, 78.2) | ( 0.00048531, 32.1) | ( 0.72262, 12) | |
| | WavePort2:1 | ( 0.64867, -155) | ( 0.00037367, 21.2) | ( 0.11115, -93.8) | ( 0.0020715, 21.4) | ( 0.48761, -97.1) | ( 0.000592, -102) | ( 0.10967, 85.8) | ( 0.0032269, 1.62) | |
| | WavePort2:2 | ( 0.00039669, 105) | ( 0.8977, 111) | ( 0.00080201, -143) | ( 0.00033916, 78.2) | ( 0.000592, -102) | ( 0.4406, 20.8) | ( 0.00071428, -105) | ( 0.0022493, 89.5) | |
| | WavePort2:3 | ( 0.11179, -94.1) | ( 0.001019, 178) | ( 0.24118, -147) | ( 0.00048531, 32.1) | ( 0.10967, 85.8) | ( 0.00071428, -105) | ( 0.92859, 133) | ( 0.00074119, -111) | |
| | WavePort2:4 | ( 0.0011089, 46.6) | ( 0.0012699, 91.6) | ( 0.00077955, 30.8) | ( 0.72262, 12) | ( 0.0032269, 1.62) | ( 0.0022493, 89.5) | ( 0.00074119, -111) | ( 0.68551, -78.9) | |

$$0.4406^2 + 0.897705^2 = 1.0$$

1 cm Gap

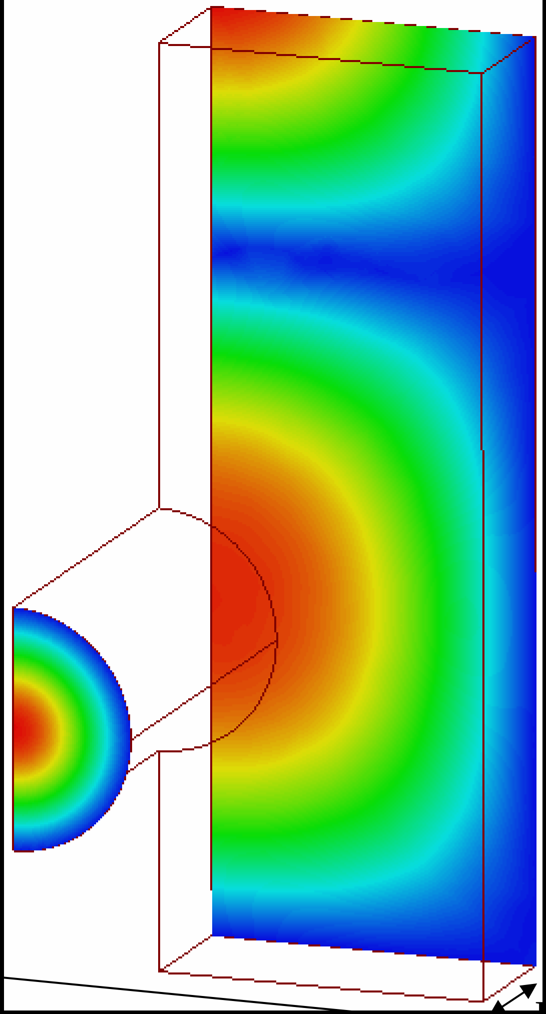
Not in scale !!!!!

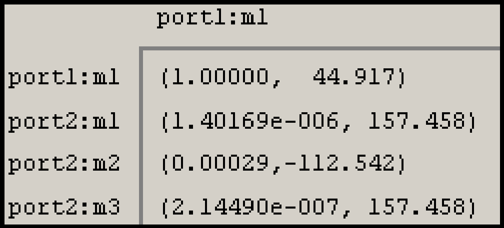


Symmetry plane

~2-4 mm thickness

# WR650 to 6cm Beampipe Waveguide Coupler



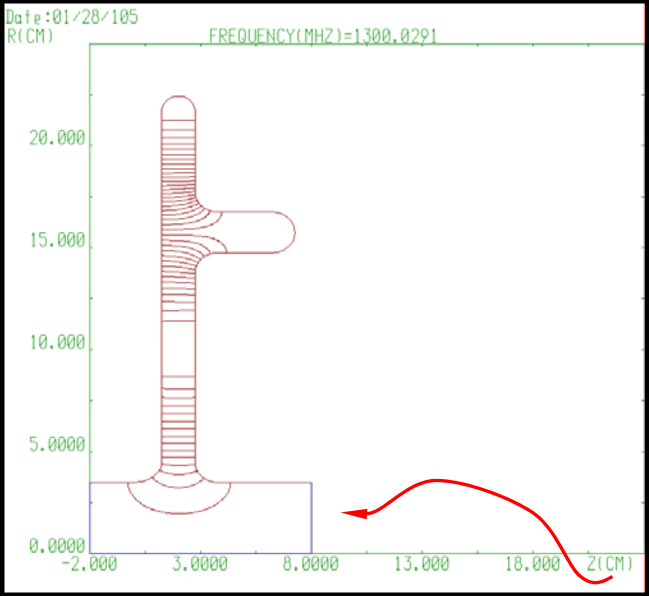


| | port1:m1 |
|---|---|
| port1:m1 | (1.00000, 44.917) |
| port2:m1 | (1.40169e-006, 157.458) |
| port2:m2 | (0.00029,-112.542) |
| port2:m3 | (2.14490e-007, 157.458) |

# Chock coupler for 1.3 GHz superconducting structure

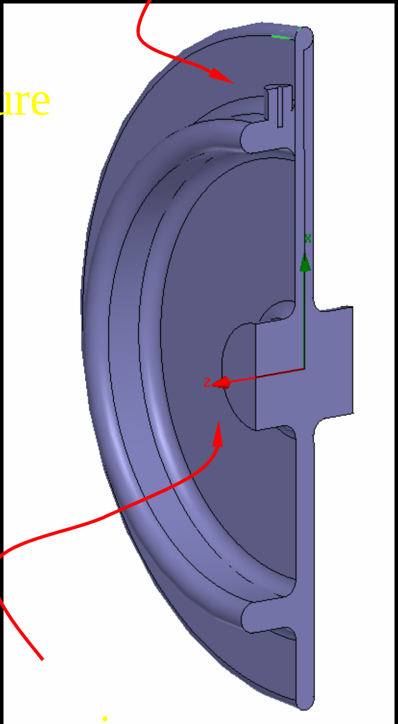
## Properties

- Circular symmetric flange to superconducting structure
- No current on the flange joint
- Symmetric fields on axis
- Takes little longitudinal space
- Could be used in the middle of structure



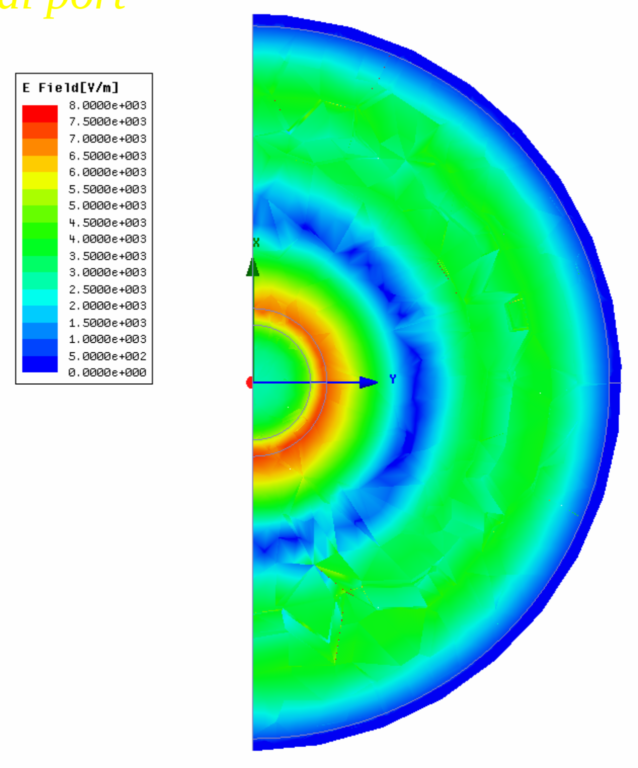
Electric field lines calculated by 2D finite-element code SLANS

*Input coaxial port*



*Beam pipe*

3D geometry with coupling port



Magnitude of electric fields on chock mid-plane excited by coaxial port, 3D HFSS calculation

*V.A. Dolgashev, SLAC, 28 January 04*

- RF Sources:
  - Small RF sources cabple of powering one or two cavities are important to speed R&D efforts
    - We would like to develop a compact inexpensive rf crossed field device. 30 such devices can replace a klystron (In the current design the power from the klystrons are divided 30 ways!) This would be more efficient and, although not obvious, I believe less expensive. The development would capitalize on L-band commercial cooker magnetrons that have an efficiency of 90%.
    - Solid state sources become a viable alternative at L-band. Our experience with these devices at the much more difficult X-band could help in the development of a completely solid state source.
    - Through the SBIR program we would like to we could develop a new multi-beam klystron. The output cavity and structures would rely on our experience in overmoded and multimoded rf systems. This will give the klystron designer the opportunity to separate the beams and hence increase the reliability of these klystrons. This klystron will operate at voltage lower than 30 kV and output power close to 1 MW.
- Accelerator Structure Couplers: The present design for these devices is very complicated and expensive. We could contribute to the modification of these devices to increase their reliability and decrease there cost.

# Conclusion

- By Relating spacing of cavities to the RF distribution system it is possible to eliminate about 20000 Circulator ($20 M to $200 M) without any clear draw backs

- *One should think about the main linac as a system*. The separation of the development of the RF sources from the modulators from the distribution system from the power couplers from linac / cryogenic module development will result in lost opportunities

- Spatially combined RF devices can provide RF sources. It can also provide switches to enhance the charging and discharging of the cavities, i.e., active couplers.