Klystron Cluster Concept for ILC High-Power RF Power Distribution

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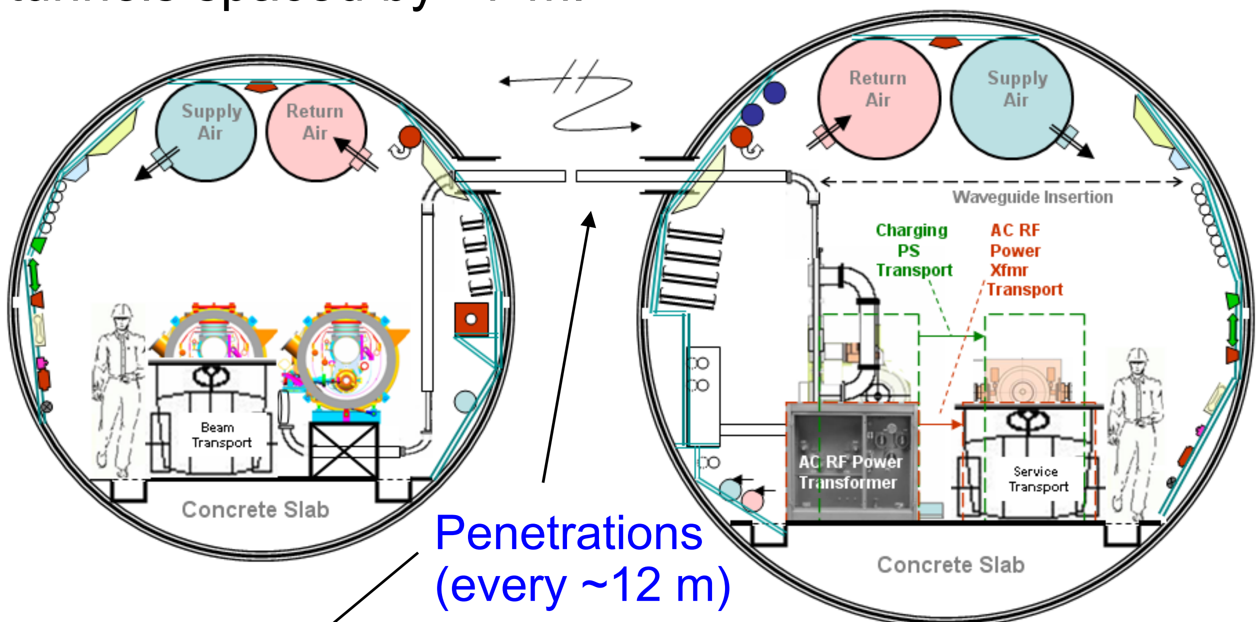
Baseline Tunnel Layout

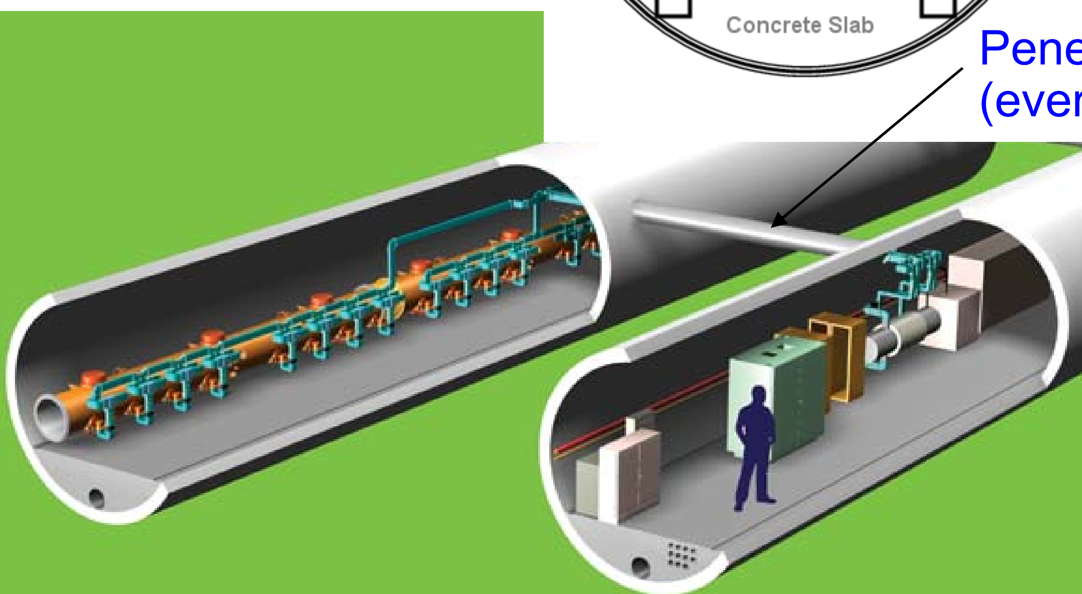
Two 4-5 m diameter tunnels spaced by ~7 m.



Accelerator Tunnel

Waveguides
Cryomodules

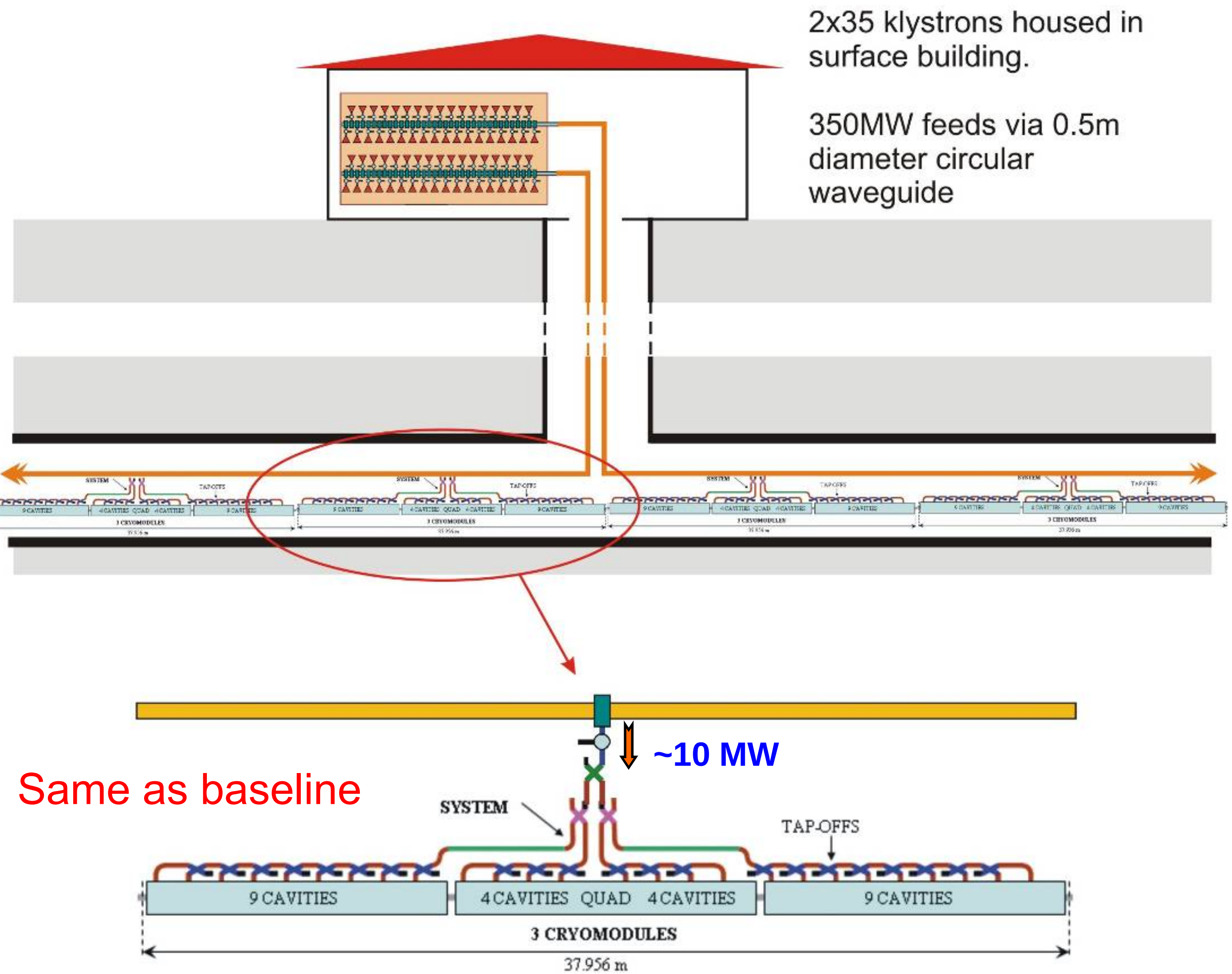
Penetrations
(every ~12 m)



Service Tunnel

Modulators
Klystrons
Electrical Dist
Cooling System

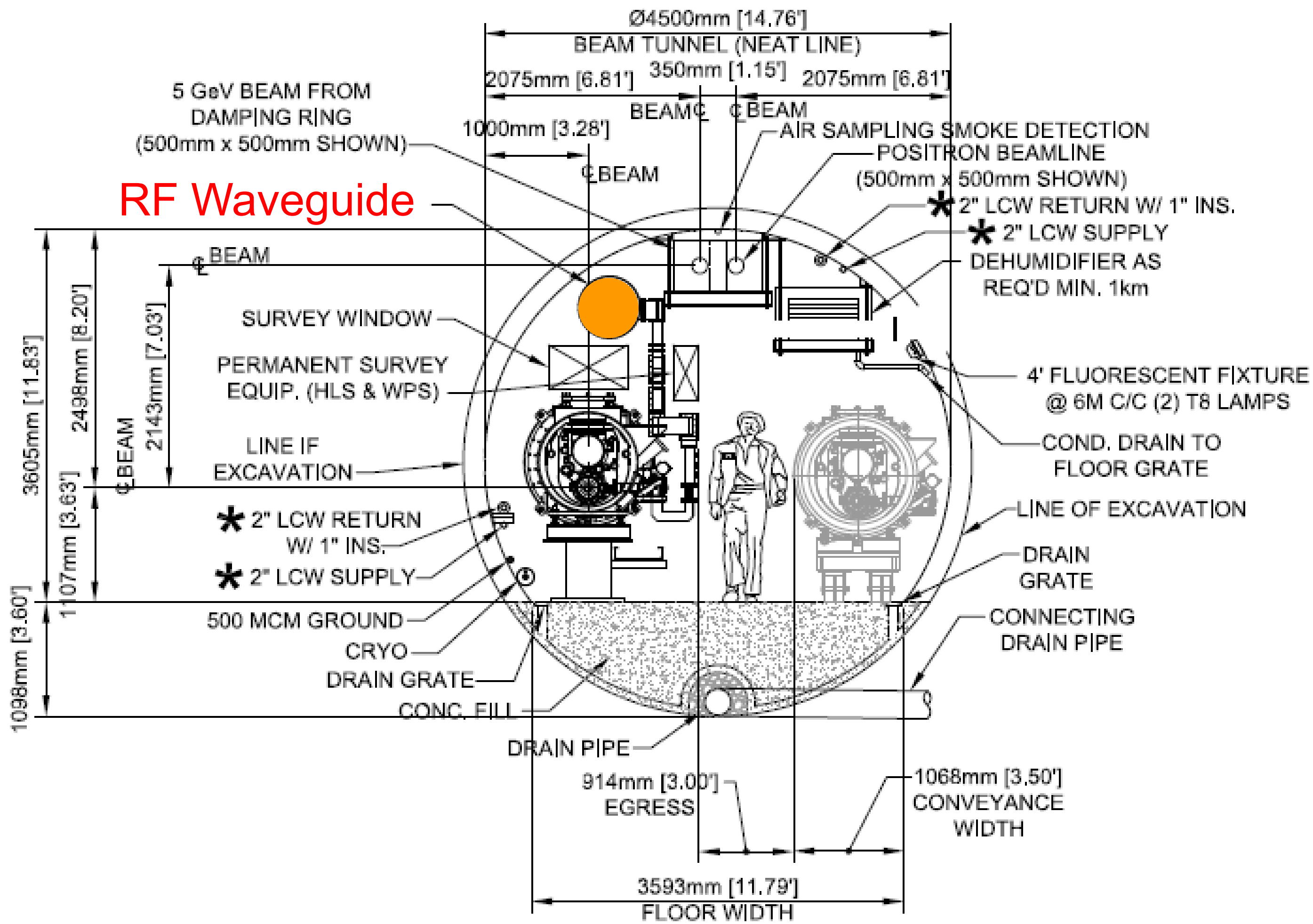
Klystron Cluster Concept



Each tap-off from the main waveguide feeds 10 MW through a high power window and probably a circulator or switch to a local PDS for a 3 cryomodule, 26 cavity RF unit (RDR baseline).

- RF power "piped" into accelerator tunnel every 2.5 km
- Service tunnel eliminated
- Electrical and cooling systems simplified
- Concerns: power handling, LLRF control coarseness

First Pass at New Tunnel Layout



TYPICAL MAIN LINAC SECTION

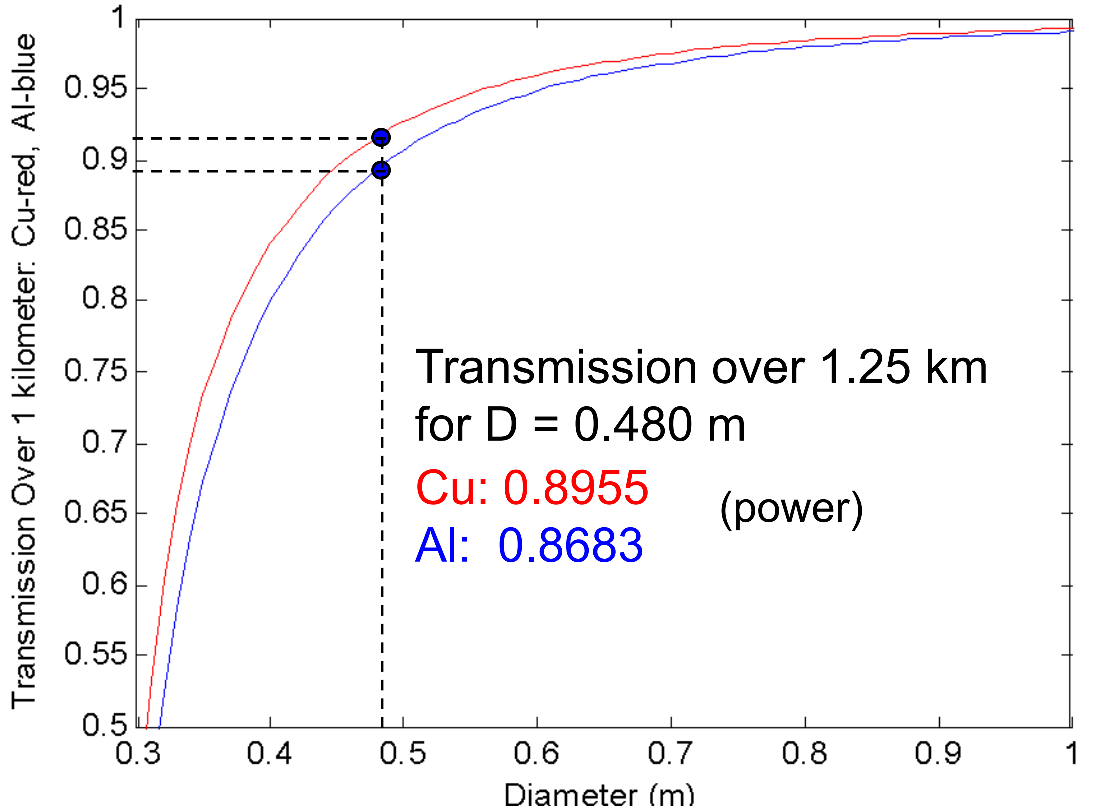
DRAFT FOR REVIEW

Waveguide Attenuation

Use low-loss TE_{01} mode in overmoded circular waveguide.
Assume smooth copper plated walls:

TE°_{01}: $$\alpha = \frac{R_s}{Z_0} \frac{1}{\sqrt{k_0^2 - (\chi_{01}/a)^2}} \frac{\chi_{01}^2}{k_0 a^3}$$

Take D = 0.480 m = 18.898"
between TE_{51} and TE_{22} cutoffs,
6.8% below TE_{02} cutoff



Average added power attenuation loss ~6%.

Al is 28% lossier than Cu.

Waveguide Tolerances

It's difficult to set tolerances for long, overmoded waveguide runs, since mode conversion depends not only on distortions but on their longitudinal profile.

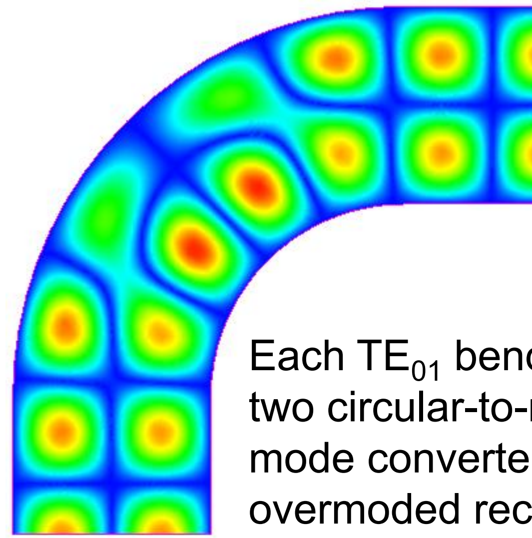
Using formulae for discreet discontinuities, however, we can set tolerances at the flange joints between sections. Allowing a maximum of ~0.1% per discontinuity type along an rf unit composed of seven 5m sections, we get numbers like:

Radius:	$\Delta R < 1.12$ mm = 0.044"
Offset:	$b < 1.62$ mm = 0.064"
Tilt:	$\delta < 9.08$ mrad = 0.52°; $\left\lvert \sum \vec{\delta} \right\rvert < 26$ mrad = 1.5°
Roundness:	$\varepsilon < 0.808$ mm = 0.032".

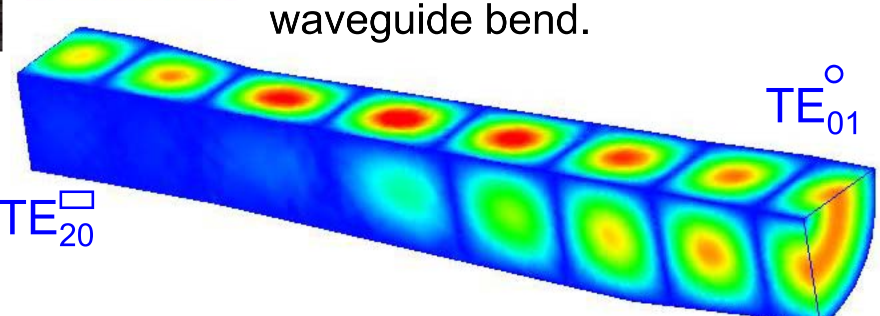
Overmoded Bend
(Two Approaches)

General Atomics high power 90° profiled curvature bend in 44.5 mm corrugated waveguide for TE_{01} mode at 11.424 GHz

Suitable design not yet produced.



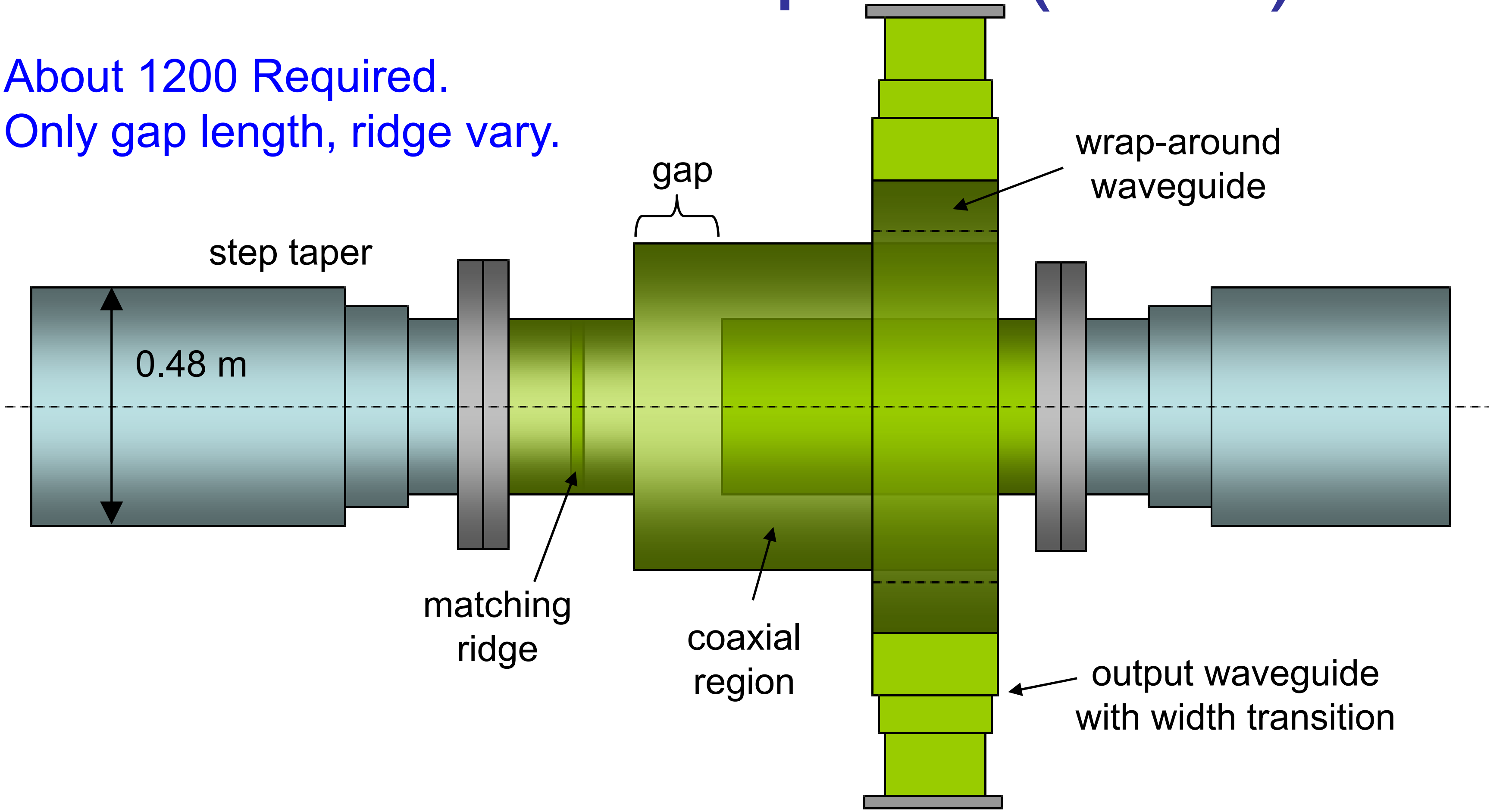
Each TE_{01} bend is composed of two circular-to-rectangular mode converters and an overmoded rectangular waveguide bend.



SLAC compact high power 90° bend in 40.6 mm circular waveguide tapered to overmoded rectangular waveguide for TE_{01} mode at 11.424 GHz

Coaxial Tap Off (CTO)

About 1200 Required.
Only gap length, ridge vary.



Power is tapped off from the circular TE_{01} mode, in 10MW increments, into a coaxial region, without breaking azimuthal symmetry (no surface E fields).

A wrap-around mode converter extracts this power from the coaxial TE_{01} mode into two output waveguides (5MW each), analogous to klystron output arms.

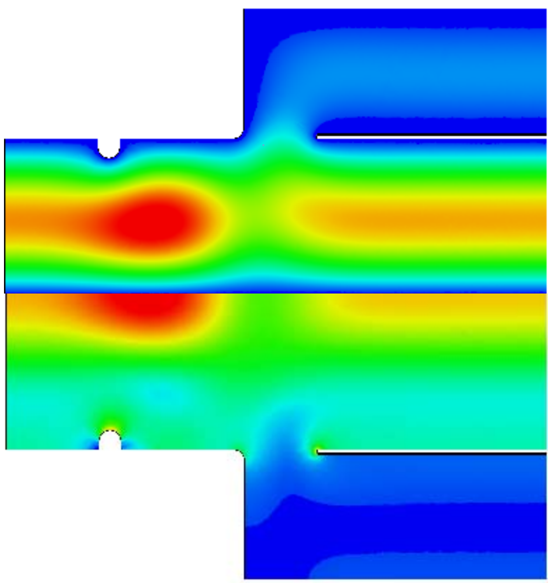
The same devices are used in reverse for launching power into the pipe.

Coaxial Power Division

With gaps ranging from <3” to ~8½”, we can get the full range of couplings needed, from ~3% up to 50%.

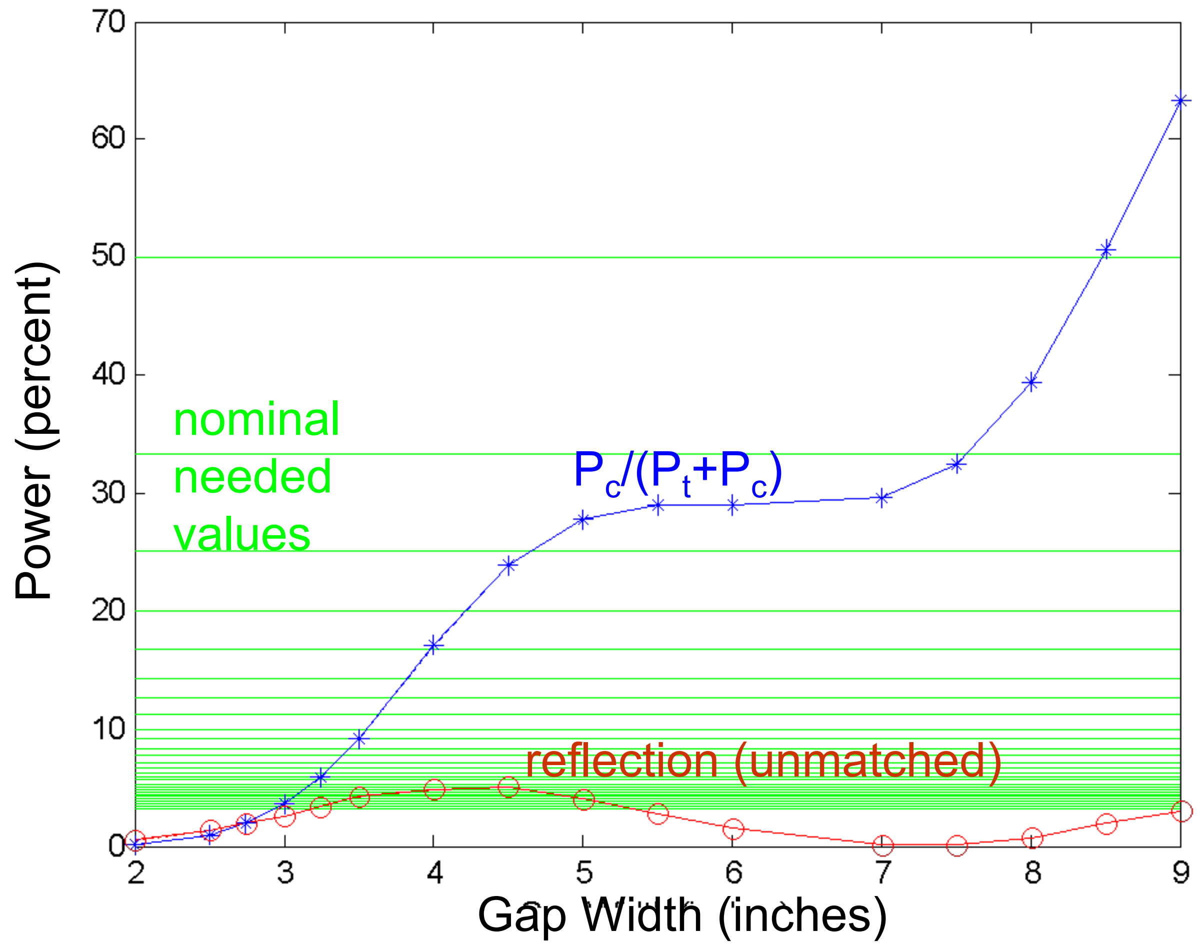
The various coupling designs will differ only in a) gap width and b) matching ridge.

All couplers share a single common design for the wrap-around section.

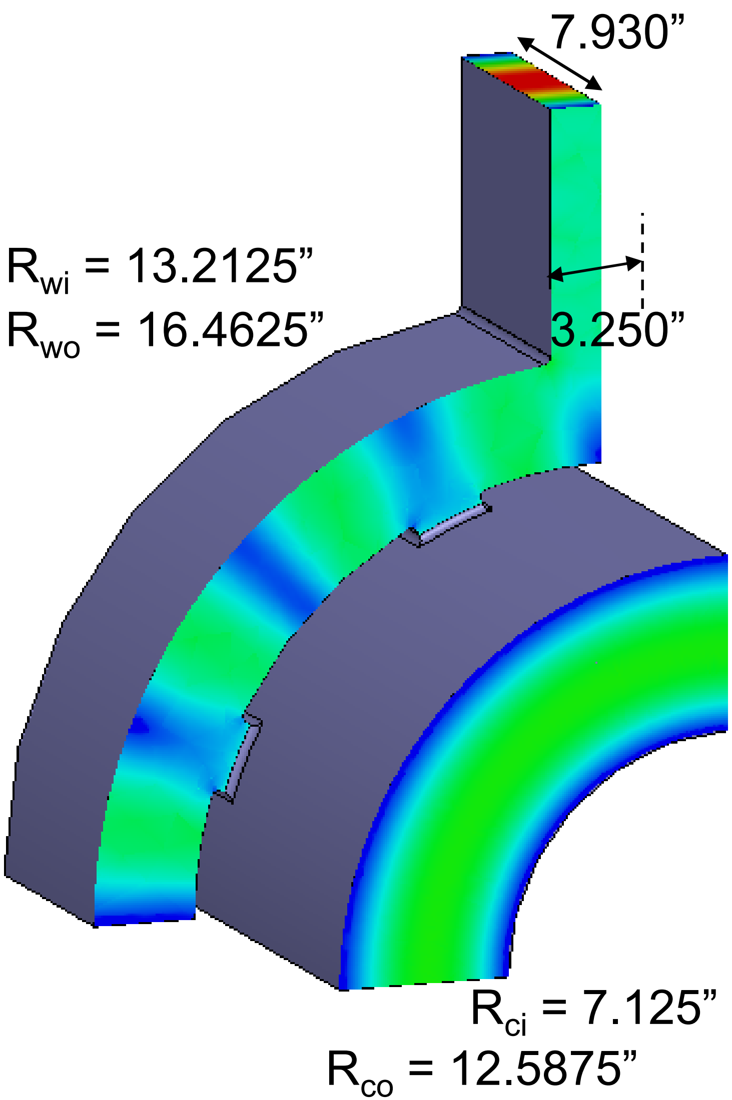


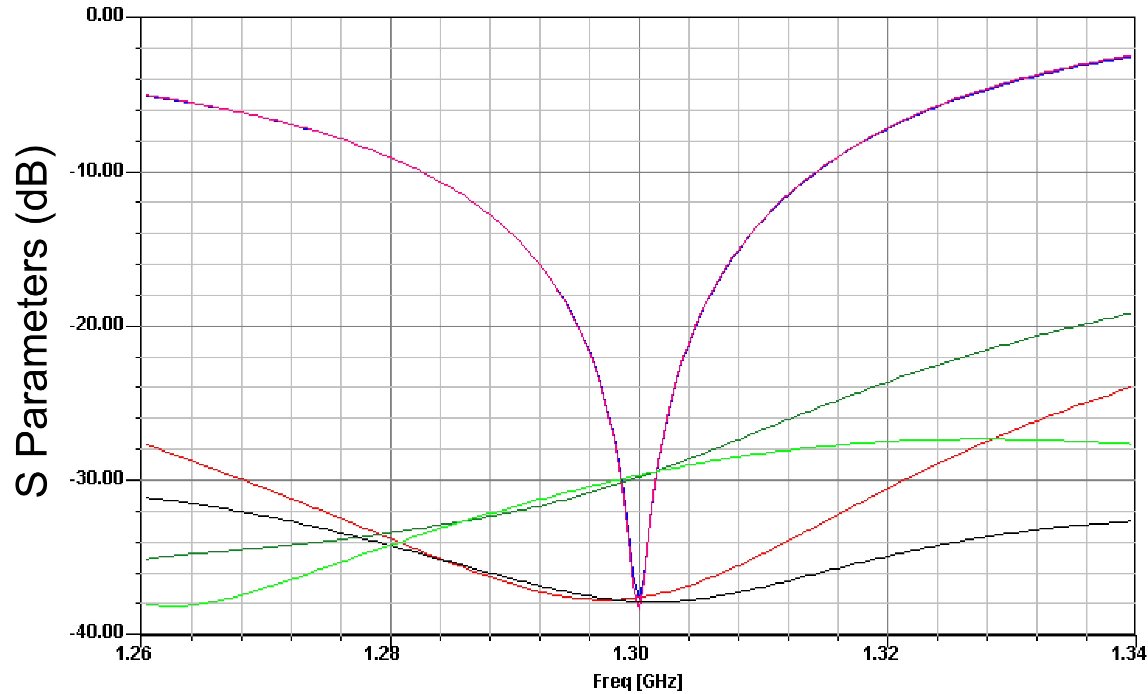
$|H|_m = 0.798\ \mathrm{sqrt}(P)$
$= 14.7$ kA/m @ 340 MW

$|E|_m = 208\ \mathrm{sqrt}(P)$
$= 3.84$ MV/m @ 340 MW



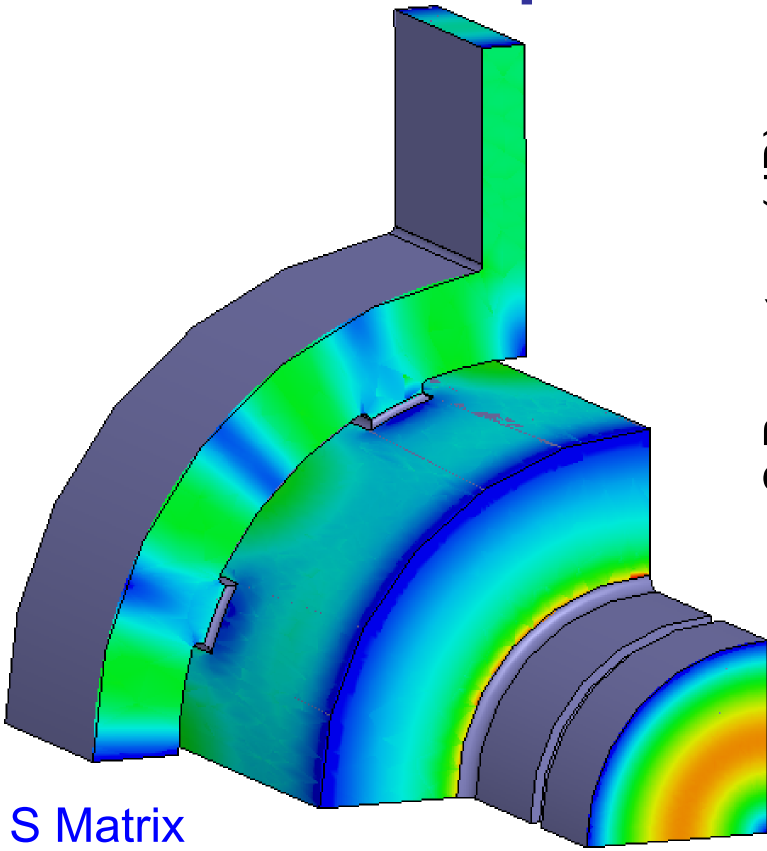
Coaxial Wrap-around

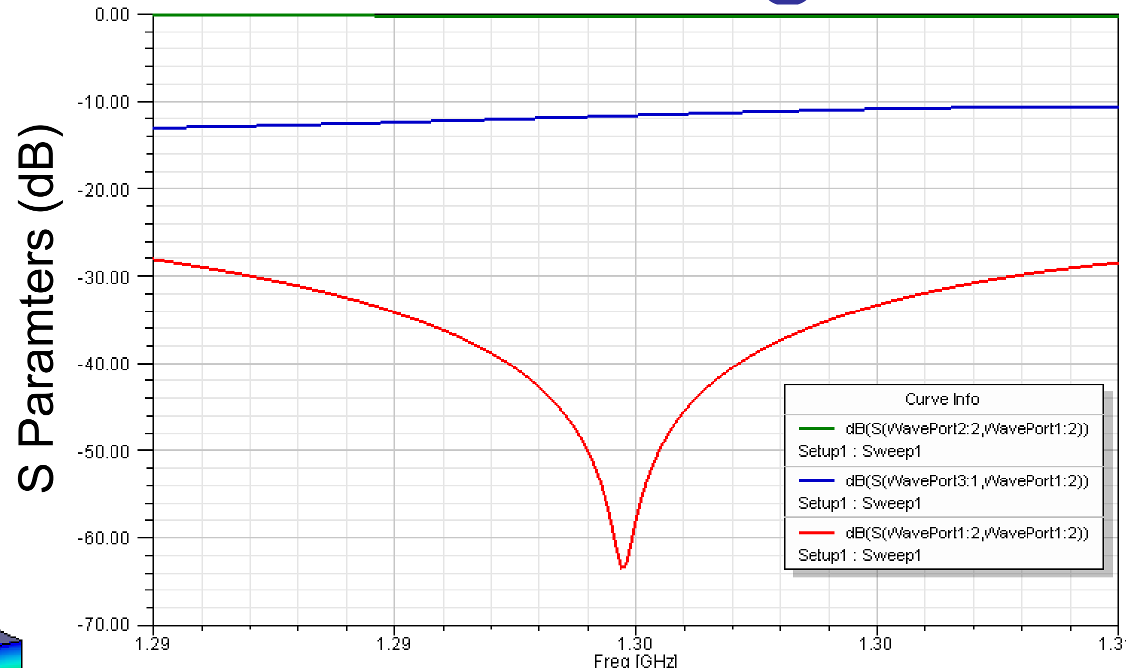




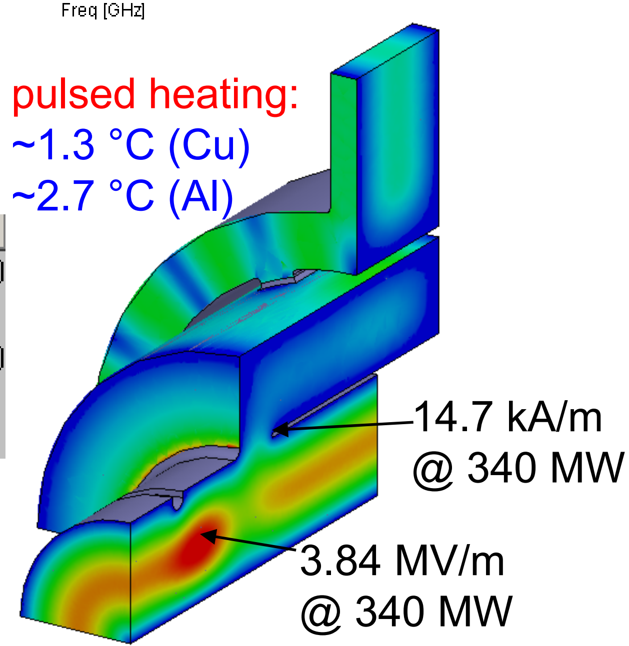
	S:WavePort1:1	S:WavePort2:3
WavePort1:1	(0.013334, -2.15)	(0.99928, -32.1)
WavePort2:1	(0.0032794, -20.2)	(0.0037883, 102)
WavePort2:2	(0.00015812, 27.2)	(0.00015907, 127)
WavePort2:3	(0.99928, -32.1)	(0.012269, 121)
WavePort2:4	(0.013353, 23.9)	(0.012966, 143)
WavePort2:5	(0.00019888, -78.9)	(0.00021591, 18.7)
WavePort2:6	(0.032654, 152)	(0.033168, -89.6)

Complete CTO RF Design





pulsed heating:
~1.3 °C (Cu)
~2.7 °C (Al)



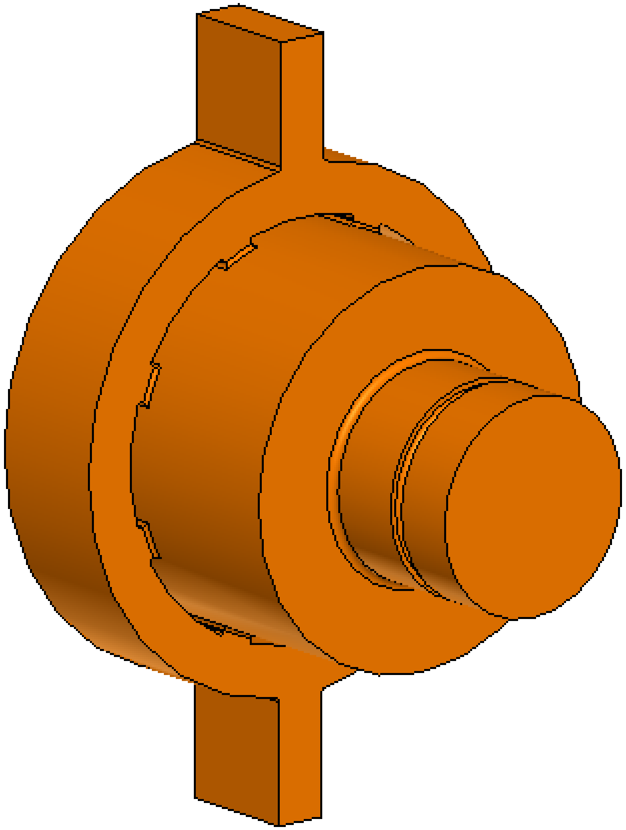
S Matrix

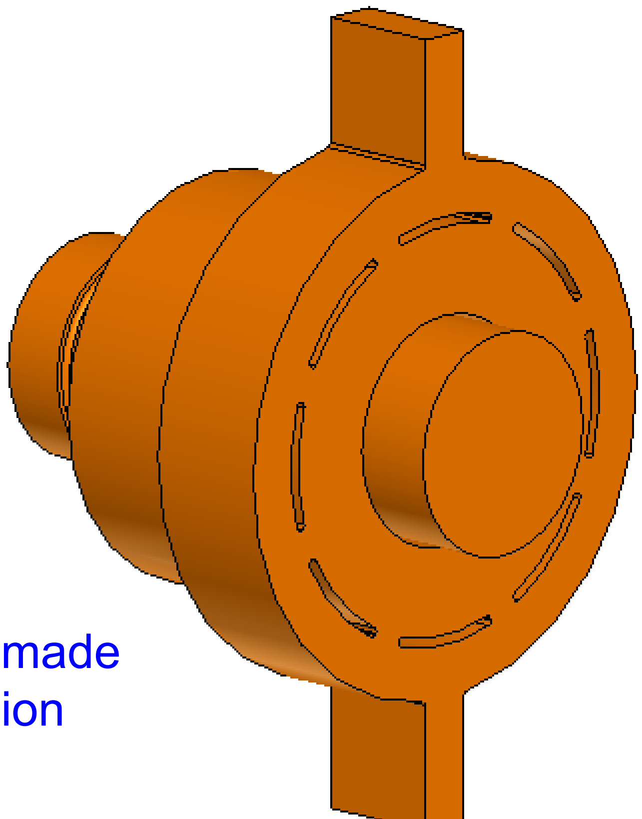
	S:WavePort1:1	S:WavePort1:2	S:WavePort2:1	S:WavePort2:2	S:WavePort3:1
WavePort1:1	(0.090946, 151)	(0.0012548, -153)	(0.99585, -2.31)	(0.0012453, 78.9)	(0.0035456, -30.9)
WavePort1:2	(0.0012548, -153)	(0.0014488, -56.6)	(0.00058577, 141)	(0.96503, -18.4)	(0.26213, 22.4)
WavePort2:1	(0.99585, -2.31)	(0.00058577, 141)	(0.090939, 24.2)	(0.0011792, 5.21)	(0.0038989, -63.5)
WavePort2:2	(0.0012453, 78.9)	(0.96503, -18.4)	(0.0011792, 5.21)	(0.067493, -5.6)	(0.2533, -144)
WavePort3:1	(0.0035456, -30.9)	(0.26213, 22.4)	(0.0038989, -63.5)	(0.2533, -144)	(0.93118, 76.6)

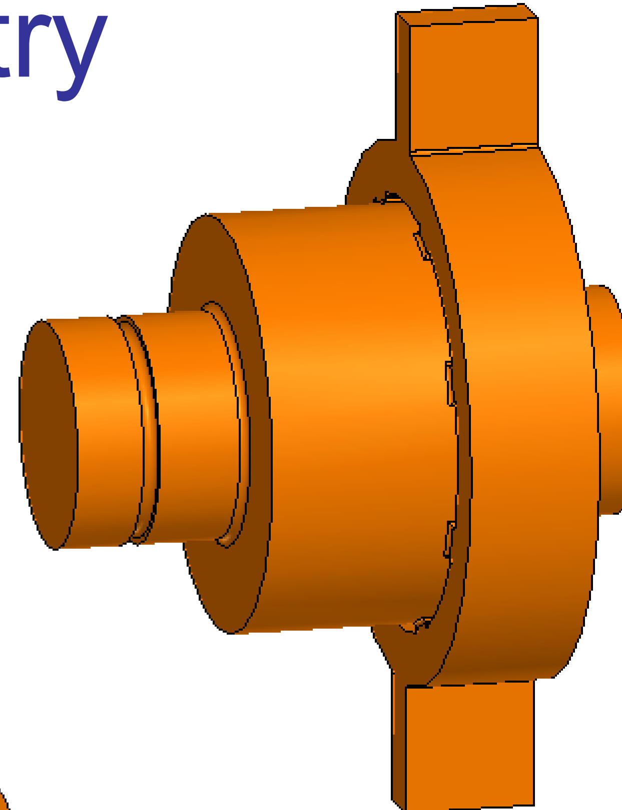
coupling: 6.86% (-11.64 dB)

return loss & parasitic modes: < -56 dB

CTO Geometry



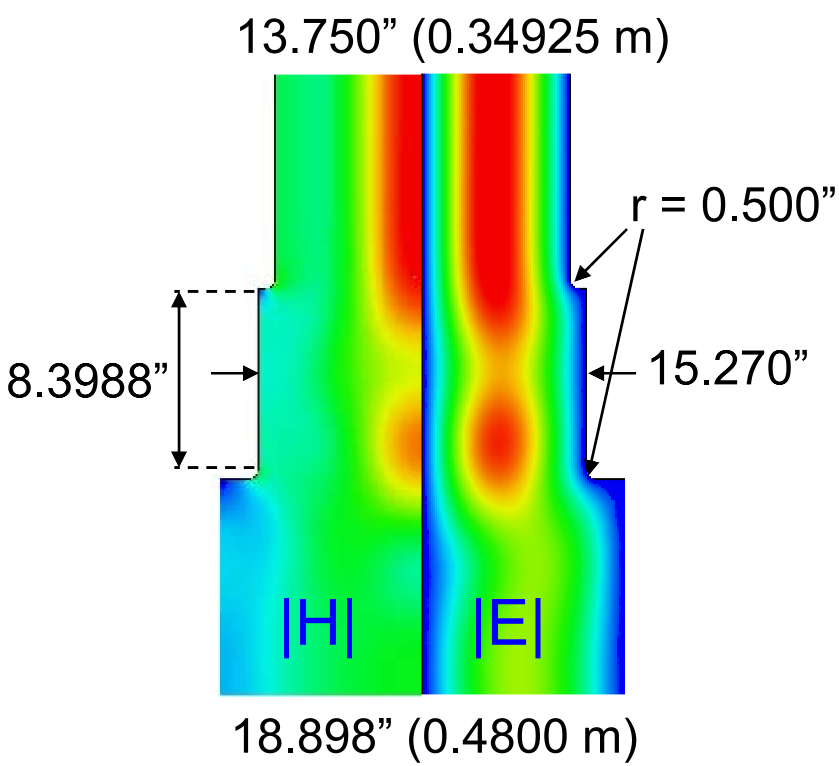




Slight modifications will be made for fabrication after discussion with mechanical engineer.

Auxiliary Parts

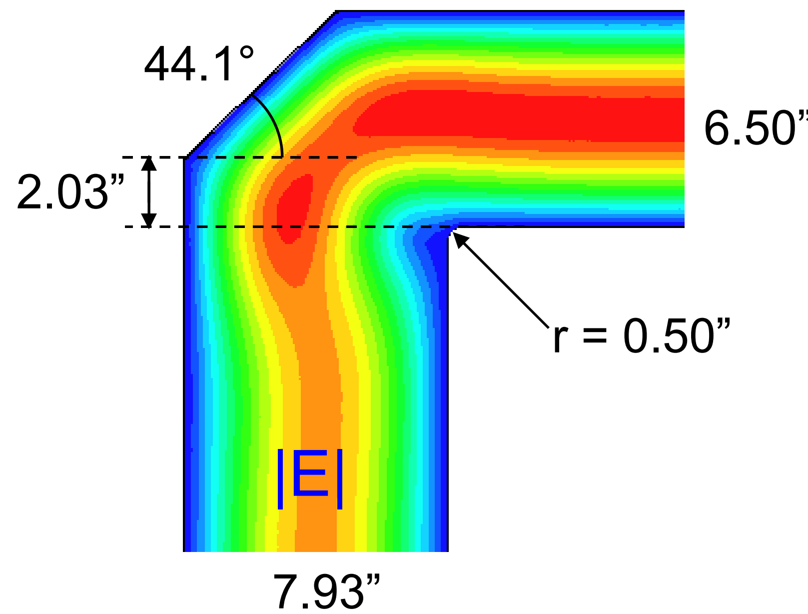
Step Taper



S =

(0.00035425, 31.6)	(1, -76.2)
(1, -76.2)	(0.00035425, -3.99)

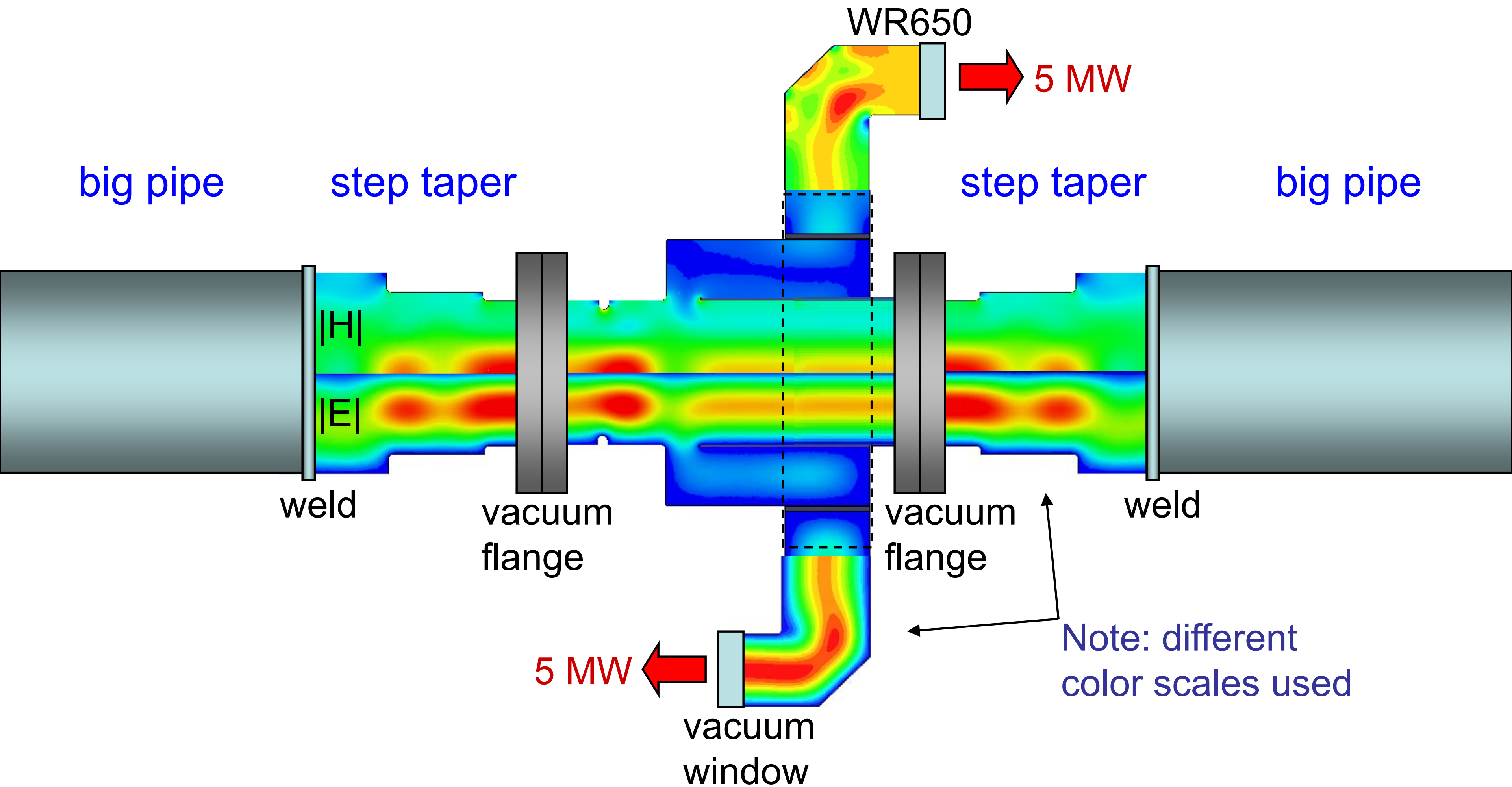
Asymmetric Bend



S =

(0.00088637, 175)	(1, -179)
(1, -179)	(0.00088637, 7.02)

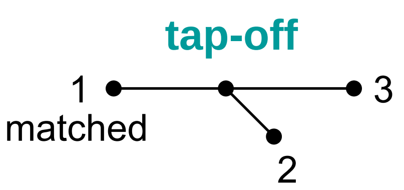
Layout of Tap-Off Region
w/ field patterns



First Launcher and Final Tap-off

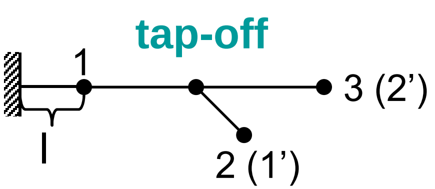
The scattering matrix for a lossless 3-port tap-off with coupling C and reference planes chosen to make all elements real (port 2→S_{22} real, port 1→S_{21} real, port 3→S_{31} real) can be written:

$$\mathbf{S} = \begin{pmatrix} 0 & \sqrt{C} & \sqrt{1-C} \\ \sqrt{C} & (1-C) & -\sqrt{C(1-C)} \\ \sqrt{1-C} & -\sqrt{C(1-C)} & C \end{pmatrix}$$



Short port 1 at a distance *l* to reduce to a 2-port coupler and adjust C and l to achieve desired coupling.

$$\mathbf{S}' = \begin{pmatrix} 1-C\left(1+e^{-i2\beta l}\right) & -\sqrt{C(1-C)}\left(1+e^{-i2\beta l}\right) \\ -\sqrt{C(1-C)}\left(1+e^{-i2\beta l}\right) & C\left(1+e^{-i2\beta l}\right)-e^{-i2\beta l} \end{pmatrix}$$



$$\beta l = 0, \pi \rightarrow \mathbf{S}' = \begin{pmatrix} 1-2C & -2\sqrt{C(1-C)} \\ -2\sqrt{C(1-C)} & 2C-1 \end{pmatrix}$$

$$\rightarrow C' \equiv \left|S'_{21}\right|^2 = 4C(1-C)$$

$$\beta l = 0, \pi, \ldots \text{ and } C = \frac{1}{2} \rightarrow \boxed{C' = 1}$$

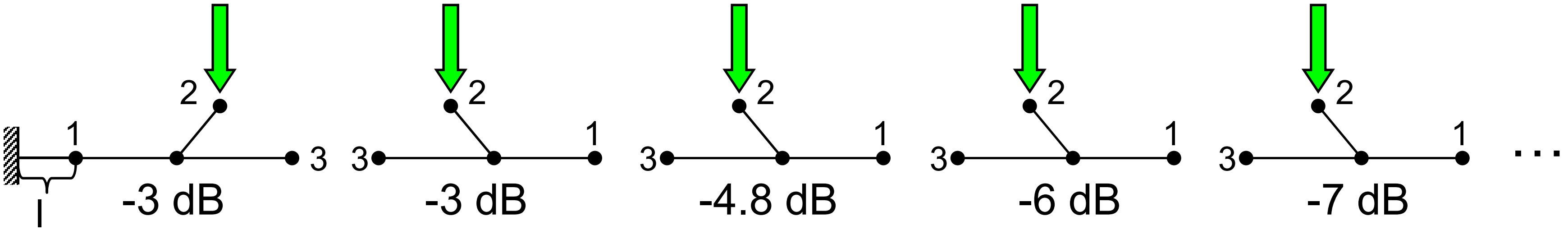
mode launcher or 100% tap-off

Arrangement of CTO's

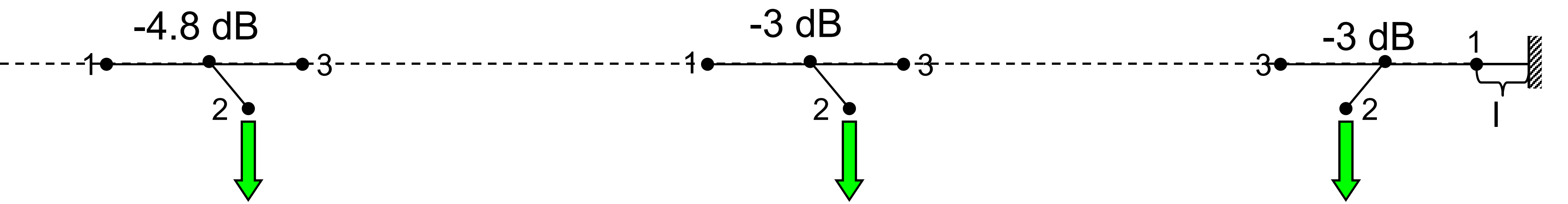
First combiner (launcher) and last tap-off (extractor) are 3 dB units reversed relative to the others and shorted (with proper phase length) at port 1.

All others depend on proper ratio of flowing to added power and proper relative phase.

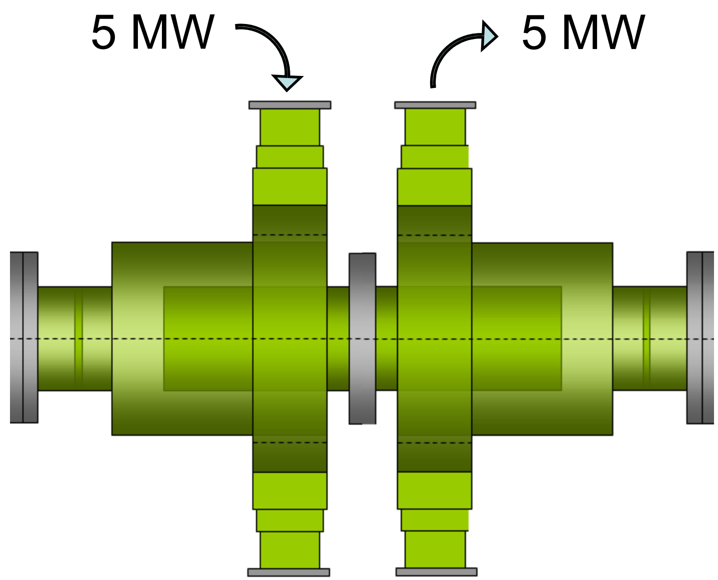
Power Combining:



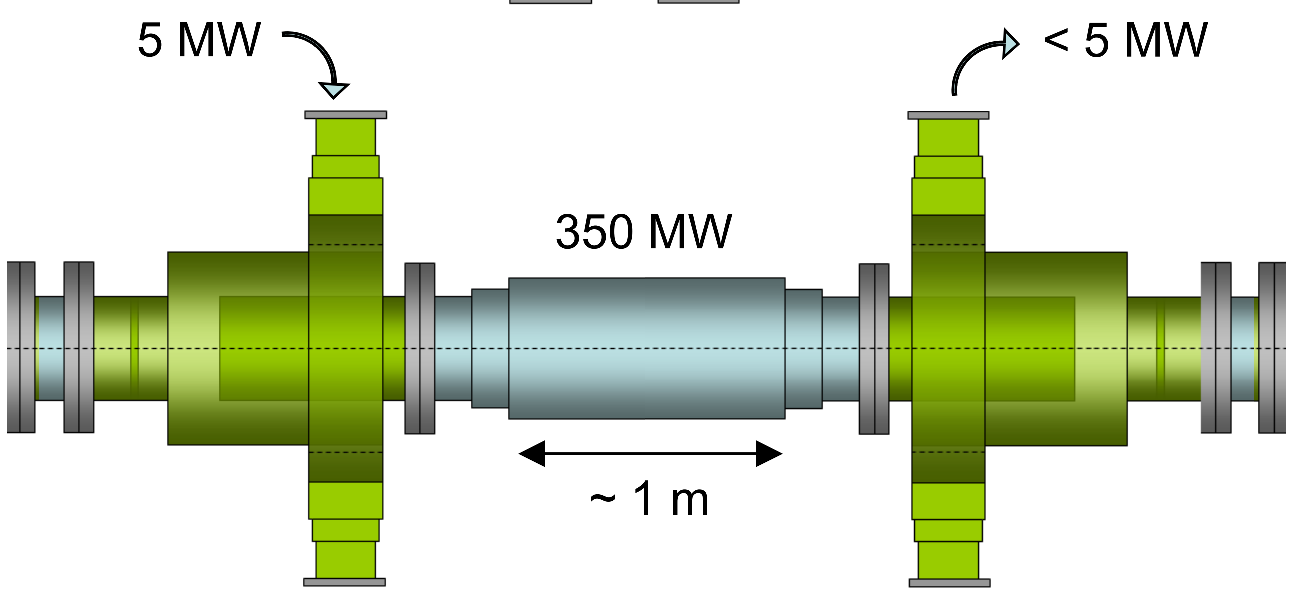
Power Dividing:



Concept Development Steps



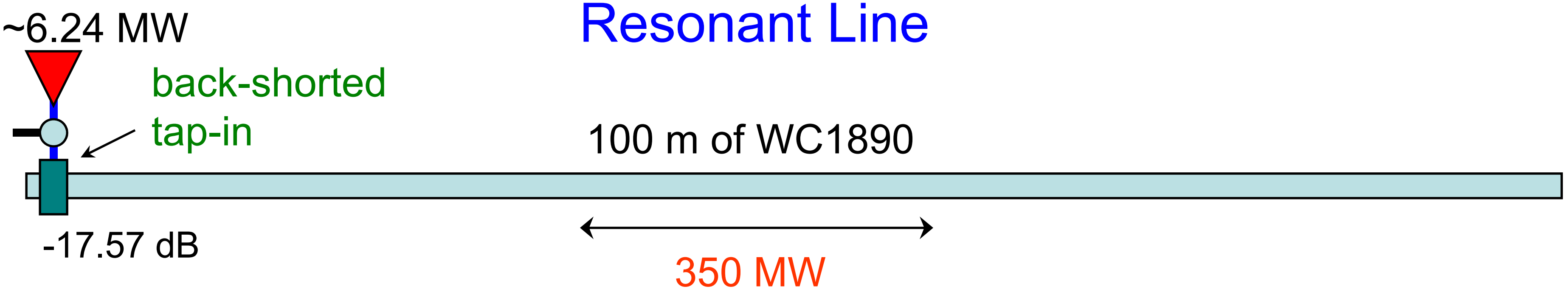
Step 1: Run 10 MW through back-to-back, blanked-off CTOs w/o pipe step up: no resonant rf build up



Step 2: Add pipe step up, adjust shorts (and thus coupling) to resonantly produce 350 MW SW

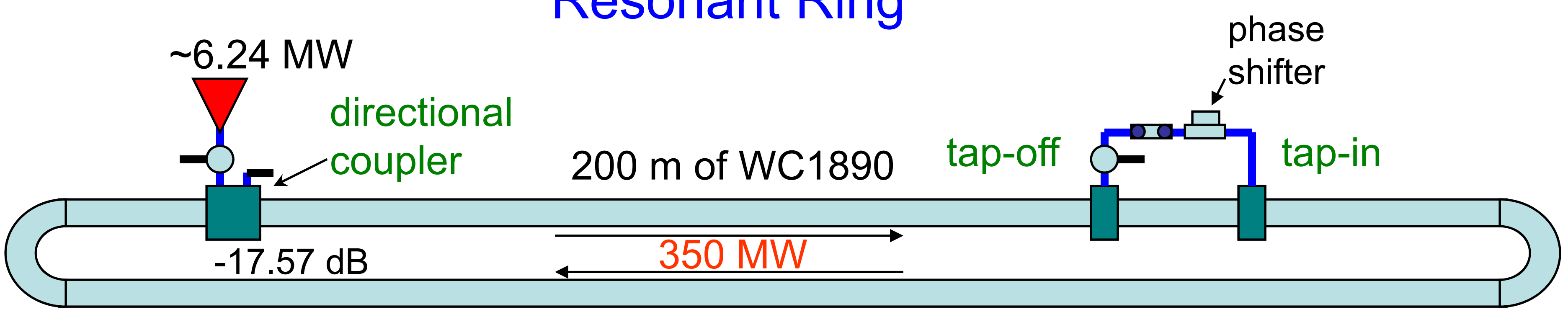
Step 3: Use resonant waveguide to build up the stored energy equivalent to 350 MW traveling waves - provides more realistic rf turn-off time if a breakdown occurs

Resonant Line



Step 4: Use resonant ring to test bends and 'final design' tap-in/off

Resonant Ring



Required Power and Coupling
(for a 100 m line or 200 m ring)

Round trip loss: 1.8 %

Round trip delay time: 823 ns (vs 800 - 9000 ns shutoff time in ILC)

Stored energy: 288 J

Dissipated power: 6.2 MW = input power to produce 350 MW critically coupled

Critical coupling for the emitted field to cancel the reflected field = -17.5 dB.

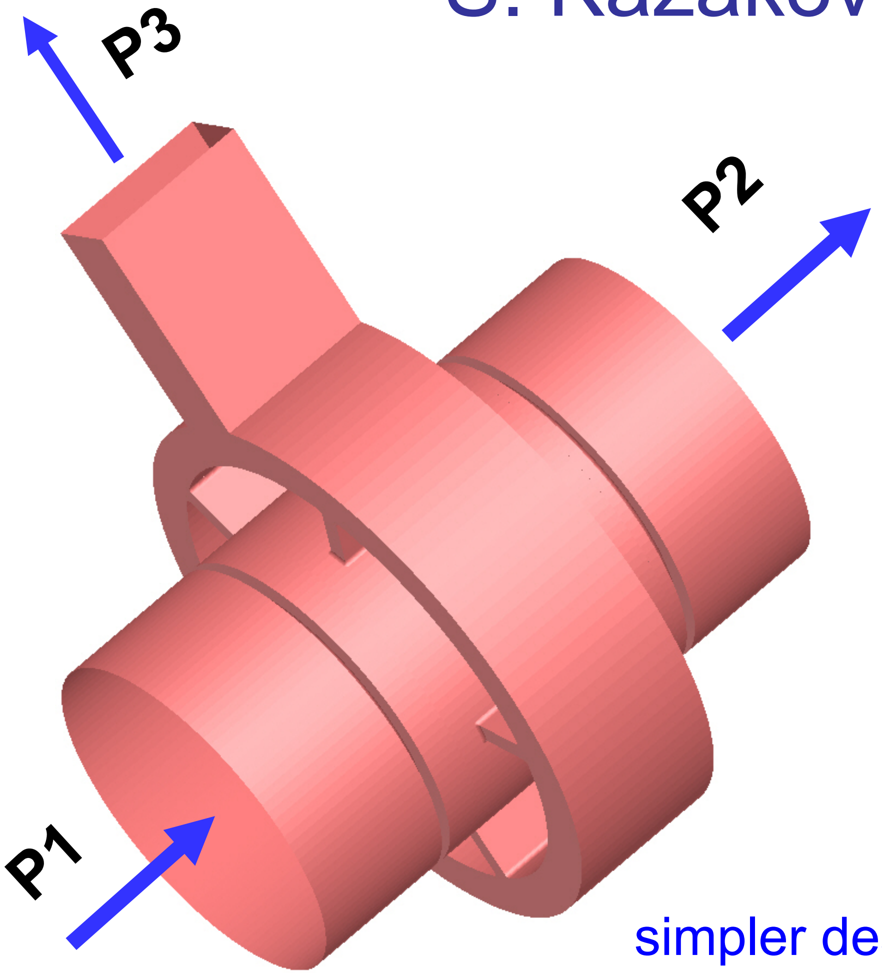
$T_c = Q_L/\omega = 23.1\ \mu s$

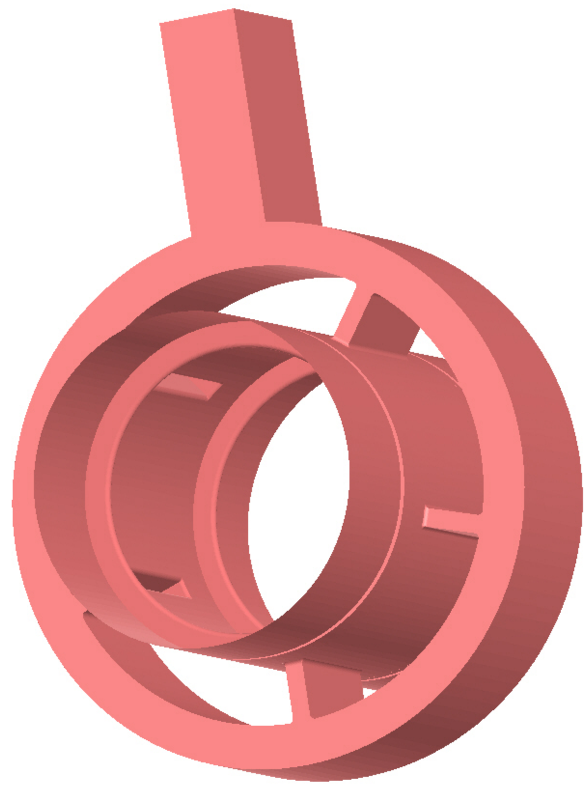
Comparison to ILC

- For ILC
  - Power in tunnel $P(z) = P_0*(L – z)/L$, where z is distance from first feed and L = distance from first to last feed.
  - RF shut off time $t_s(z) = (z_0 + z)\times 2.25/c$ where z_0 is the distance from the cluster to first feed.
  - Max of $P\times t/P_0 = 4.1\ \mu s$ for $z_0 = 100$ m, L = 1.25 km.
- Power 100 m resonant line or ring ($t = 0.82\ \mu s$) to begin study of breakdown damage.
- Would need $100 \times 4.1/.82 = 500$ m of pipe (two 250 m rings) and thee 10 MW klystrons to simulate maximum potential energy absorption $P\times t$ of ILC (albeit at twice the power and half the time).

Alternate Tap-In/Off Design

S. Kazakov (KEK)





simpler design (cost ↓)

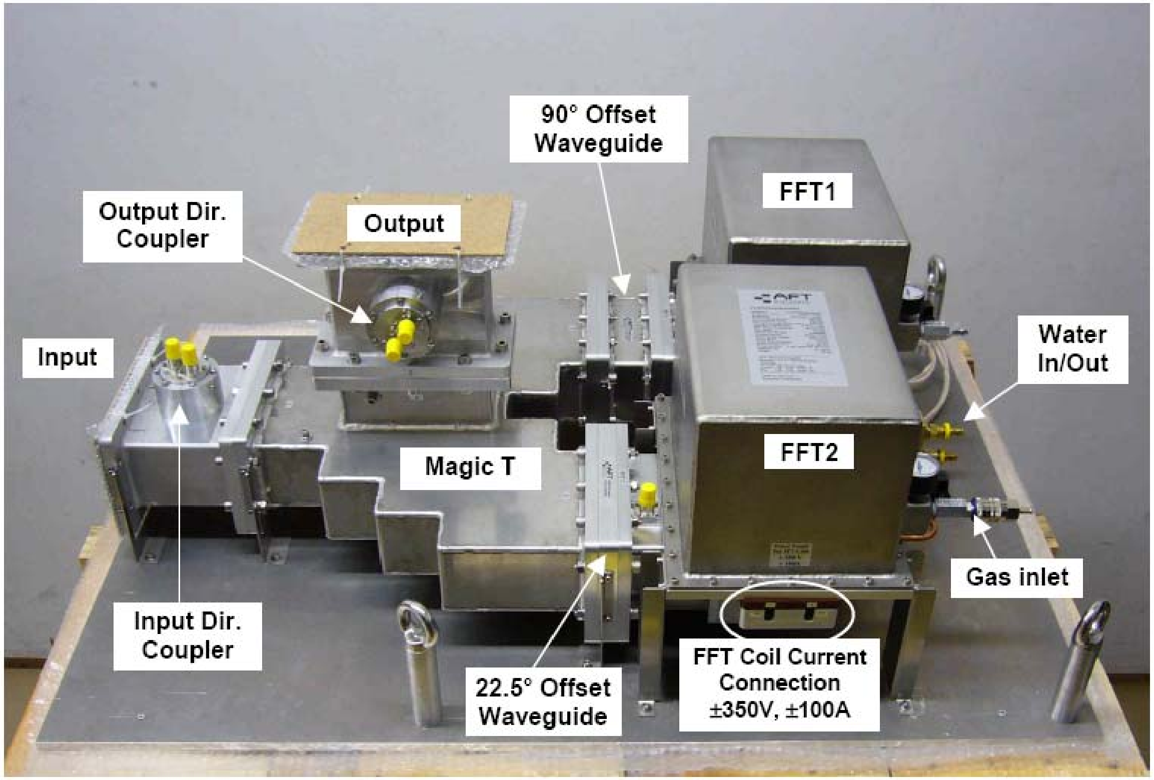
but

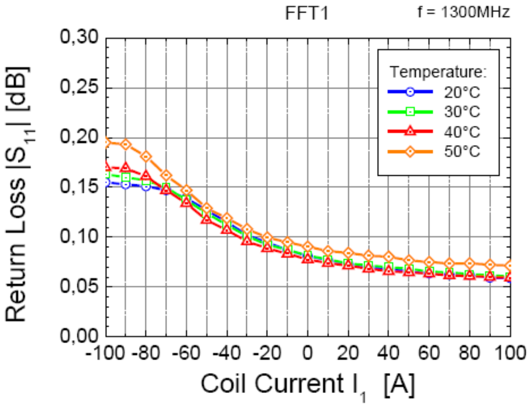
surface E-fields in high-power region (risk ↑)

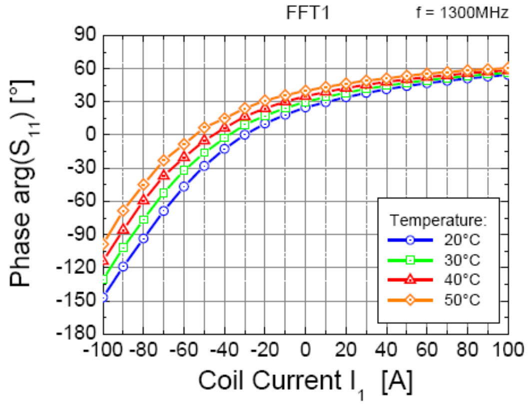
LLRF Control

- Use summed vectors from 32×26 cavities (instead of 26) to control common drive power to the klystrons.
- The increased length adds ~9 μs delay time to the response, so perturbations cannot be very fast (which should be the case as we will know the beam current before the rf pulse in the ILC).
- Assumes energy errors are uncorrelated and small
  - Do not see significant correlations in the cavity amplitude jitter in FLASH ACC 4-6 cavities.
  - If needed, could add 1 or 2 fast phase/amplitude controllers to each rf unit (to drive the unmatched cavities in the two 9-cavity cryomodules in the ACD scheme).

Fast Amplitude and Phase Control
(AFT prototype for FNAL PD)







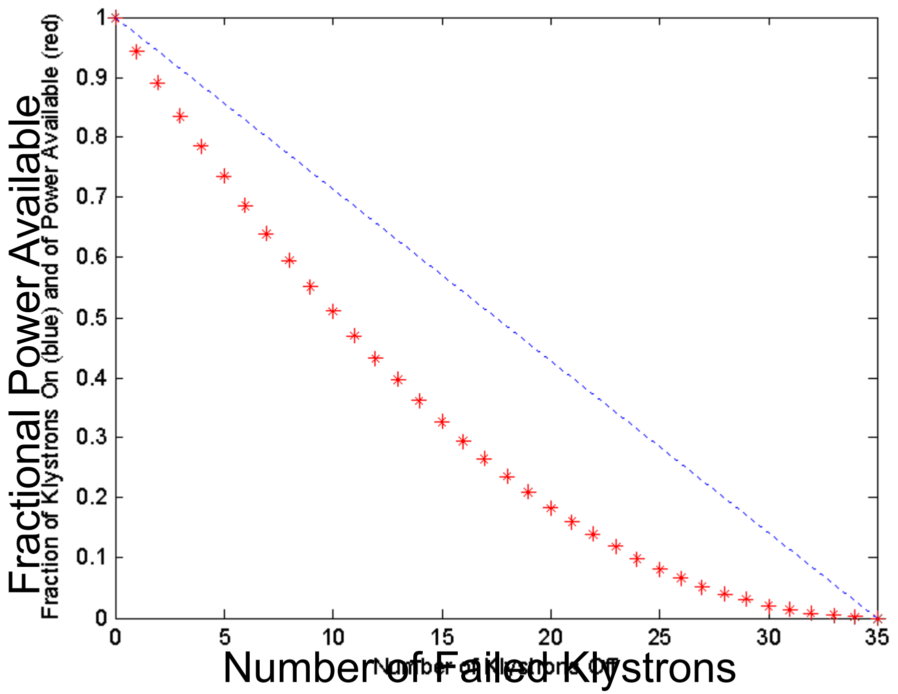
Rated for 550 kW at 1.3 GHz and has a 30 μs response time

Klystron Failure

Available power scales as the square of the fraction of combined klystrons running.

If one fails out of 35, only ~33 klystrons worth of rf is delivered; the rest goes to various loads.

The baseline is similar in that beam loading roughly doubles the gradient loss if one klystron is off – in this case however, one can detune the cavities to zero the beam loading if the klystron will be off for an extended period.



Scheme for Improved Reliability

• Assume 34 klystrons are required to feed 32 rf units with sufficient overhead.

• Combine 36 klystrons per cluster and operate with one off (cold spare) or, more efficiently, operate all at reduced voltage and 94.4% (34/36) nominal klystron power.

• In the event of a klystron failure, turn on the cold spare or turn the voltage and drive up for the remaining 35 klystrons to 100%.

⇨ For the cost of 5.9% added klystrons and related hardware and a cost of 2.9% discarded rf power when operating with one nonfunctioning klystron, we can maintain the availability of full power in the event of a single source failure per cluster.

This won't work if two or more fail in a given cluster combination, but that scenario should be rare.

Beam-to-RF Timing

Relative beam (c) to rf (v_g) travel times for each feed

$$v_g = \frac{c^2}{v_p} = \sqrt{1-(k_g/k_0)^2}\,c = 0.8103\,c$$

Upstream: 1.25 km $\times$ (1/v_g + 1/c) = 9.32 μs

Downstream: 1.25 km $\times$ (1/v_g - 1/c) = 0.98 μs

For the upstream feed, the rf-to-beam timing will vary by 9.32 μs. Centered, this represents ±0.8% of nominal fill time.

To first order, the gradient variation this produces along the beam will probably cancel, but 1.25 km may be too long a distance for canceling this systematic error, leading to filamentation.

As a remedy, the cavity Q_L's and powers can be tweeked to vary the desired t_i accordingly. This will be done anyway to deal the gradient spread.

Summary

Surface klystron clusters can save ~300 M$ (~200 M$ from eliminating service tunnel and ~100 M$ from simpler power and cooling systems).

The GDE Executive Committee encourages R&D to pursue this idea.

The proposed CTO tap in/off design is likely to be robust breakdown-wise. Have a plan to demonstrate its performance, although with only 1/5 of the worst case ILC stored energy after shutoff.

Need to better study:

Waveguide fabrication and tolerances – too large to be drawn, but don't want seams.

Bend design – mode preserving; low-loss; support 350 MW, 1.6 ms; compact enough for tunnel.

Impact on LLRF control, energy spread minimization, & efficiency.

Modifications to accelerator tunnel to accommodate waveguide plus other systems from tunnel systems.