Klystron Cluster RF Distribution Scheme

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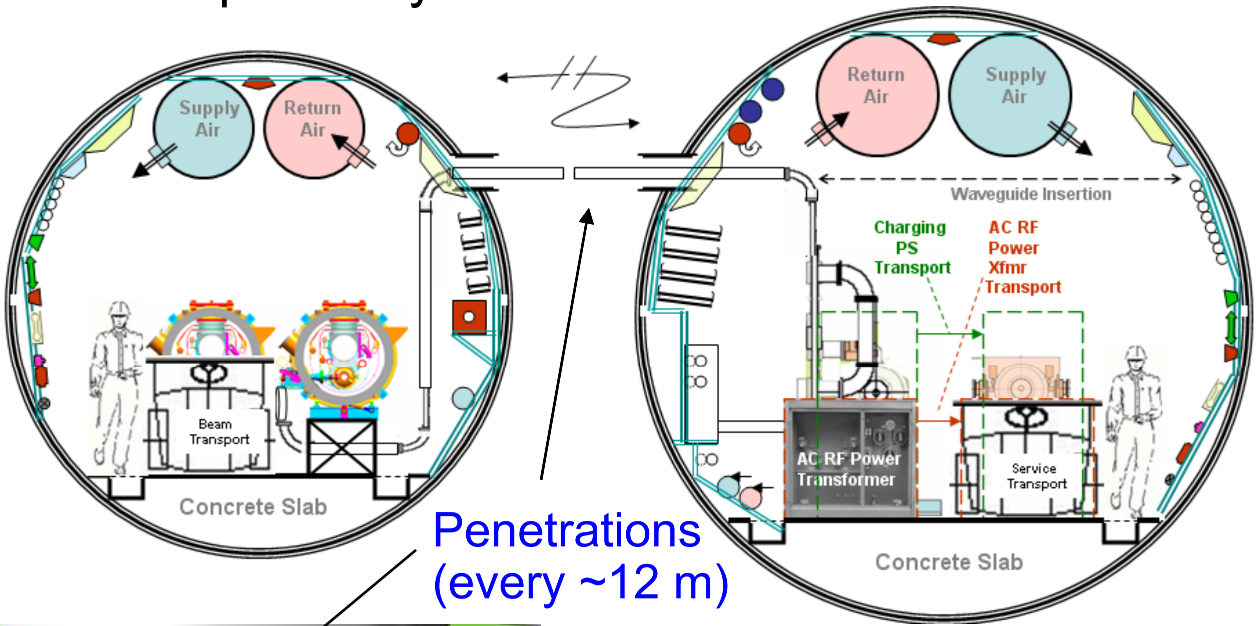
SLAC

Baseline Tunnel Layout

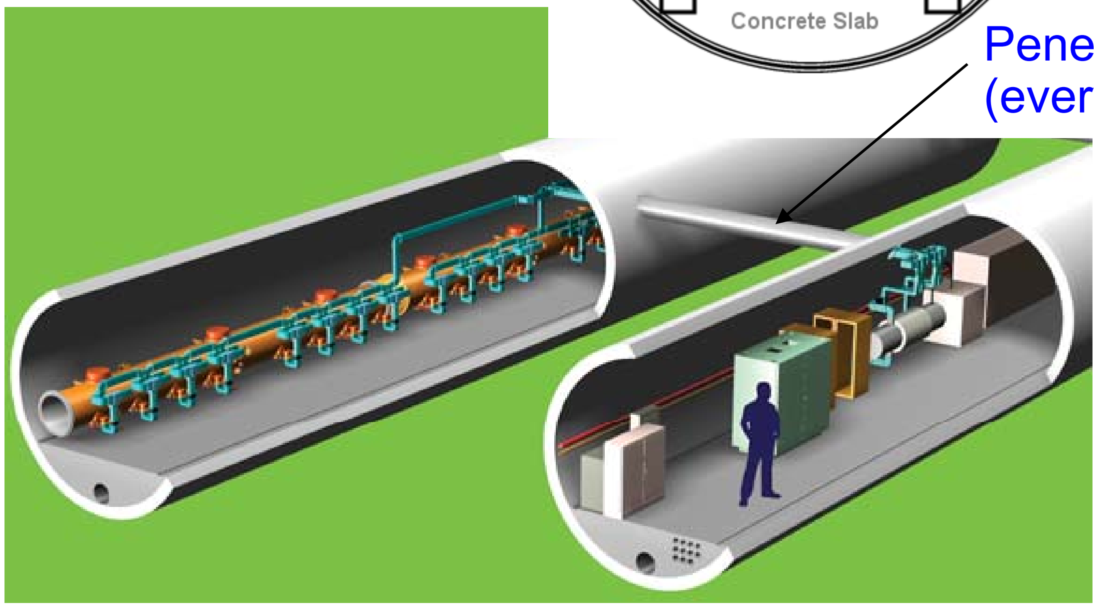
Two 4-5 m diameter tunnels spaced by ~7 m.

Accelerator Tunnel

Waveguides
Cryomodules



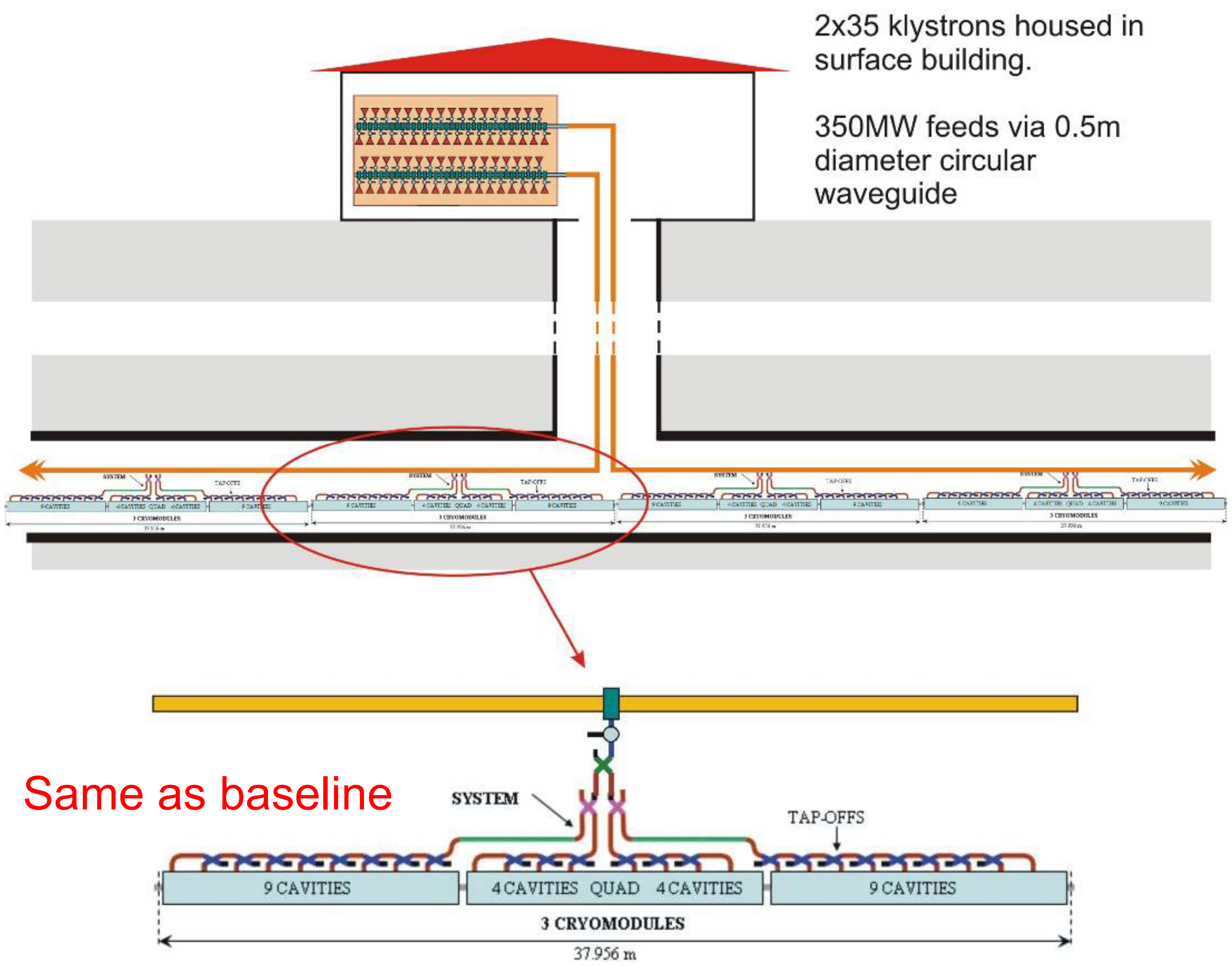
Penetrations
(every ~12 m)



Service Tunnel

Modulators
Klystrons
Electrical Dist
Cooling System

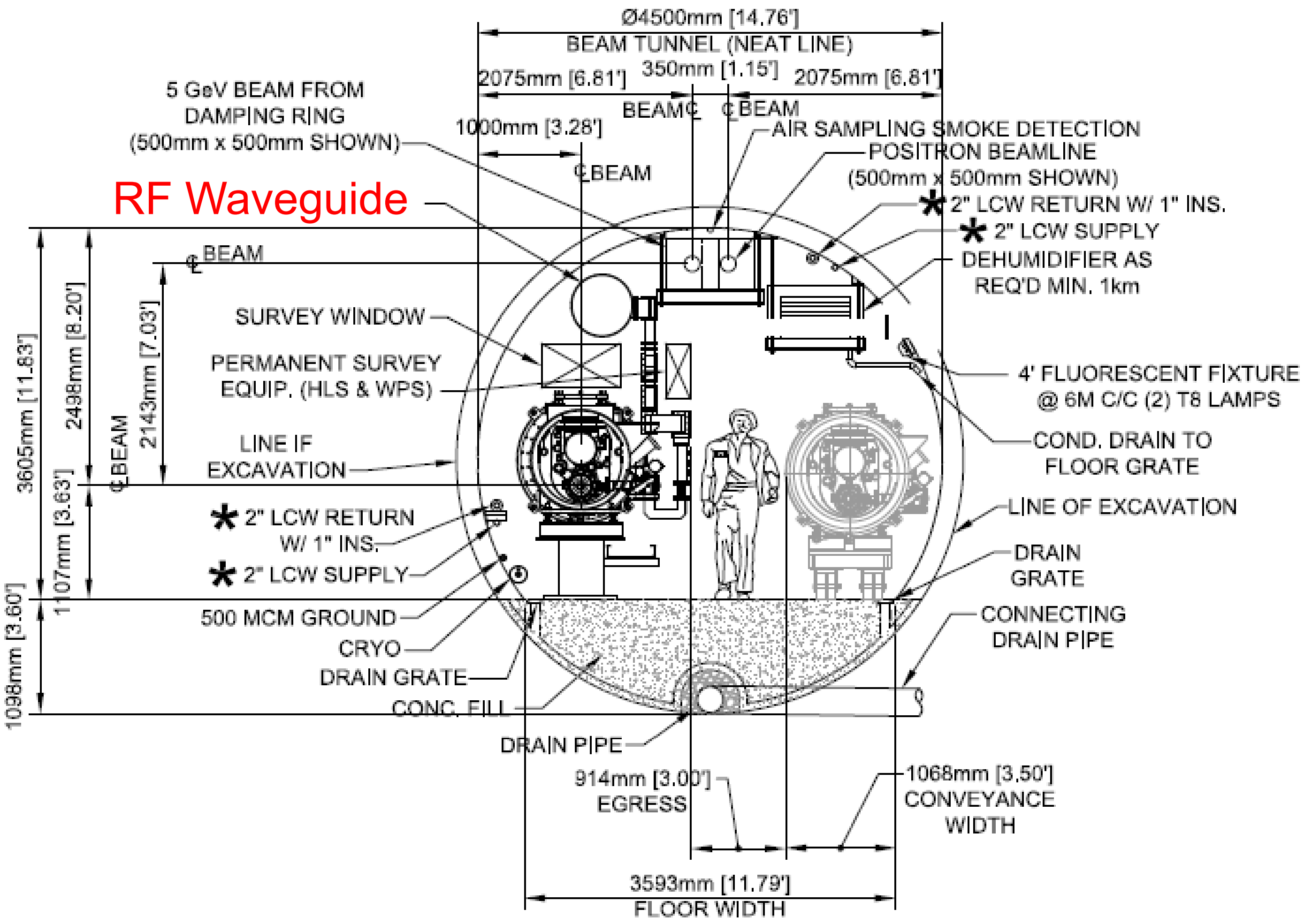
Klystron Cluster Concept



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

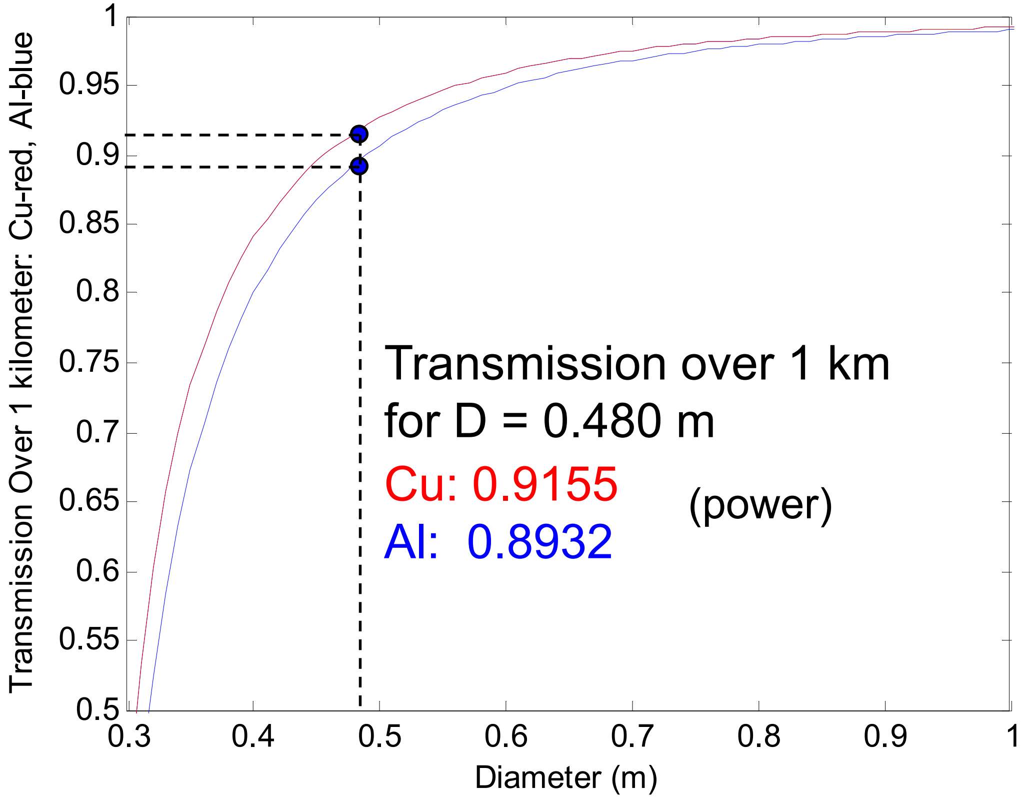
Assume smooth copper plated or aluminum walls:

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

Assume 48.0 cm Diameter

between TE_{51} and TE_{22} cutoffs,

6.8% below TE_{02} cutoff



Power Handling

Scaling by pulse width dependence, we should try to keep surface fields below 10 MV/m in couplers.

$$40 \text{ MV/m } (400 \text{ ns}/1.6 \text{ ms})^{1/6} = \sim 10 \text{ MV/m}$$

X-band design goal maximum

pulse width ratio

L-band design goal maximum

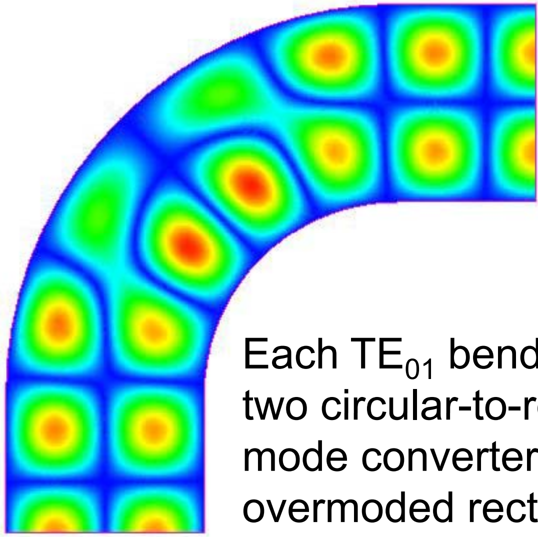
SLAC's 5 cell L-band cavity runs stably with surface fields of 20 MV/m with 1 ms pulses - given the higher power of the ILC system, we are even more conservative by choosing a lower surface field limit (i.e. 10 MV/m).

In the waveguide, 350 MW → ~1.9 MV/m peak, not on wall.

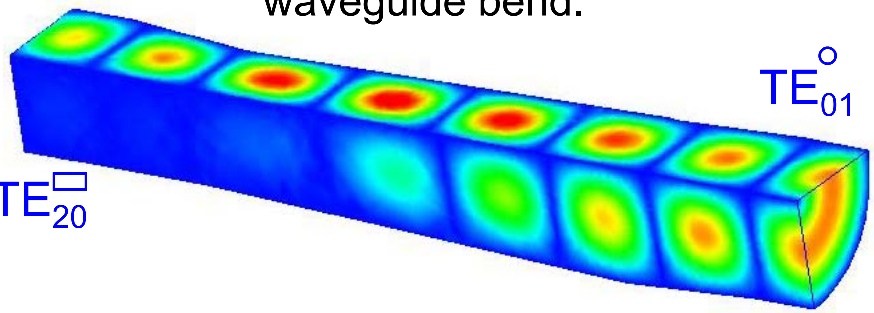
We should be able to keep surface fields below 10 MV/m threshold while coupling in and out 10 MW increments.

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



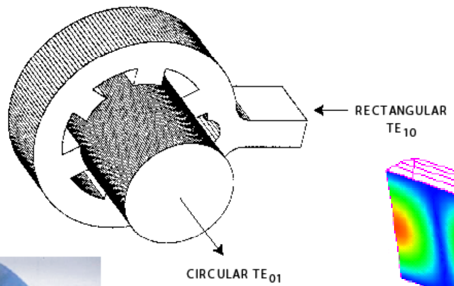
Each TE_{01} bend is composed of two circular-to-rectangular mode converters and an overmoded rectangular waveguide bend.

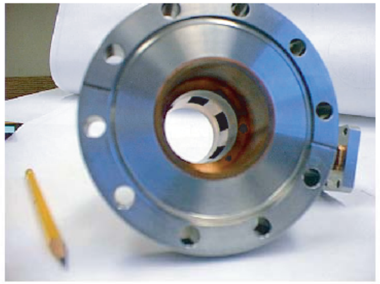


SLAC compact high power 90° bend in 40.6 mm circular waveguide tapered to overmoded rectangular waveguide for TE_{01} mode at 11.424 GHz

X-Band Launchers and Tapoffs from NLC/GLC Program

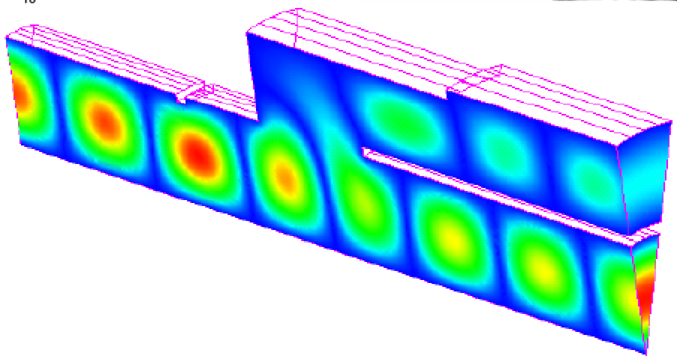
WRAP – AROUND
MODE
CONVERTER



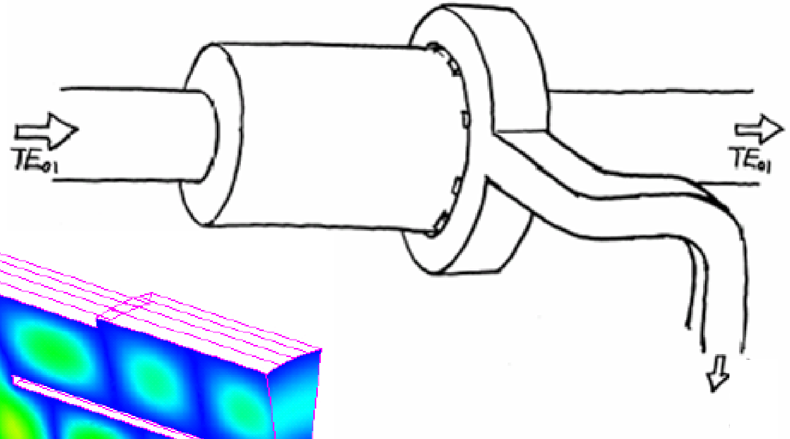


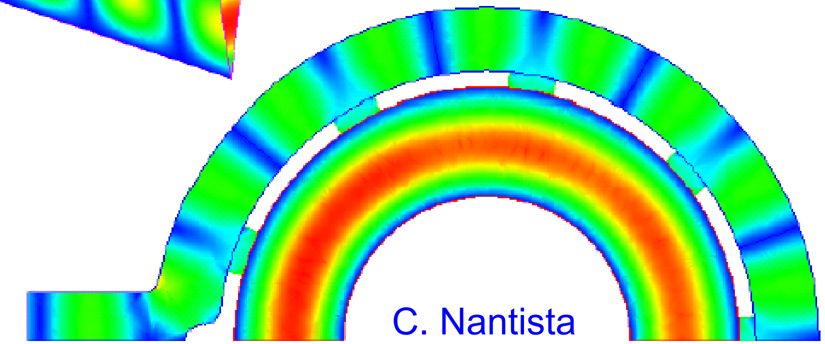
Processed to 485

RF Pulse Length = 1



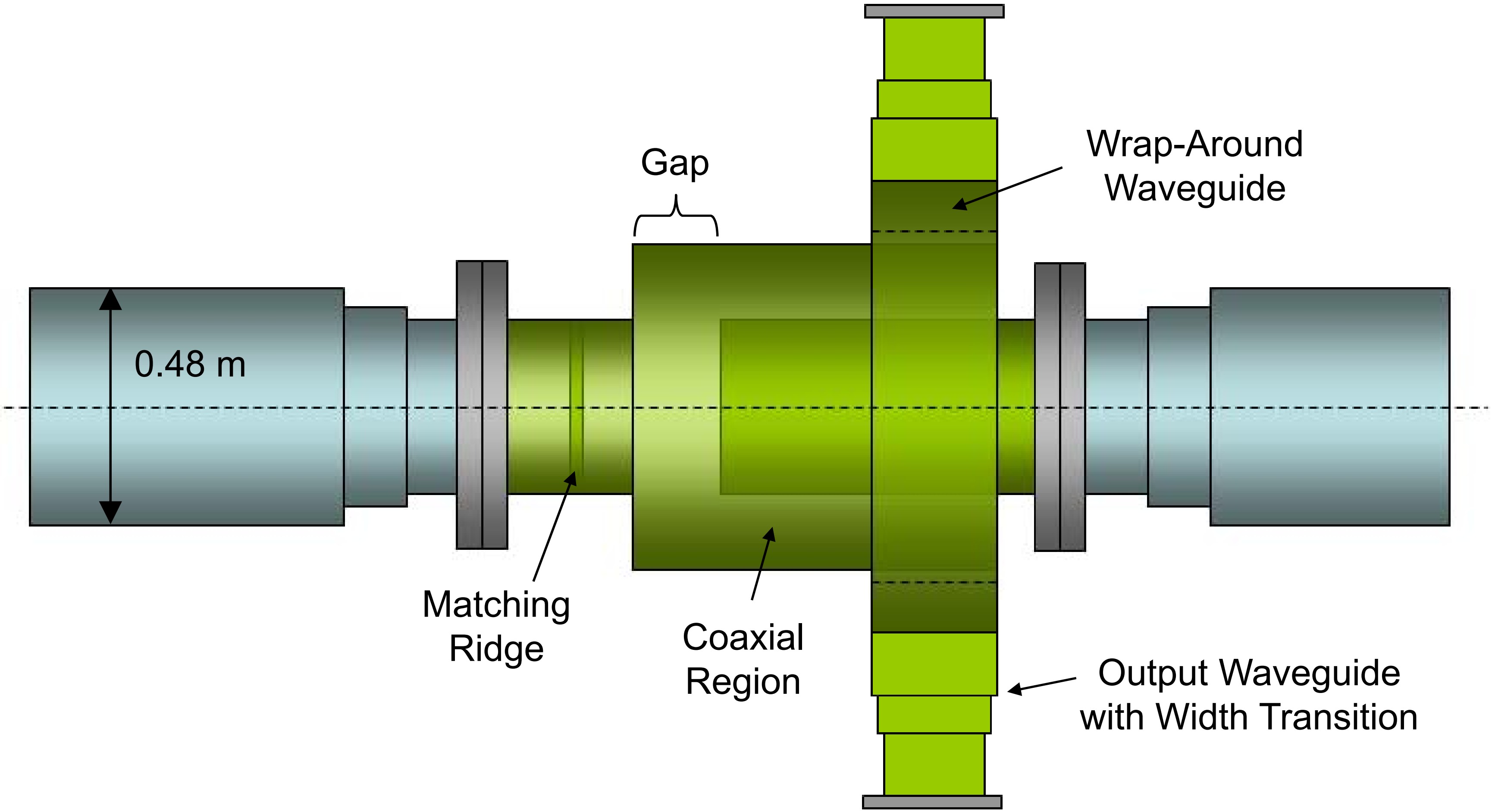
Co-axial TE_{01} Fractional Tap-offs





ILC: Co-Axial Tap Off (CATO)

About 1200 Required – Only Gap Length, Ridge Varies



Design by Chris Nantista

Choice of Diameters

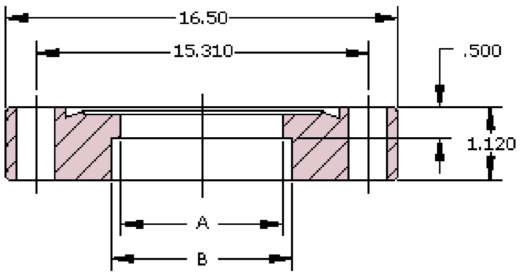
mode cut-off diameters

	D_c (m	inches) =
	0.1352	5.3210
	0.1765	6.9499
	0.2242	8.8267
TE_{01}:	0.2813	11.0735
	0.2813	11.0735
	0.3084	12.1413
	0.3770	14.8418
	0.3903	15.3676
	0.3914	15.4077
	0.4052	15.9529
	0.4683	18.4385
	0.4709	18.5410
	0.4923	19.3805
TE_{02}:	0.5150	20.2749
	0.5150	20.2749
	0.5506	21.6785
	0.5570	21.9301
	0.5884	23.1638
	0.6179	24.3249
	0.6266	24.6697
	0.6297	24.7897
	0.6352	25.0090
	0.6439	25.3493
	0.6814	26.8259
	0.7082	27.8808
	0.7165	28.2091
	0.7294	28.7151
	0.7318	28.8115
TE_{03}:	0.7468	29.4010

13.750” – Input/output diameter
Largest commercial vacuum flange

18.898” (0.480 m) – Transmission pipe diameter
Low loss and below TE02 cut off

25.175” – Step-up diameter
(TE02 node at 13.750”)



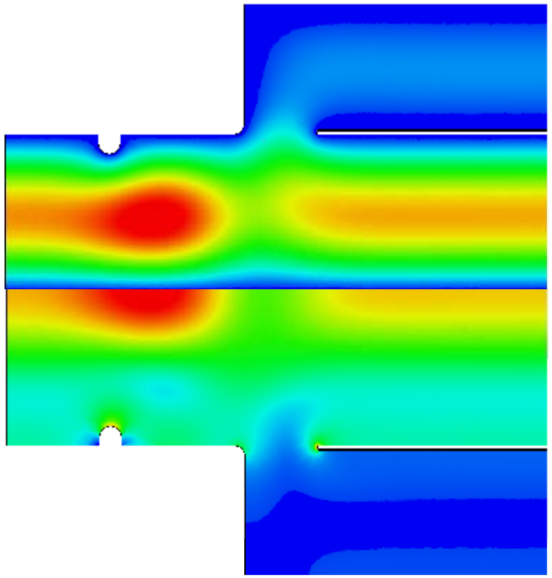
- MODEL REFERENCE: REF# F16501400
- PART NUMBER: 110040
- ID NOMINAL: 14
- BOLT HOLE: CLEARANCE
- A: 13.750
- B: 14.020
- FIG: 2
- HOLES: 36
- HOLE DIAM: 0.390
- WT LB: 18

Coaxial Power Division

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

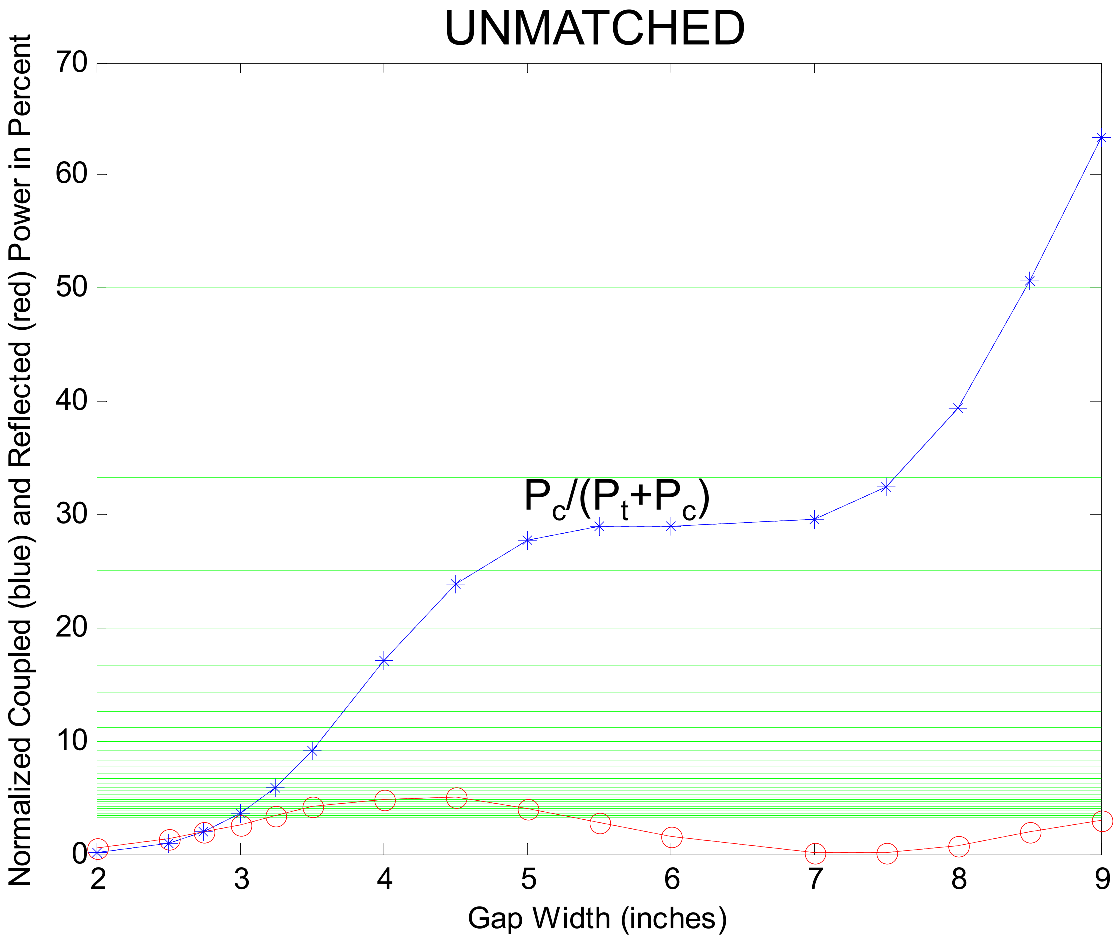
The various coupling designs will differ only in a) gap width and b) matching ridge.

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

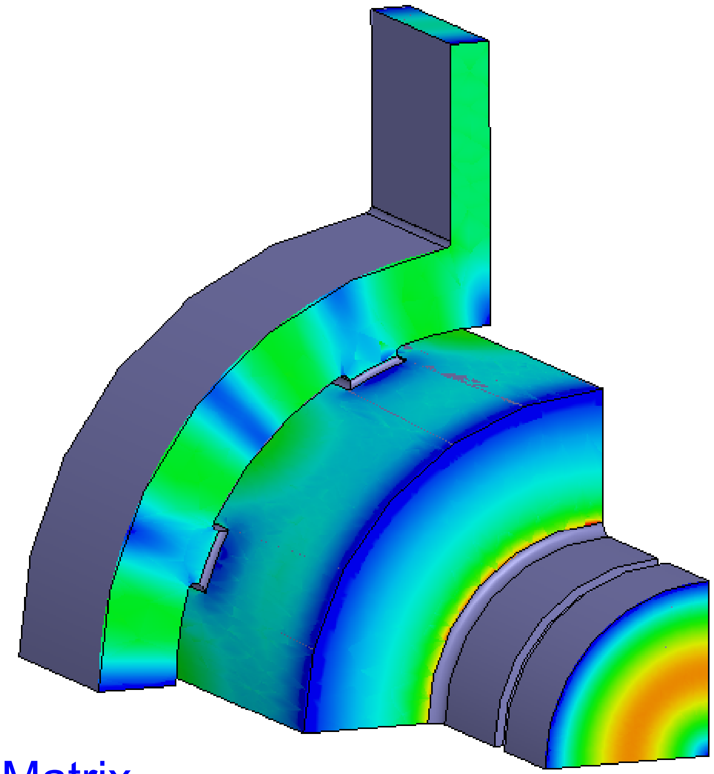


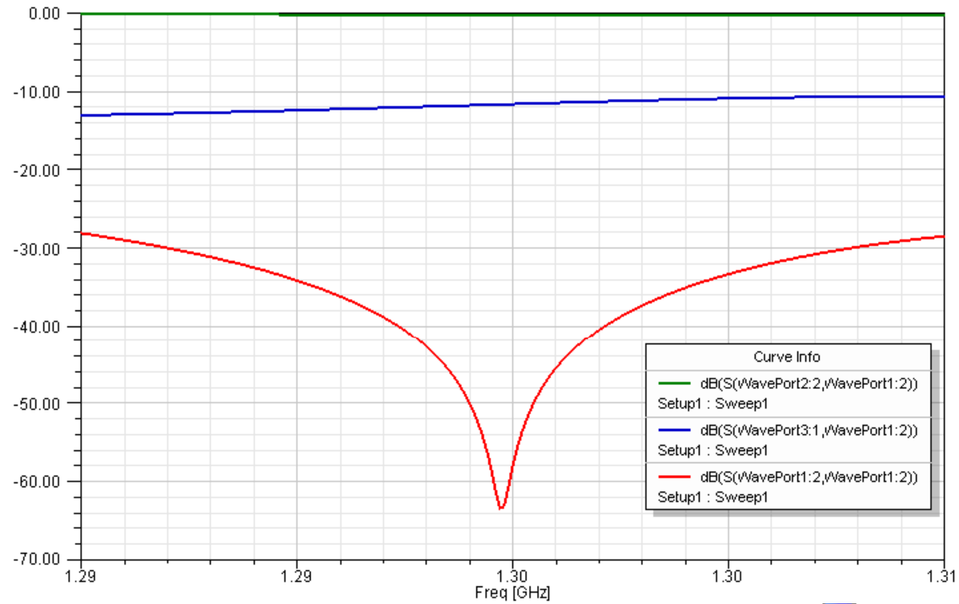
$|H|_m$ = 0.798 sqrt(P)
= 14.7 kA/m @ 340 MW

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



Complete CATO RF Design





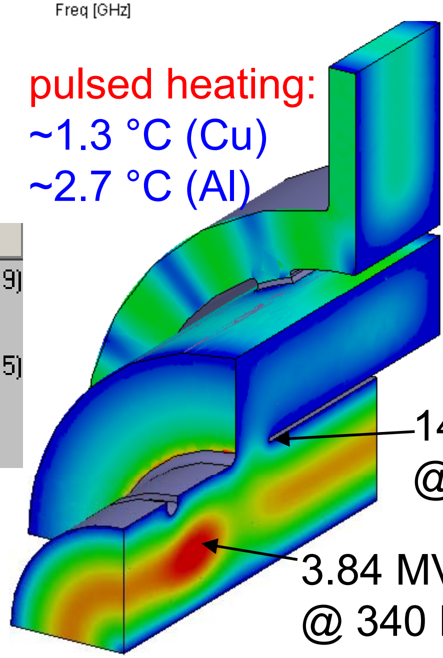
S Matrix

	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

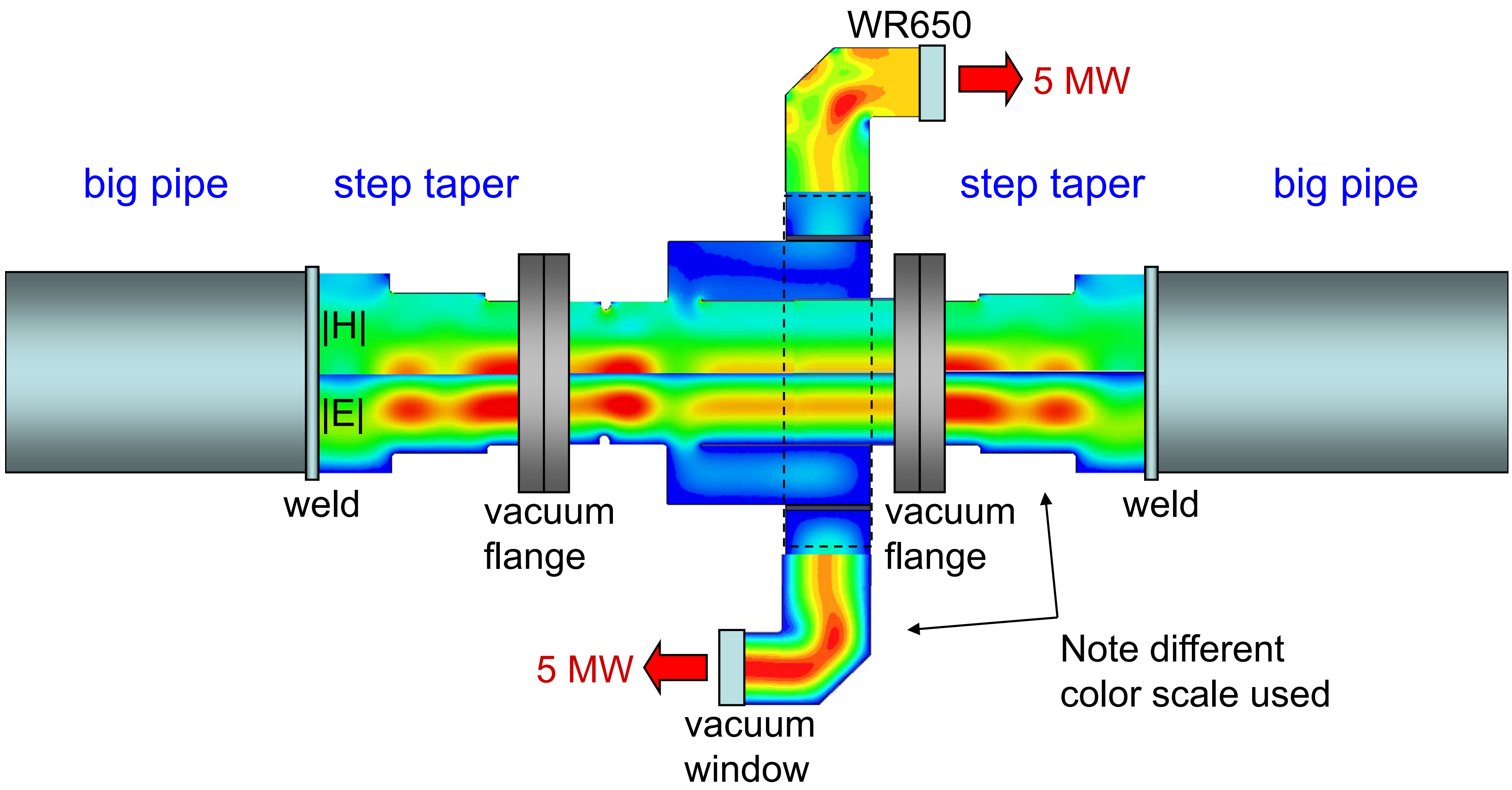
pulsed heating:
~1.3 °C (Cu)
~2.7 °C (Al)



14.7 kA/m
@ 340 MW

3.84 MV/m
@ 340 MW

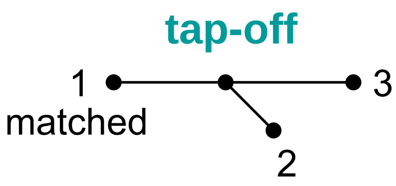
CATO Magnetic and Electric Fields



First Launcher and Final Tap-off

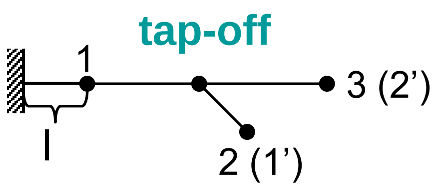
The scattering matrix for a lossless 3-port tap-off with coupling C and reference planes chosen to make all elements real (port 2→S_{22} real, port 1→S_{21} real, port 3→S_{31} real) can be written:

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



Short port 1 at a distance l to reduce to a 2-port coupler and adjust C <u>and</u> l to achieve desired coupling.

$$S_{22} \rightarrow S_{11}' = S_{22} - S_{12}e^{-i2\beta l}S_{21} = 1 - C\left(1 + e^{-i2\beta l}\right)$$
$$S_{23} \rightarrow S_{12}' = S_{23} - S_{13}e^{-i2\beta l}S_{21} = -\sqrt{C(1-C)}\left(1 + e^{-i2\beta l}\right)$$
$$S_{32} \rightarrow S_{21}' = S_{32} - S_{12}e^{-i2\beta l}S_{31} = -\sqrt{C(1-C)}\left(1 + e^{-i2\beta l}\right)$$
$$S_{33} \rightarrow S_{22}' = S_{33} - S_{13}e^{-i2\beta l}S_{31} = C\left(1 + e^{-i2\beta l}\right) - e^{-i2\beta l}$$



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

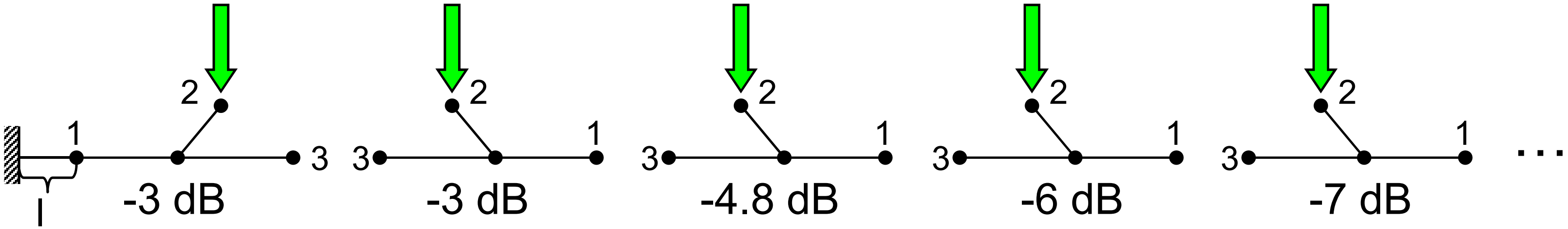
$$\beta l = 0, \pi \rightarrow \mathbf{S}' = \begin{pmatrix} 1 - 2C & -2\sqrt{C(1-C)} \\ -2\sqrt{C(1-C)} & 2C - 1 \end{pmatrix}$$

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

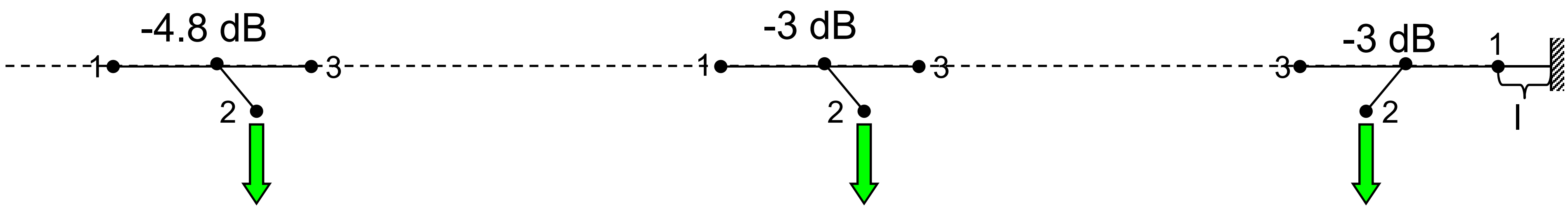
$$\boxed{\beta l = 0, \pi, \ldots \text{ and } C = \frac{1}{2} \rightarrow C' = 1}$$

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.

Power Combining:

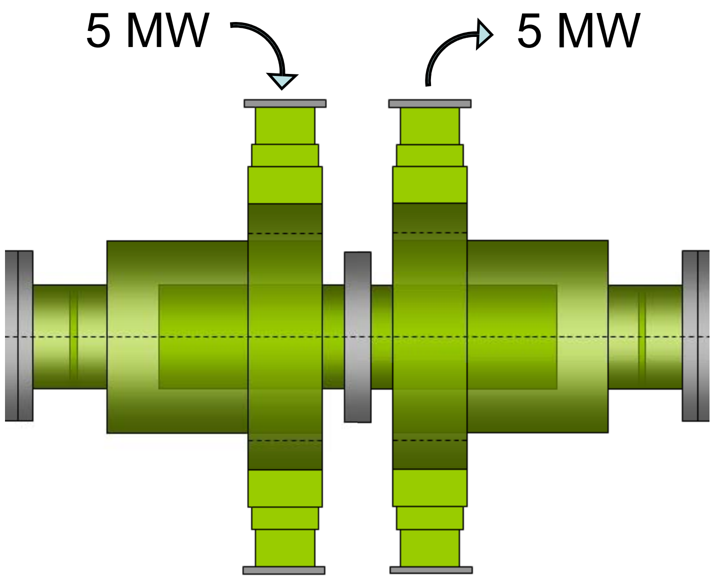


Power Dividing:

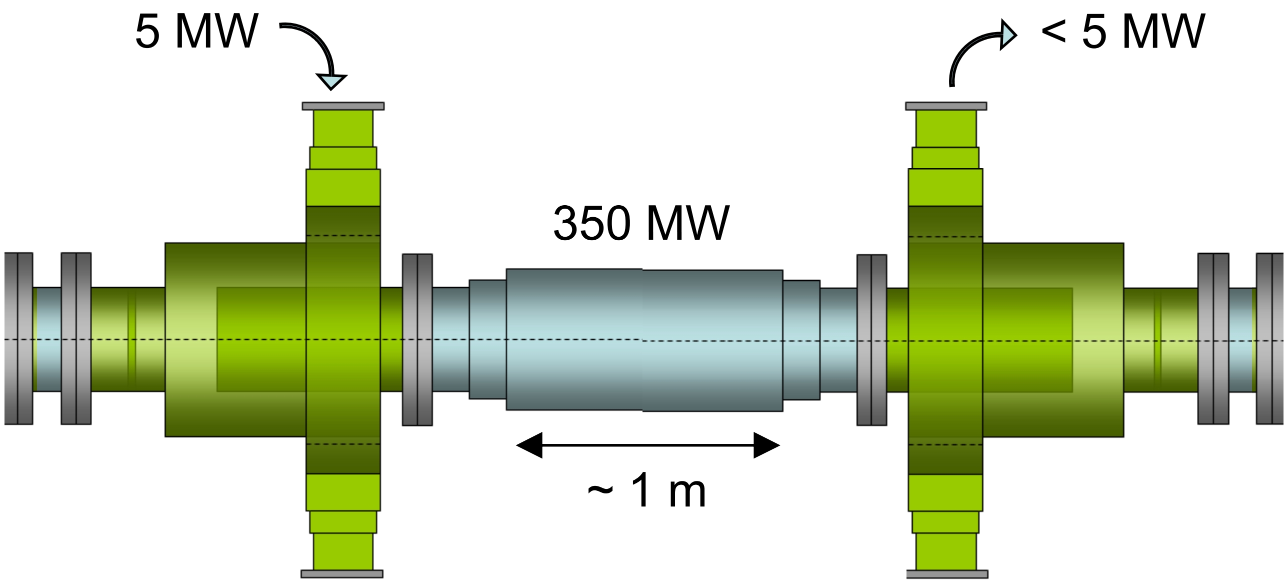


Concept Development Steps

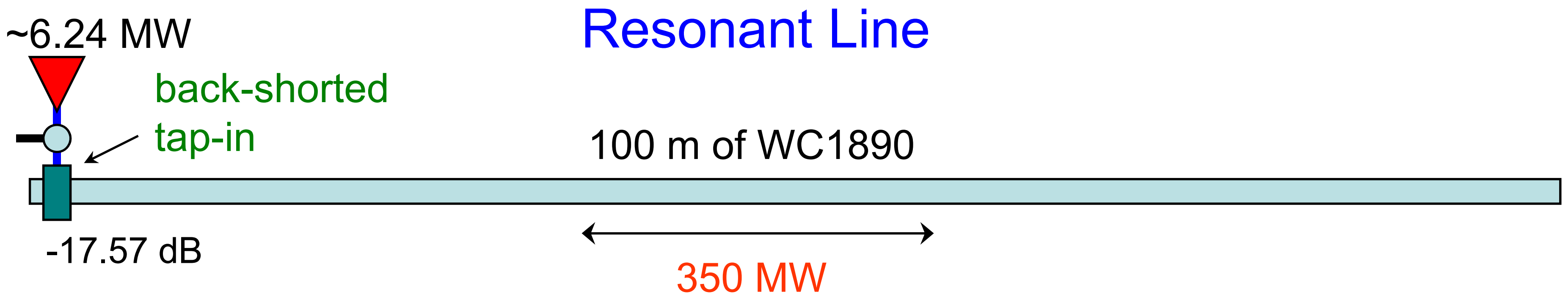
Step 1: Run 10 MW through back-to-back, blanked-off CATOs w/o pipe step up: no resonant rf build up



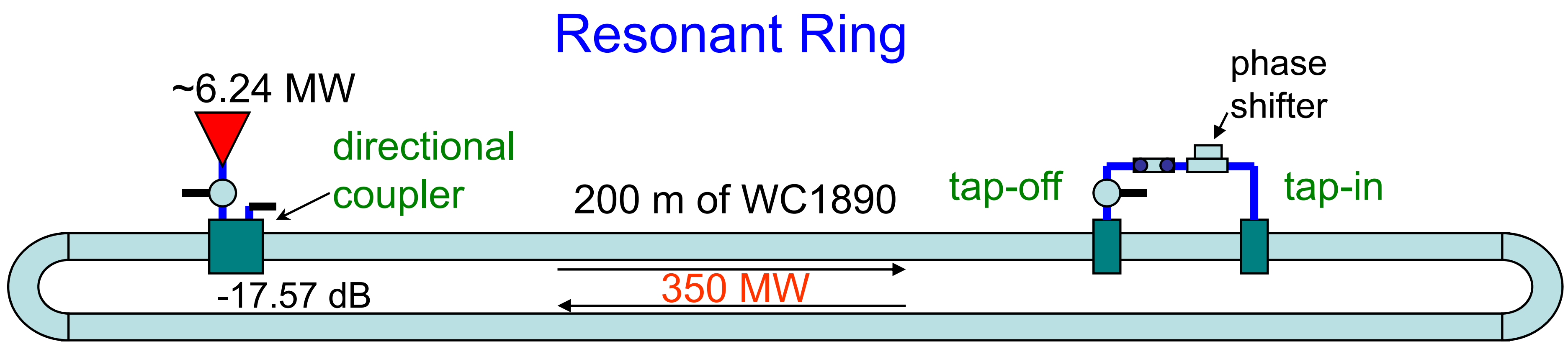
Step 2: Add pipe step up, adjust shorts to resonantly produce 350 MW SW



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 have a breakdown



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



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

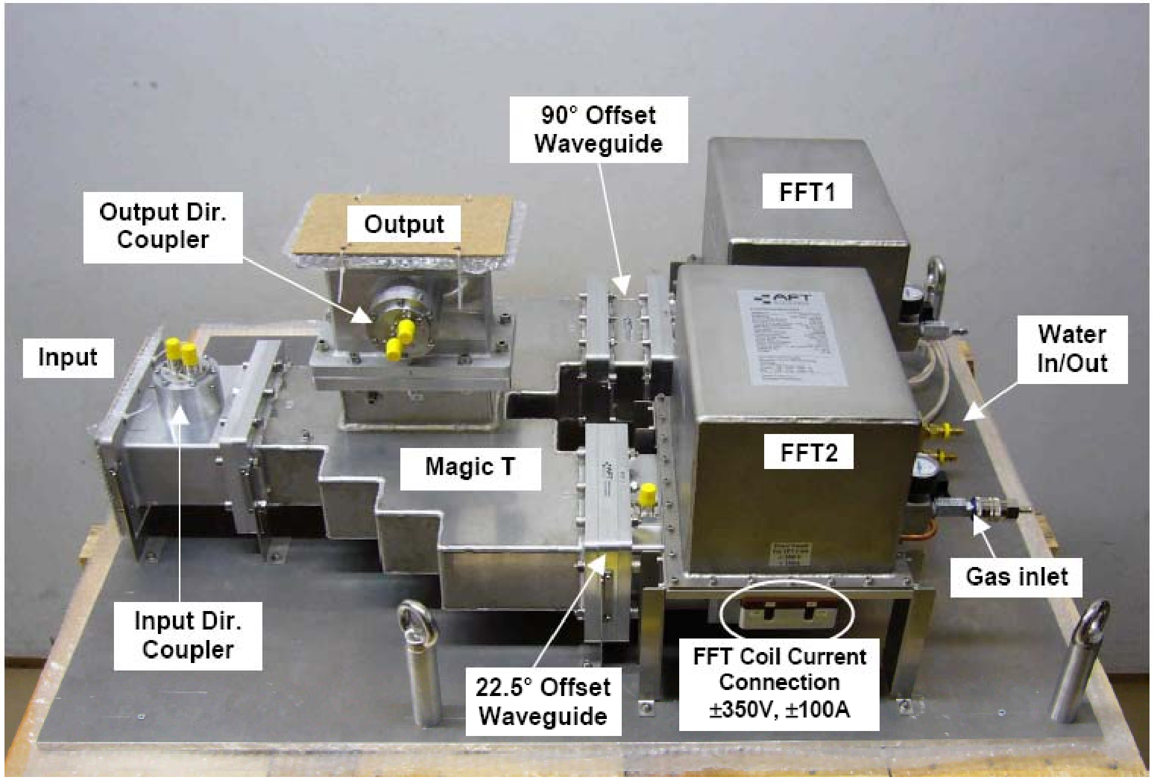
- For ILC
  - Power in tunnel (P) = Po*(L – z)/L, where z is distance from first feed and L = distance from first to last feed
  - RF shut off time (t) = (zo + z)*2.25/c where zo is the distance from the cluster to first feed
  - Max of P*t/Po = 4.1 us for zo = 100 m, L = 1.25 km
- Power 100 m resonant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

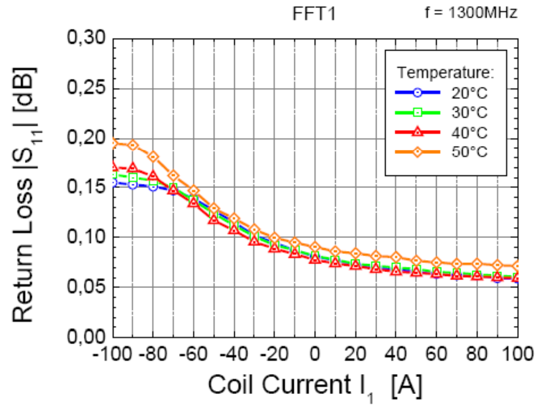
LLRF Control

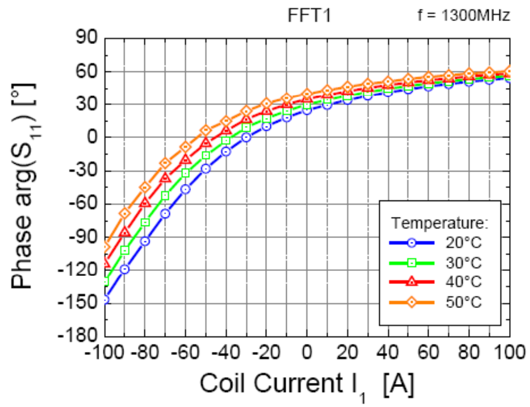
- Use summed vectors from 32*26 cavities (instead of 26) to control common drive power to the klystrons.
- The increased length adds ~ 9 us delay time to the response, so perturbations cannot be very fast (which should be the case as we will know the beam current before the rf pulse in the ILC).
- Assumes uncorrelated, local energy errors are 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)







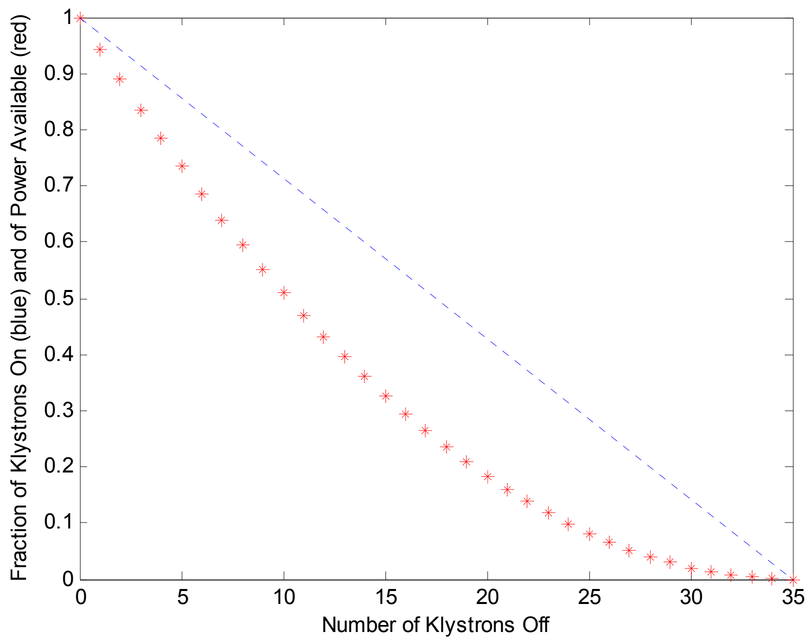
Rated for 550 kW at 1.3 GHz and has a 30 us response time

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 are 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 (vg) 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 CATO 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 (KEK working with industry on this).

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.