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# Cavity Couplers and Testing

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# Caveat

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- All of the RF circuit analysis I'm going to go through is technically correct for normal conducting and superconducting cavities, although my background is primarily SRF.
- With SRF cavities, it's possible to do low power testing because the Qs are so high, and you don't have to worry about huge heat dissipation.
- For normal conducting cavities, almost all the design for high power couplers are the same, but for all but the lowest gradient testing.
- The notable exception is the cryogenic requirements for SRF high power couplers.

# Couplers

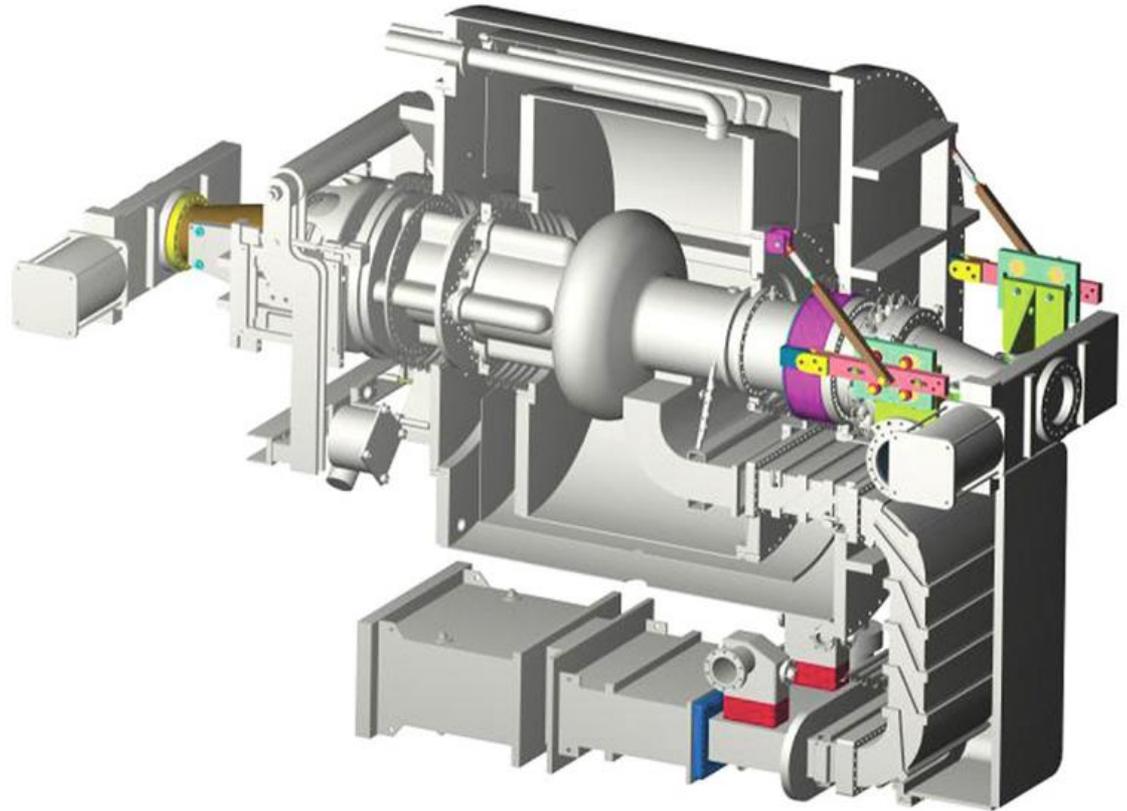
We can generate power in a variety of ways, but we have to get it from the source to the cavity.

Waveguides/Coax  
Transmission Lines

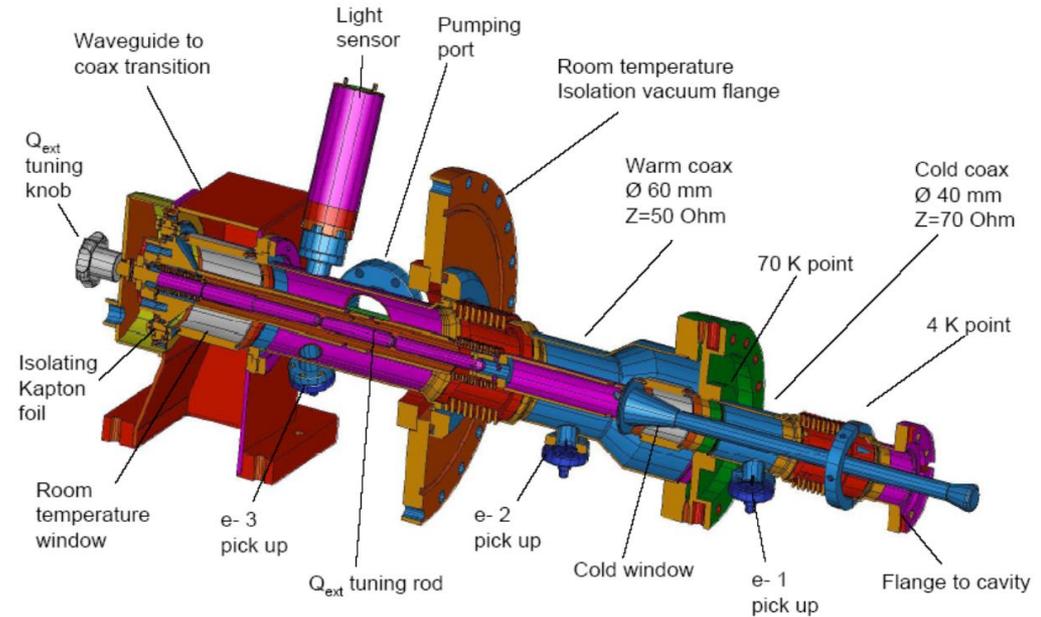
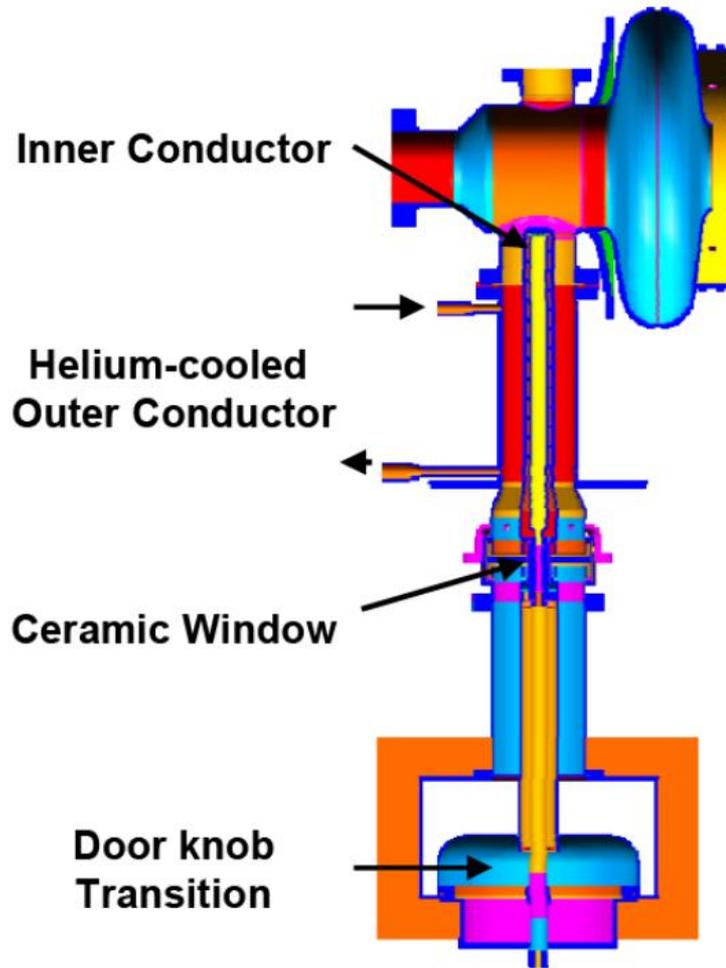
$$f_c = \frac{c}{2\pi} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}$$

For rectangular waveguide,  
but no cutoff for coaxial lines.

Higher power = Larger Coax



# High-Power Couplers

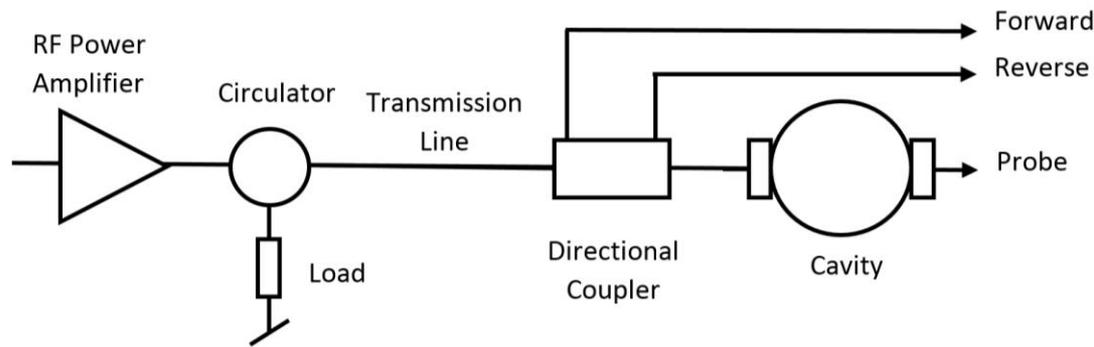
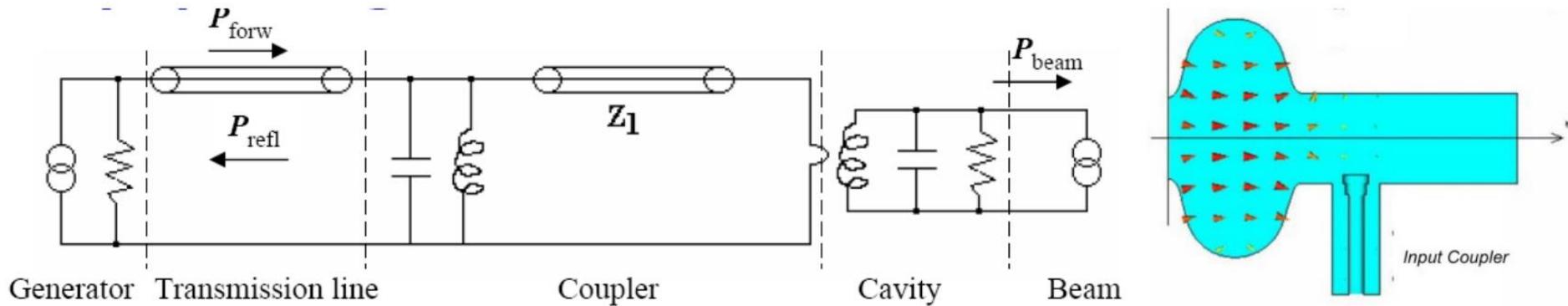


<http://arxiv.org/ftp/arxiv/papers/1501/1501.07129.pdf>

Design Topics for Superconducting RF Cavities and Ancillaries

H. Padamsee

# Equivalent Circuit for Driving a Cavity



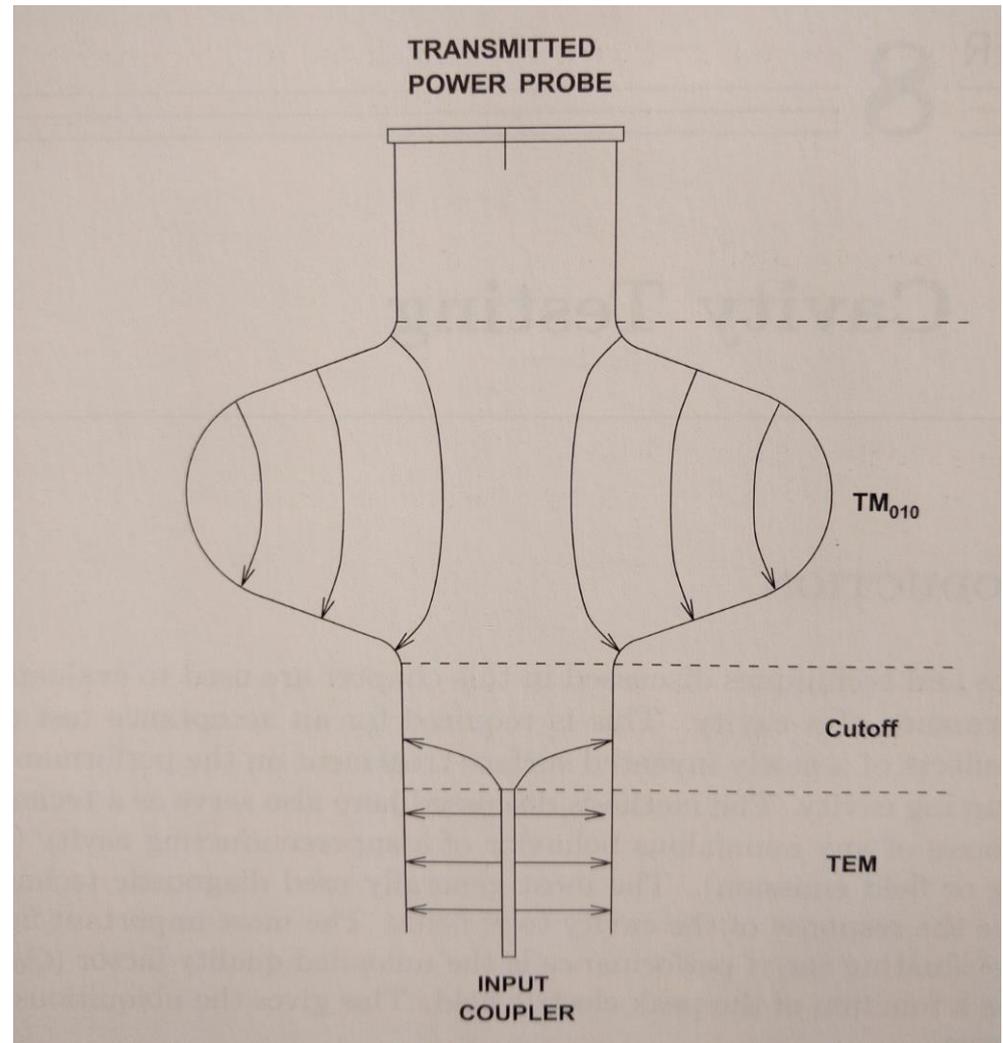
Many models are simplification, but all the relevant parts are there:  
 Generator, Transmission Line, Coupler, Cavity, Beam

# Cavity Mode-Coupler Mode Interface

Power flowing in the coupler must be 'coupled' to the cavity mode.

How easily power flows into the cavity mode is related to the convolution of the cavity mode structure and the coupler field structure.

Coupler interface is geometry based.



# Coupler Definitions

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- We will now have to make the distinction between different quality factors.
- $Q_0 = \frac{\omega U}{P_d}$  where  $P_d$  is the dissipated power in the cavity walls
- Note that this depends on the geometry of the cavity, but also on the cavity material properties. When quality factor is quoted, this is often the number that people mean.
- $P_{tot} = P_d + P_e + P_t$
- Total power lost from the cavity is the sum of the losses in the walls and the power flowing out of both of the cavity couplers.
- Generally, cavities are tested with an input and probe couplers.
- Input is meant to supply power, probe is a small field tap.

## Loaded Q

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- A real cavity has these three kinds of losses, and we need to first, treat them together, and then figure out how to solve for them separately.
- Define a combined  $Q_L$  called the Loaded Q.
- $Q_L \equiv \frac{\omega U}{P_{tot}}$
- With no driving term, power will flow out of the cavity in relationship to the stored energy:
- $\frac{dU}{dt} = -P_{tot} = -\frac{\omega U}{Q_L}$ , giving  $U = U_0 e^{-\frac{\omega t}{Q_L}}$
- The cavity stored energy decays, with no drive, with a time constant  $\tau_L = \frac{Q_L}{\omega}$ . Note, this is power, the voltage will decay twice as fast.

## External Q

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- $\frac{P_{tot}}{\omega U} = \frac{P_c + P_e + P_t}{\omega U}, \frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_e} + \frac{1}{Q_t}$
- With the definition of the Q-External as:
- $Q_e = \frac{\omega U}{P_e}, Q_t = \frac{\omega U}{P_t}$
- Note that these definitions are for power flowing out of the cavity, which are effective losses, but the energy still exists somewhere as RF, not as heat.
- We can define some very useful quantities:
- $\beta_e \equiv \frac{Q_0}{Q_e} = \frac{P_e}{P_d}, \beta_t \equiv \frac{Q_0}{Q_t} = \frac{P_t}{P_d}$
- $Q_0 = Q_L(1 + \beta_e + \beta_t)$

# Measurements

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- The probe is generally approximated to be very weakly coupled ( $\beta_t \ll 1$ ) because we desire it to be a small diagnostic signal ( $< 1$  mW).
- So, let's assume that we're driving the cavity with one coupler only for now.
- What we're looking for:
- Cavity response to a driving signal.
- $P_f, P_r, P_t, Q_0, Q_e, Q_t$  (we'll deal with probe signals later)
- Going through the circuit analysis:
- $$\Gamma(\omega) = \frac{\beta_e - 1 - iQ_0\delta}{\beta_e + 1 + iQ_0\delta}, \delta = \frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}$$
- On Resonance:  $\Gamma = \frac{\beta_e - 1}{\beta_e + 1}$

# Steady State Behavior

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- So, we're driving a cavity with a fixed forward power on resonance.
- There are 4 Powers we care about:
  - $P_f$ : Forward Power, coming from the generator to the cavity.
  - $P_r$ : Reverse Power, coming back from the cavity.
    - $P_e$ : Emitted power, from the cavity stored energy, leaking out through the coupler.
    - $P_{ref}$ : Reflected power, incident power directly reflecting off of the cavity coupler boundary.
    - Reverse power is the vector sum of those two field components.
  - We'll worry about transmitted power later.

# Steady State Behavior

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- $$U_0 = \frac{4\beta P_f}{(\beta+1)^2} \frac{Q_0}{\omega}$$

- $$\beta_e = \frac{\left(1 \pm \sqrt{\frac{P_r}{P_f}}\right)}{\left(1 \mp \sqrt{\frac{P_r}{P_f}}\right)}$$

- Note, that there is an ambiguity here. There are three states possible:
- Undercoupled: Weak coupling, most power reflected
- Overcoupled: Strong coupling, large emitted power
- Matched: Equal emitted and reflected 180° out of phase
  - $P_f = P_d!$

# Dynamic Measurements

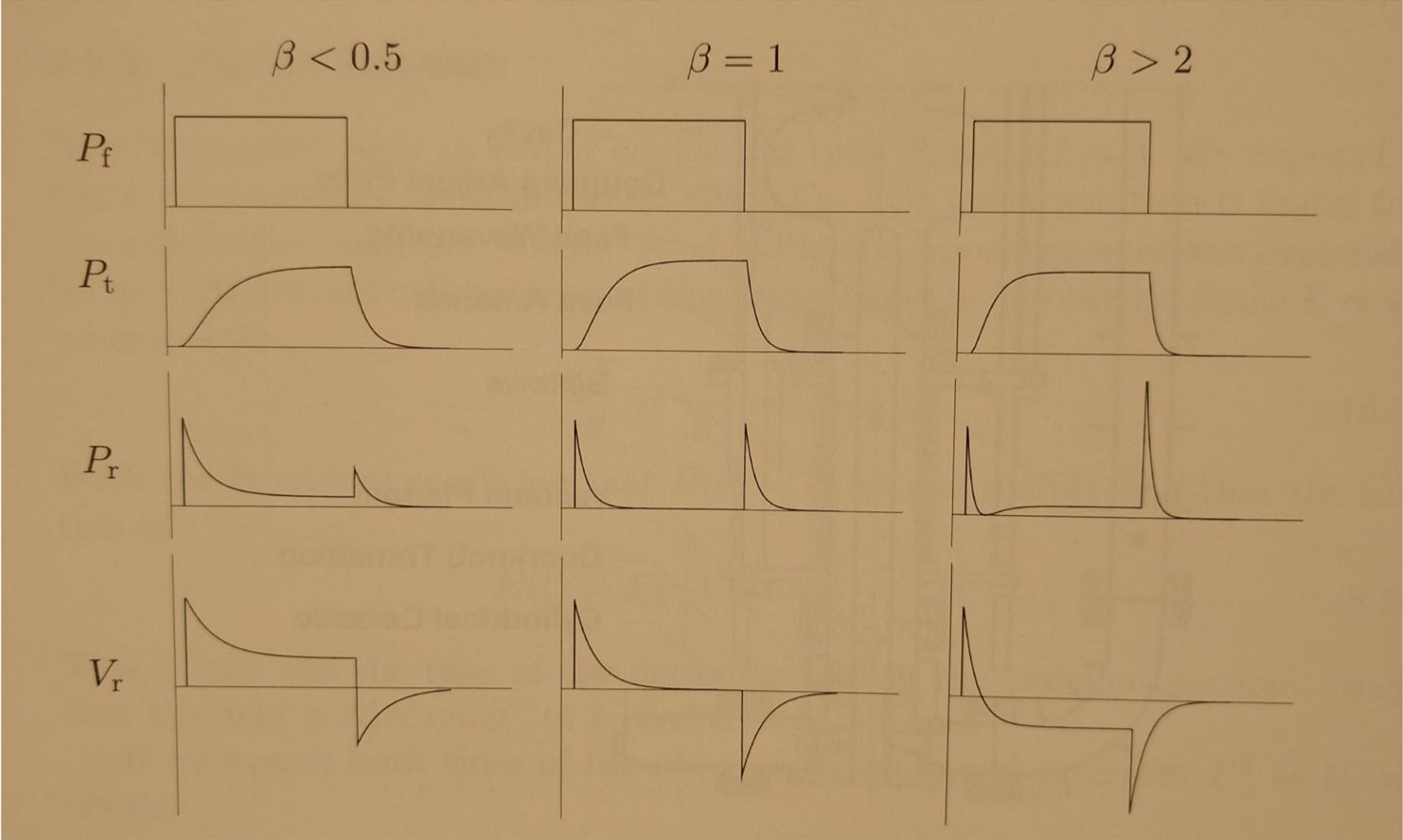
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- Must break the ambiguity.
- Turning the RF drive on and off gives us this information.
- Overcoupled will be dominated by emitted power, undercoupled is dominated by reflected power.
- Turning off the drive power removes the reflected power component!

- On:  $E(t) = E_0 \left[ 1 - e^{-\frac{t}{2\tau_L}} \right]; P_r = \left\{ 1 - \frac{2\beta}{1+\beta} \left[ 1 - e^{-\frac{t}{2\tau_L}} \right] \right\}^2 P_f$

- Off:  $E(t) = E_0 e^{-\frac{t}{2\tau_L}}; P_r = \left\{ \frac{2\beta}{1+\beta} e^{-\frac{t}{2\tau_L}} \right\}^2 P_f$

# Square Wave Response

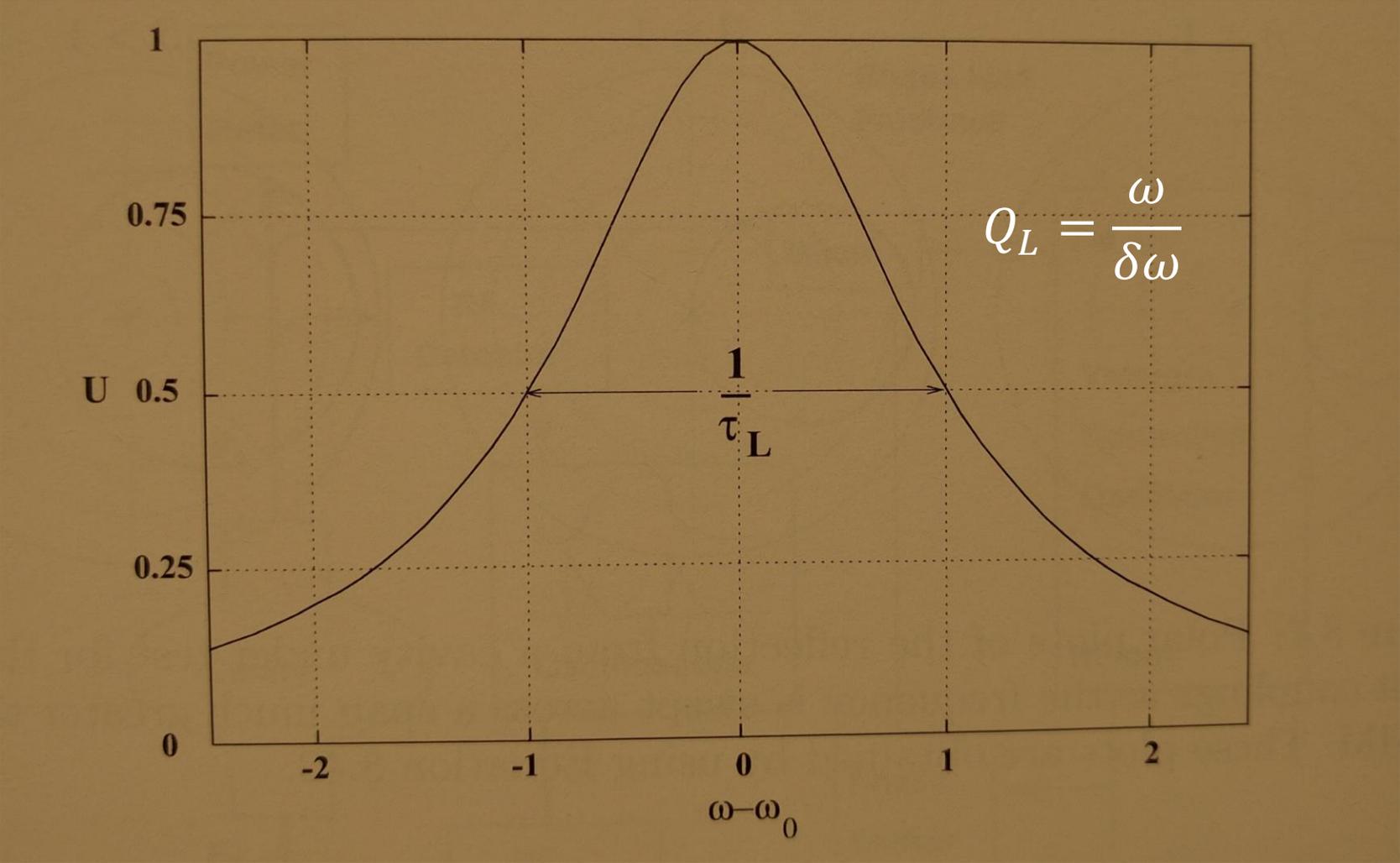


# Calibrations

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- Combining low field static and dynamic measurements characterizes the cavity.
- This gives us a measure of the stored energy,  $U$ , and can be used with a simultaneous measurement of the probe power to calculate  $Q_t = \frac{\omega U}{P_t}$ .
- Once we know  $Q_t$ , all we need is a static measurement to directly measure the stored energy in the cavity (thus gradient!).
- Also, an energy balance tells us that  $P_d = P_f - P_r - P_t$ , so we've also measured  $P_d$ , thus  $Q_0$ .
- $Q_0 = \frac{Q_t P_t}{P_f - P_r - P_t}$

# Cavity Bandwidth



# Signal Calibration

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- Note, all of the powers I've been quoting have been at the cavity, just outside the couplers.
- These signals must be measured somewhere else, further away.
- Directional couplers are used to tap signals off of drive and response lines, often quite a distance from the cavity. Also, these cables are often not phase matched, so each signal has its own gain and phase.
- Procedures vary as to the calibration procedure, with each lab using a slightly different technique.
- These procedures are all vulnerable to their own systematic errors, which must be carefully considered.

# Production Testing of SRF Cavities

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- Qualification of SRF cavities starts with matched, or nearly matched cavity testing.
- $$P_d = \frac{\omega U}{Q_0} \approx \frac{(2 * \pi * 1.3E9[Hz] * 3.7[J])}{3E10} = 1[W]$$
- A 1 [W] amplifier can get  $\sqrt{1012 * 2\pi * 1.3E9 * 3.7} = 5.5 \text{ MV!}$
- Full gradient is  $\sim 35 \text{ MV/m}$ , so that's pretty good!
- For a copper cavity, this would be half a kilowatt or more!

# Testing Issues

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- Multipacting
  - Resonant electron excitation consumes RF power and limits achievable field
  - Heating drops Q and can quench cavity
  - Very RF drive level/phase/frequency, process over time
- Radiation/Field Emissions
  - Surface features/particles enhance fields on the surface, and cause electron emission
  - Electrons hitting the wall can/do cause X-Rays, and can produce soft photo-neutrons in extreme cases (real, real bad)
  - Can blow up/reclean
- Monitor both with RF response, cavity vacuum response, electron pickups, arc detectors.
- Both can happen in cavity and coupler!
- In the coupler, you can DC bias the inner and outer conductor to suppress

# SRF Cavity Testing Process (Vertical Testing)

- Cavity Cooldown
- Vacuum/Instrumentation Check
- Calibrate external RF Cables (input and pickup warm/cold cables)
- Find cavity frequency, lock to cavity at low power
- Dynamic RF calibration (Loaded Q, coupling constants, gradient calibration)
- Power rise up to higher gradient, CW or pulsed
  - Watch for radiation/multipacting/quench
  - Condition away radiation if possible
- QvE measurement of Quality Factor
  - Potential calorimetric measurements as well

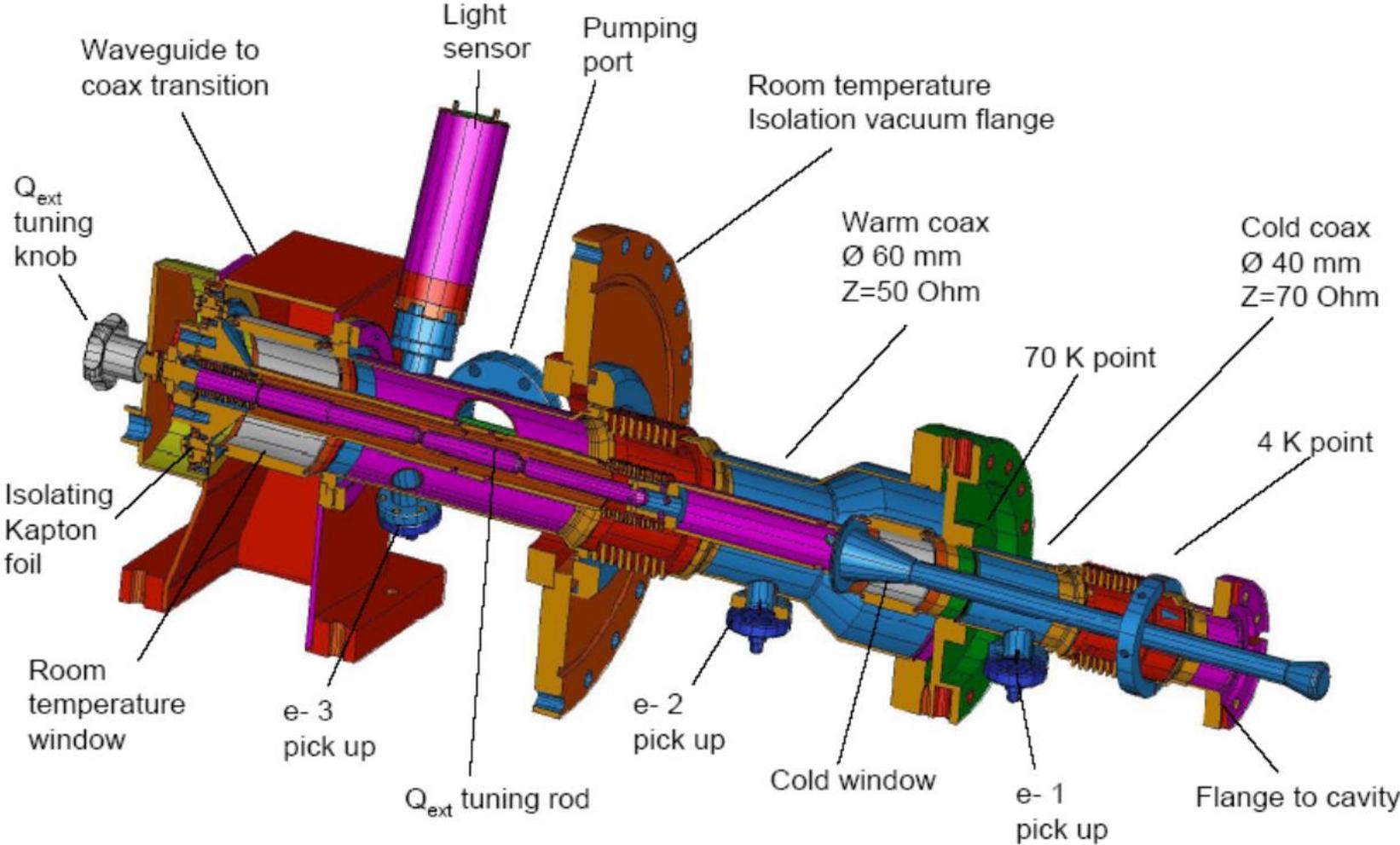


# Coupler Design Issues

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- RF Design Wants:
  - Good transmission at the design frequency
  - Proper coupling/coupling range into cavity
  - Avoid Multipacting bands
  - Good RF window design
- Mechanical Design Wants:
  - Thermal Behavior
    - How are we going to cool it?
  - Vacuum Break
  - Low cryo heat leak
  - Need to be able to install
  - Ease of fabrication/production
  - Copper coating is the most complicated thing in the universe

# High-Power Couplers



# Integrated Testing

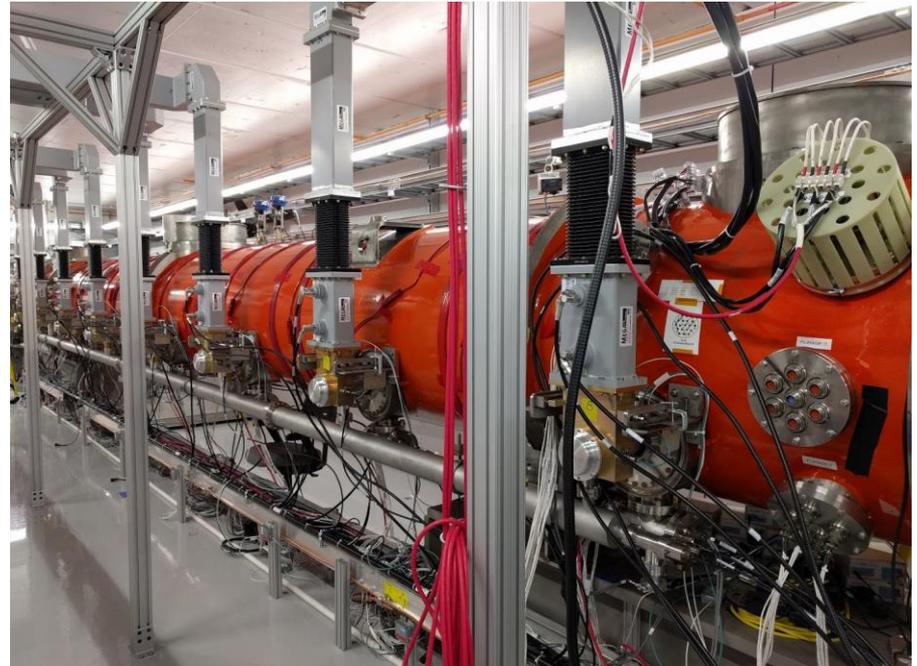
- Horizontal testing of a cavity allows iterative testing of cavity technology
  - Cavity
  - Jacketing
  - High power coupler
  - Mechanical tuner
  - Instrumentation
  - Cooling System
- Testing can be done with any combination of these systems installed depending on technical need



3.9 GHz LCLS-II Dressed Cavity installed at the Horizontal Test Cryostat at FNAL

# Cryomodule Testing

- The goal of production testing of cryomodules is to achieve as close to machine operational conditions as possible
  - Frequency
  - Temperature
  - Stability (Harder than it sounds!)
  - High power RF/Low Level RF
  - Phase/Amplitude Locked
  - Sometimes beam
- Includes verification of all details
  - Cavities, tuners, couplers, instrumentation, cryogenics



# Superconducting Technology

- Superconducting RF
  - Operates at 2 Kelvin (super-fluid helium)
  - Made from specialty high-purity niobium
  - All welds are done by electron beam in vacuum to maintain material purity
  - Heavily etched for optimal RF surface (field enhancement)
  - Washed carefully with high-pressure rinsing using ultra-high purity water
  - Requires rigorous/time-consuming cleaning and assembly in a class 10 clean-room
  - Very easy to ruin cleanliness



# Higher Order Mode Couplers

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Higher Order Modes are produced in cavities, especially in high current machines.

This power must be removed while not extracting the operational mode.

Specific design is HEAVILY influenced by specific cavity/beam interaction and engineering requirements.



# SPX Cavity Design

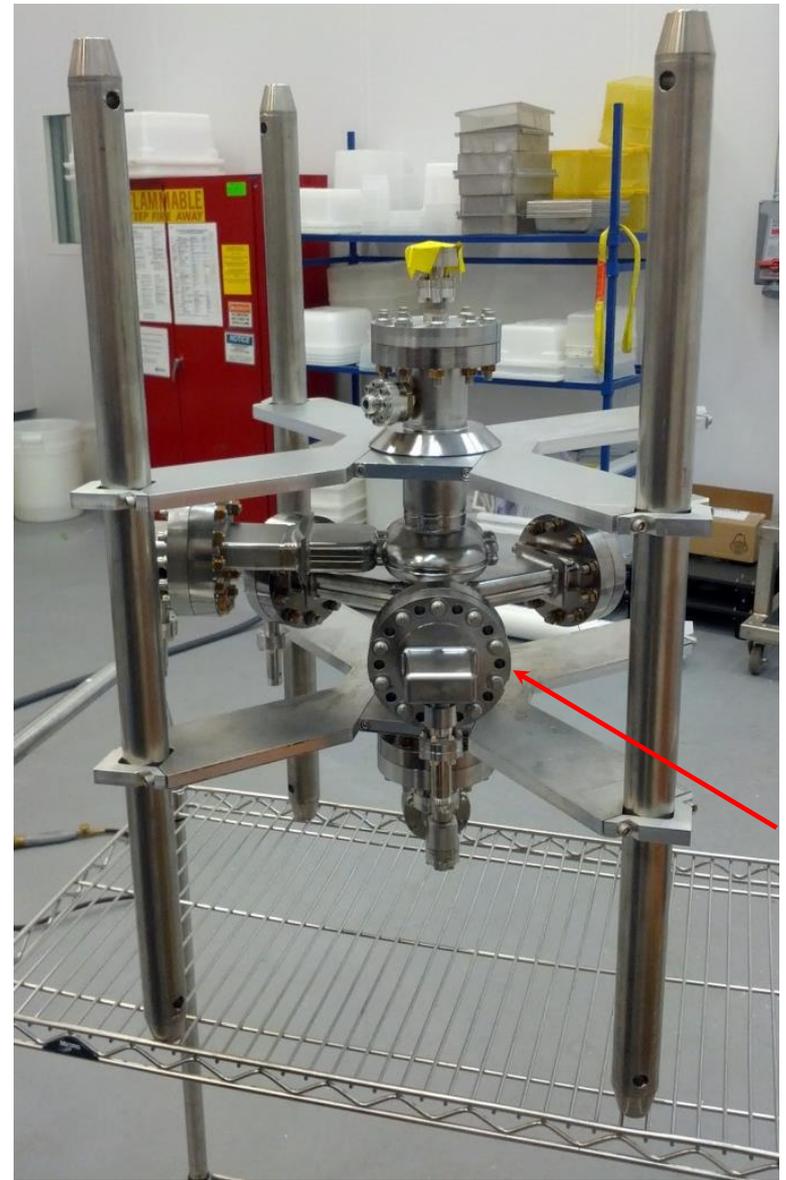


- Notable RF Features:
  - Forward Power Coupler
  - Wakefield damping
    - Higher-order modes like quadrupole and above
    - Lower-order mode is the monopole
    - Because the monopole mode is symmetrically similar to the beam, it must be damped very heavily
  - Field Probe

# Vertical Cavity Testing - Cavity Preparation



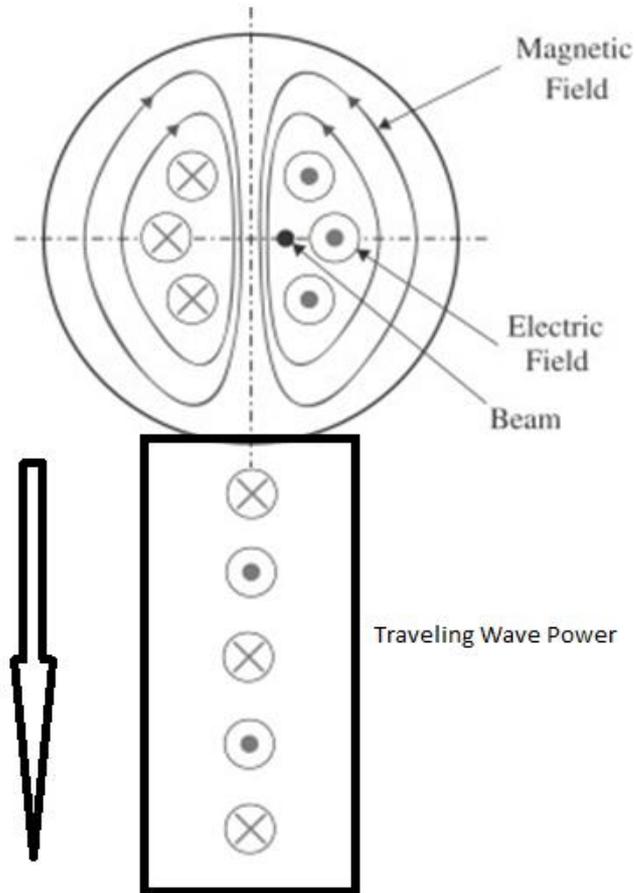
LOM



FPC



# Lower-Order Mode Damping

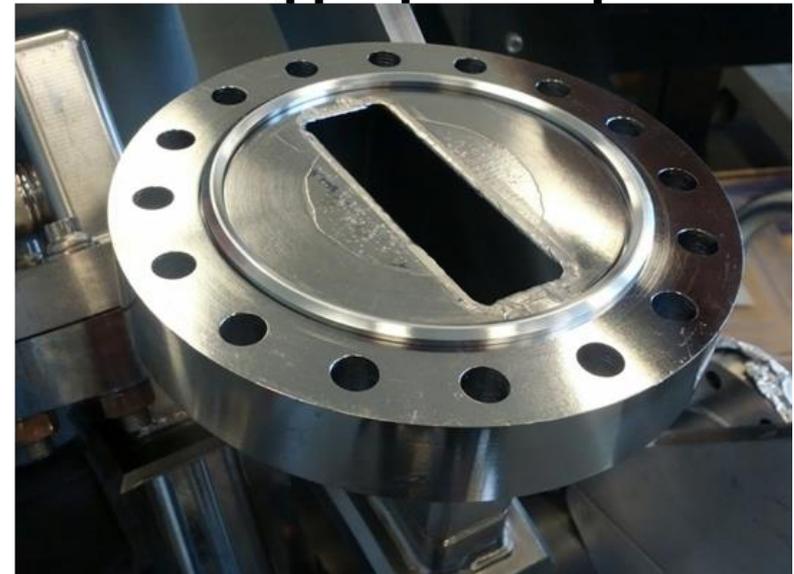
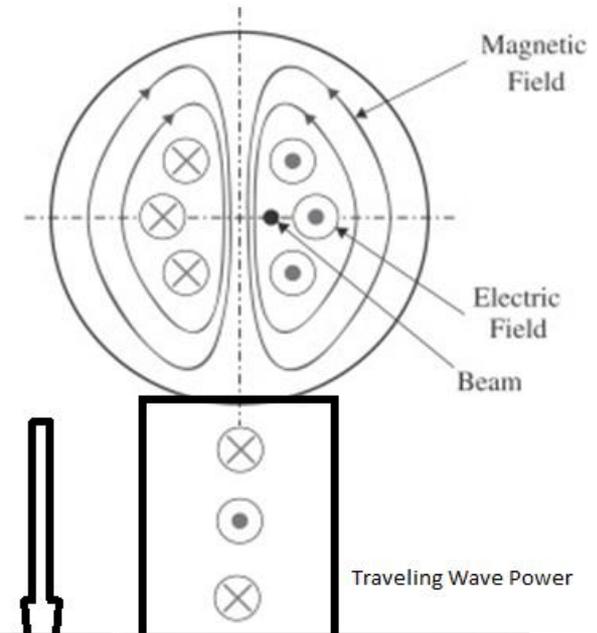


## ■ Clever Use of Symmetry

- On-Cell damping solves the problem of damping the monopole mode wakefields
- However, ***only symmetry is stopping this from damping the operational mode***
- If not done properly, large amounts of operational mode power leak into this waveguide
- Remember, Vertical Test = No Wakefields
- Fabrication methods could not hold the required tolerances

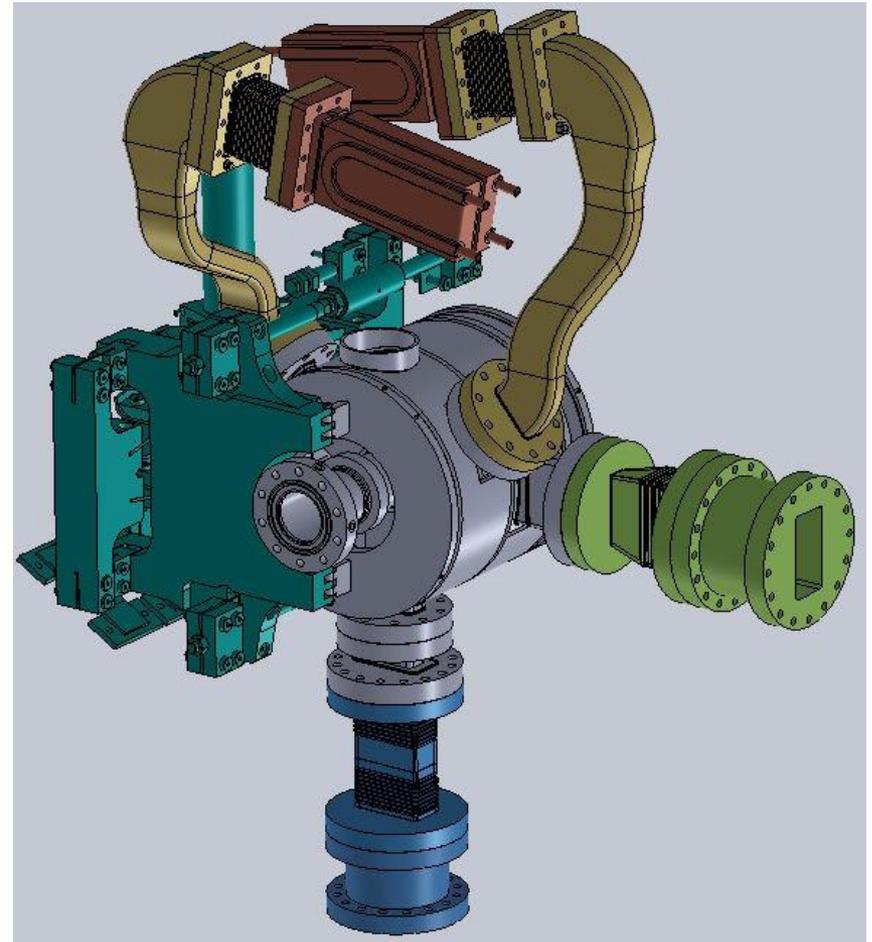
# Vertical Cavity Testing - LOM Tuning

- Poor initial tests were due to operational power leaking into LOM waveguide and causing losses/heating
- Differential deformation aligns cavity and waveguide center, minimizing field leakage as intended



# SPX0 - Waveguide Systems

- HOM (tan/brown) dampers in cryomodule
- LOM (green) power extracted to external load
- FPC (blue) matched into cavity
- Tuner (teal) used to control cavity resonant frequency

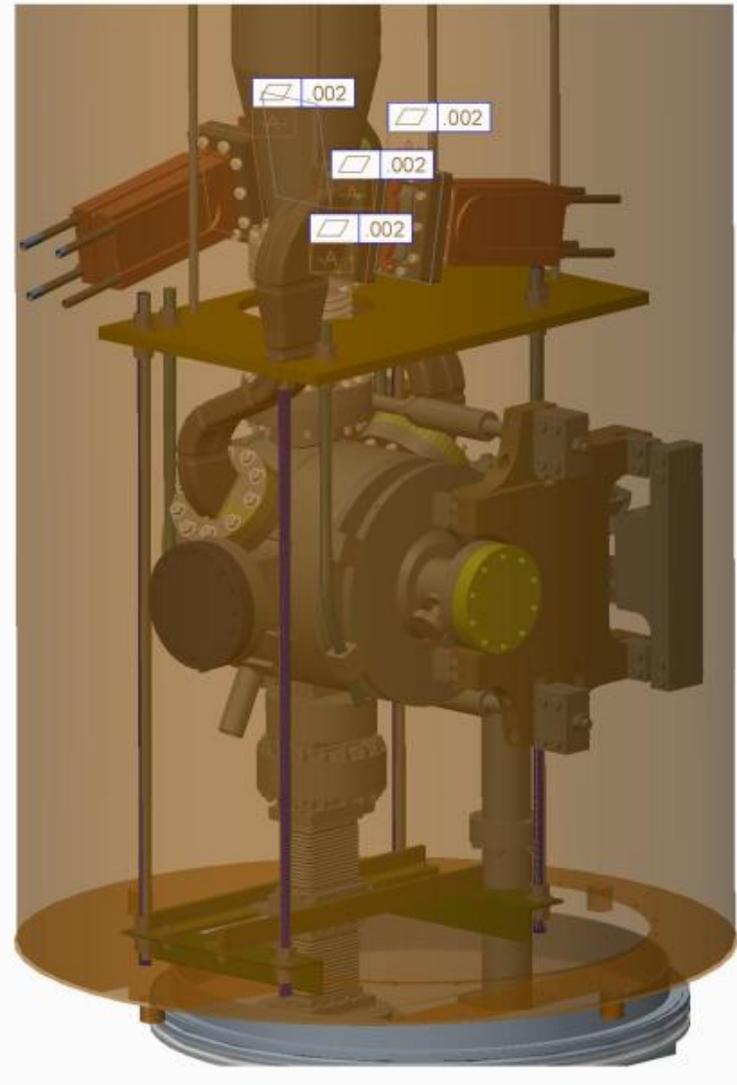


# Horizontal Cavity Test - Helium Vessel



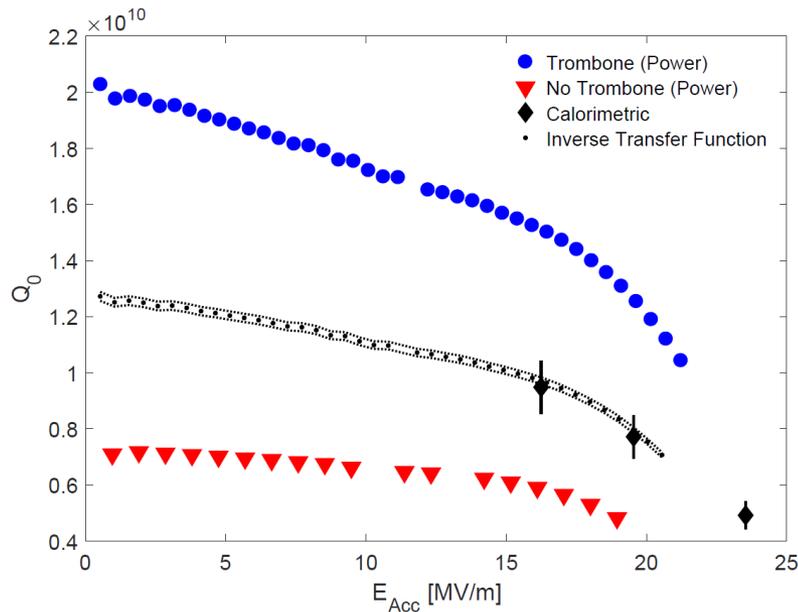
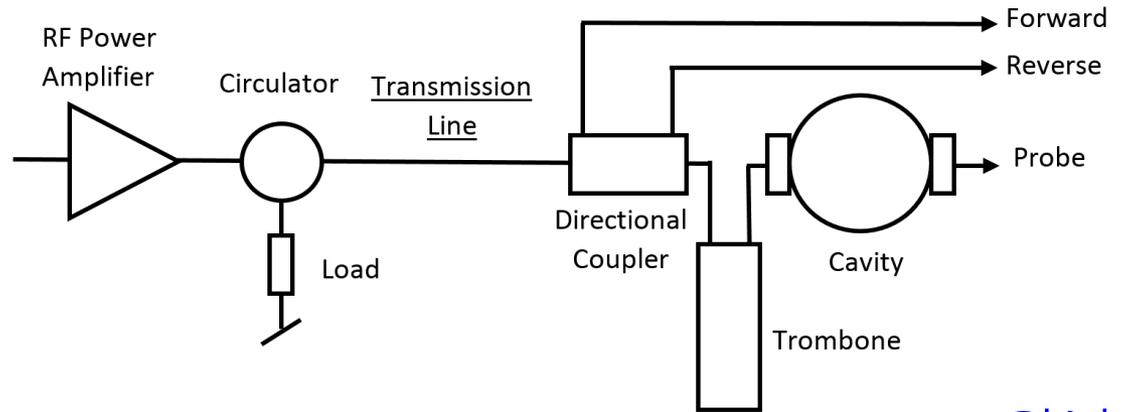
# Horizontal Cavity Test - Systems Integration Testing

- Goal is to test as many SPX0 systems as possible
- Integrate all systems
  - 5kW 2.815 GHz Klystron
  - Digital RF Systems
  - EPICS data recording
  - Tuner controls
  - Cryogenics & Vacuum
- SRF Performance
- Tuner Range/Resolution
- Digital RF Controls Studies



# RF Circuit Systematic Error

- Calibration procedure assumes perfect RF components
- Directional couplers and circulators are inherently limited
- Especially when the input coupling isn't close to matched, these can be sizable systematic errors
- Digital techniques and phase shifters can be used to identify and correct for these systematic errors



<https://arxiv.org/abs/1602.02689>  
<https://arxiv.org/abs/1804.04747>