# RF Coupler Tutorial

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# Why a Tutorial on RF Couplers?

- SRF couplers are technically challenging
  - RF accelerators in general, and SRF accelerators in particular, have dealt with a significant number of problems in making reliable RF power and HOM couplers
  - In the design process for high-intensity lepton and hadron SRF accelerators at high gradients, RF coupler performance is a major consideration
- The knowledge base in building good RF couplers can be difficult to embrace
  - Designing a reliable, cost effective, and high performance coupler is a highly multidisciplinary task
  - The experience base on how to build “the best” couplers is spread about the globe
  - Technology summary papers amass results, but often don’t distill them to “best practices”
- The stakes are high
  - A failed coupler design on a major machine that degrades performance and availability has a serious impact on accelerators as scientific instruments and SRF as a technology choice

*This talk shall attempt to briefly summarize the technology of RF couplers and to distill what has been learned into a basic recipe for realizing a robust design*

# A Sampling of How and Why Couplers Fail (Circa ~ 2003) Demonstrates the Range of Issues that Need Attention

**"Full" Failure Modes:**

- Vacuum leaks
  - cracked window due to excessive tension or shear forces
  - punctured window due to electron activity
  - leaking brazes and welds
  - leaking flanges
  - cracked bellows
  - burned bellows

**Performance Limiting Modes:**

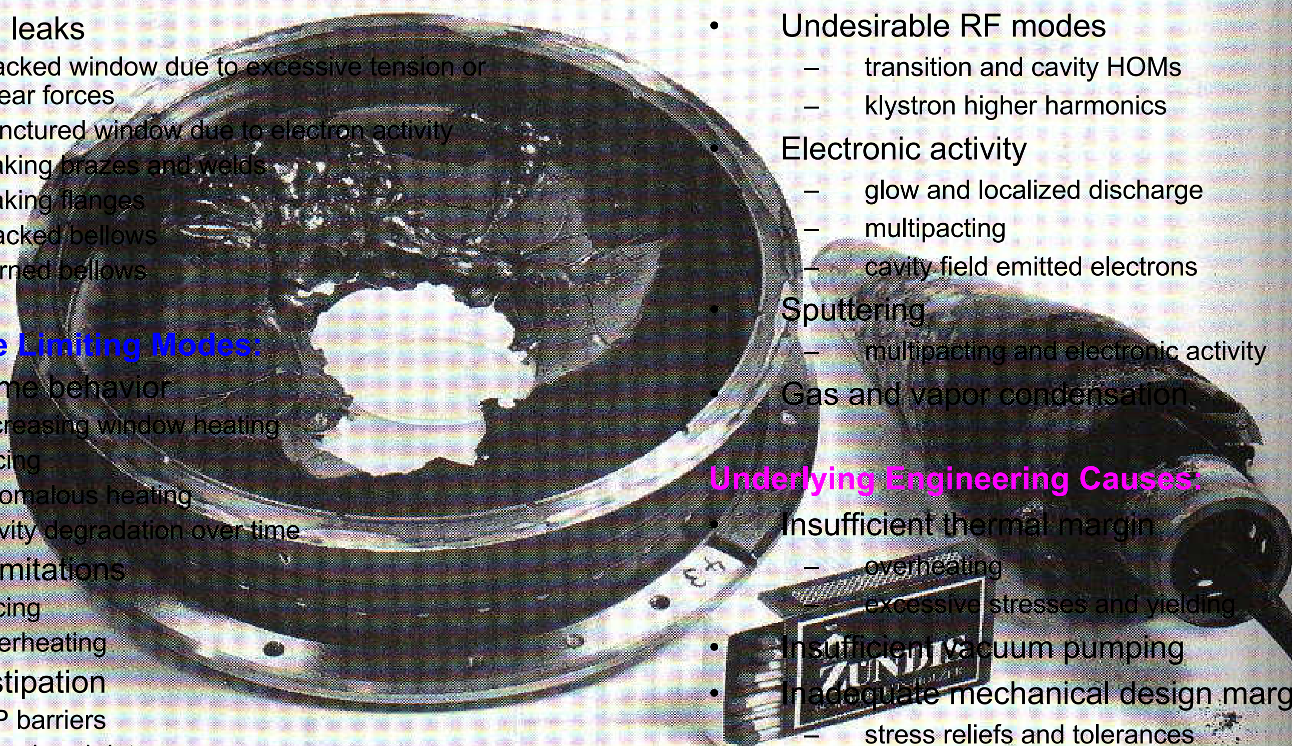
- Worrisome behavior
  - increasing window heating
  - arcing
  - anomalous heating
  - cavity degradation over time
- Power limitations
  - arcing
  - overheating
- RF constipation
  - MP barriers
  - pass band detune
  - window metalization

**Underlying Physics Causes:**

- Undesirable RF modes
  - transition and cavity HOMs
  - klystron higher harmonics
- Electronic activity
  - glow and localized discharge
  - multipacting
  - cavity field emitted electrons
- Sputtering
  - multipacting and electronic activity
- Gas and vapor condensation

**Underlying Engineering Causes:**

- Insufficient thermal margin
  - overheating
  - excessive stresses and yielding
- Insufficient vacuum pumping
- Inadequate mechanical design margin
  - stress reliefs and tolerances
- Poor process control
  - plating
  - ceramic manufacturing

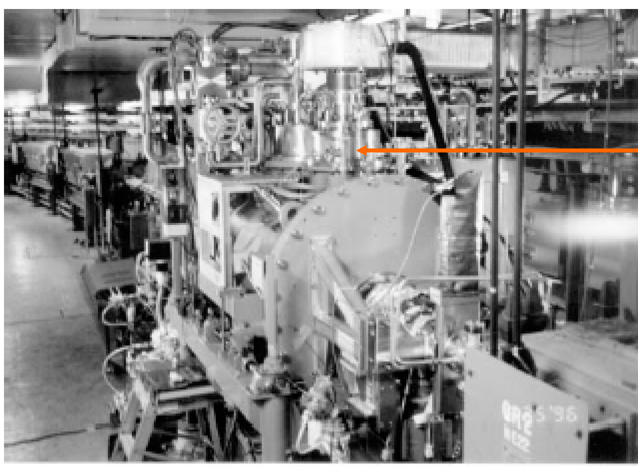



Operation without Conditioning Fig.13

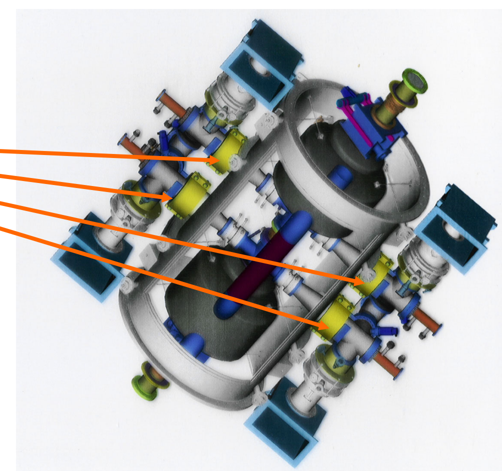
# What Constitutes an RF Coupler in General?

- Is an RF transmission line component that electrically handles up to ~MWs of RF power and thermally handles 10's to 100's of kW average power
- It needs to survive in a cryogenic environment and withstand thermal cycling
- It hermetically seals the ultra-clean interior of an SRF cavity
- It needs to be very reliable and reasonably priced
- They generally fall into two categories:
  - Pulsed Power: Handles high voltage, but generally more modest average power heating
  - Continuous Wave (CW) Power: Needs to handle high voltage, <u>and</u> high average power heating loads

- A failed RF coupler can not only prevent an accelerator from working properly, it can also take significant money and effort to recover from



*couplers convey RF energy to and from SRF cavities in a cryomodule*



# Cost Perspectives Related to a Broken/Failed Window

Collected information:

- A given large accelerator 100's of SRF couplers on a given machine (JLab has >300)
- A capability recovery cost of 80-100 k$ per coupler failure seems reasonable
- If a failure mechanism is not understood, 100's of k$ can be spent on research and diagnosing

Illustrative scenario:

- 5 couplers fail in 2 years of operation (95% success)
- 14 FTE-months is used to study the problem and determine fixes
- fixes are designed and implemented taking 8 FTE months + M&S
- 700 - 900 K$ is spent on addressing coupler-related problems

Cost and effort estimates for one failed unit

| | |
|---|---|
| • remove CM from tunnel = | 10 h |
| • replace coupler = | 15 h |
| • replace CM into tunnel = | 20 h |
| • subtotal = | 45 h |
| • disassemble CM = | 80 h |
| • reprocess cavity = | 40 h |
| • reassemble CM = | 100 h |
| • subtotal: | 265 h |
| • cost at $100/hr = | $26,500 |
| • lost beam time cost = | $20,000? |
| • M&S plus new cplr = | $45,000 |
| • total estimated cost = | $91,500 |

*A failed FPC's makes a cavity inoperable in the accelerator, a failed HOM either renders the cavity inoperable, or ends up degrading the beam quality. Either way, a failed RF coupler is expensive and it pays to design them well.*

# Fundamental Power and HOM Couplers are Similar in Some Ways and Different in Others

Fundamental Power Couplers (FPC)

- convey desired RF power at $f_0$ over narrow band to the SRF cavity
- are typically either coaxial or waveguide
- are a mechanical bridge between ambient and cryogenic environments

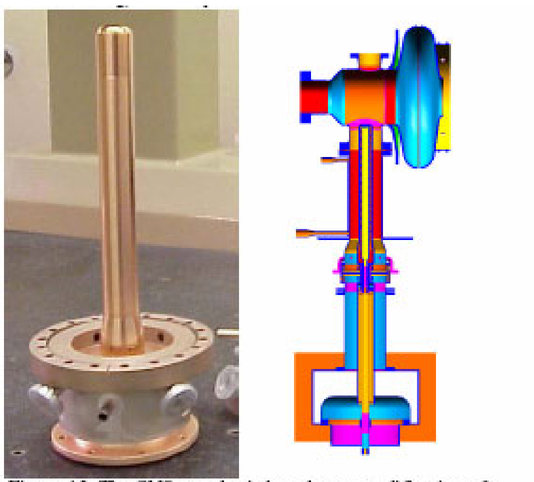
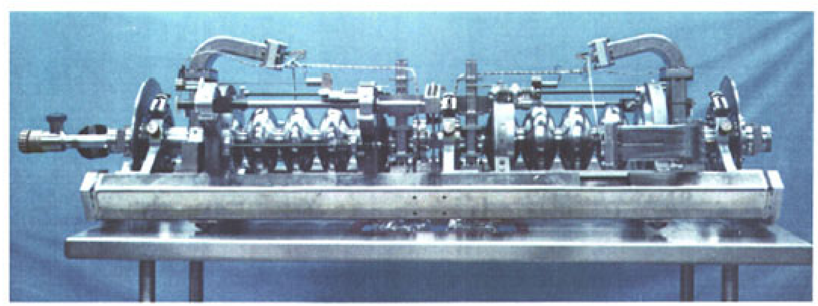


Figure 12. The SNS coupler is based on a modification of the KEK-B coupler. The window matching design has been applied in the past to room-temperature systems. The SNS coupler developments has greatly benefited from the experience and the collaborations of several laboratories and industries around the world and has reached 2 MW peak in high-power tests [91].

HOM couplers

- remove unwanted RF power from a cavity due to beam-induced HOMs
- can be waveguide or coaxial-like filter
- can locally dissipate or convey energy away from the cavity cryogenic environment
- need to efficiently transmit RF over a broad band of frequencies that does *NOT* include $f_0$
- may connect ambient to cryo environments, depending on whether HOM power is dissipated in the cryomodule or not



# Examples and Typical Features of Fundamental Power Couplers

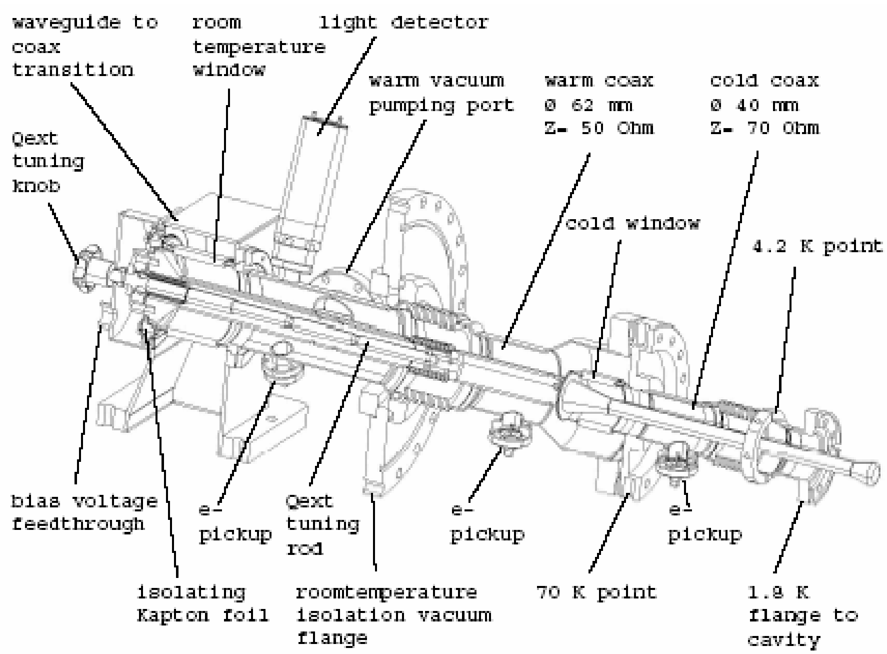



Figure 1: TTF III coupler.

Table 1. Couplers processing procedure on the coupler test stand

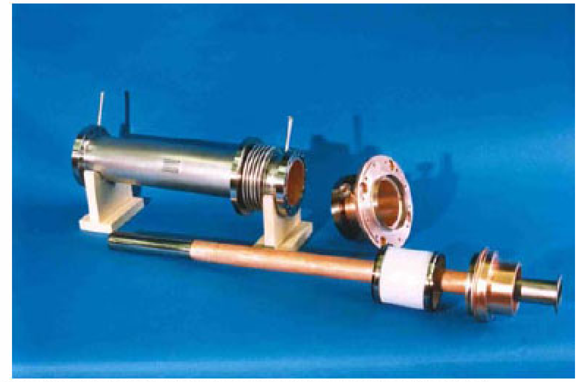


Fig. 2: The first version of the LEP power coupler.

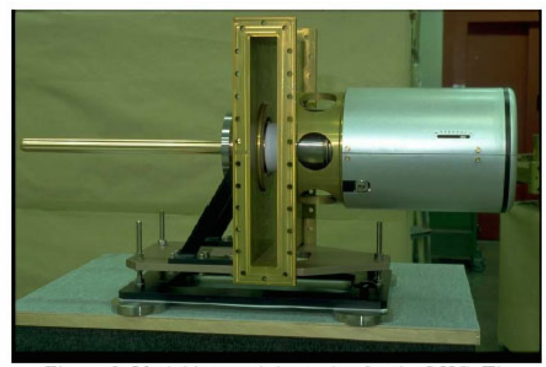
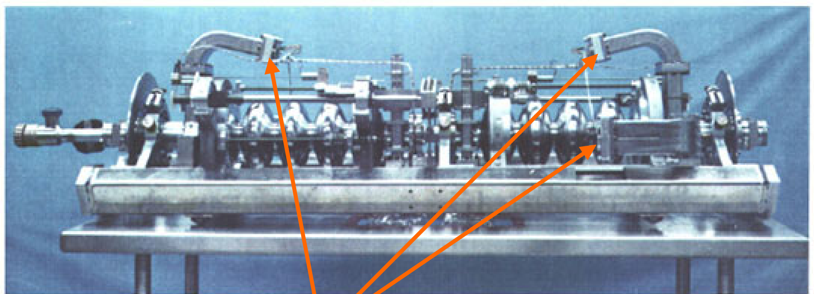
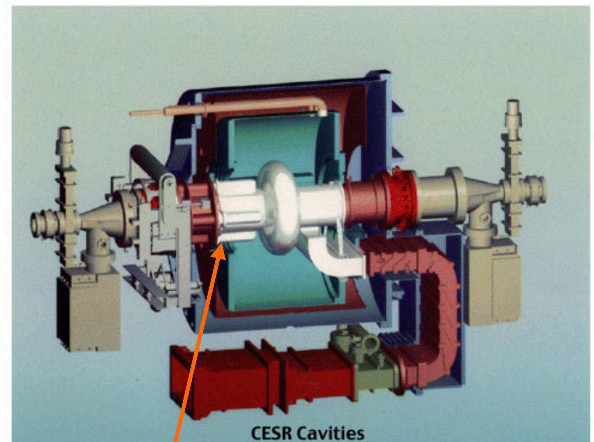


Figure 2. Variable coaxial coupler for the LHC. The variable insertion mechanism allows a change in coupling factor by over an order of magnitude. This coupler has a cylindrical window in the waveguide. [9]

# Examples and Features of HOM Couplers

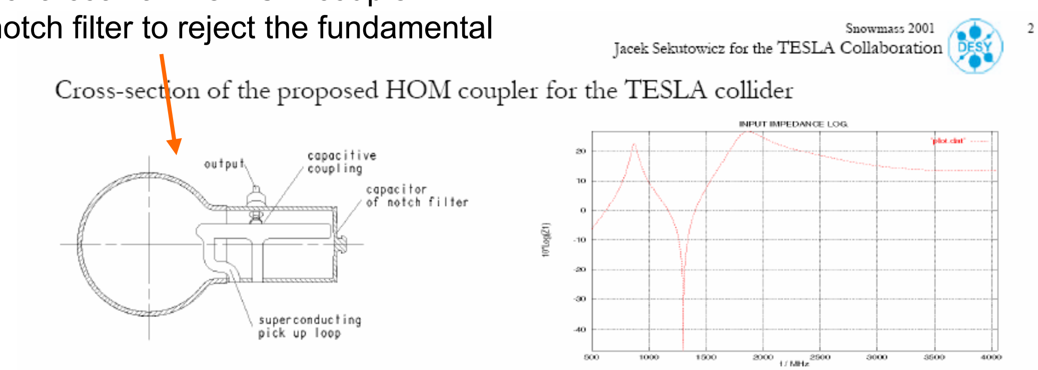


waveguide HOM couplers with
dissipative loads on a JLab cavity



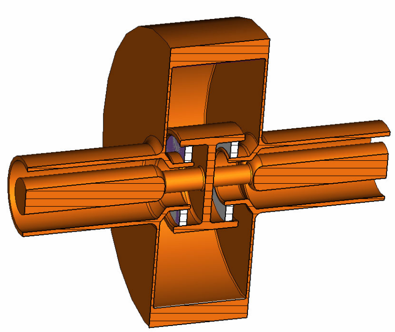

fluted beam tube leading to ferrite
dissipative loads on a CESR cavity

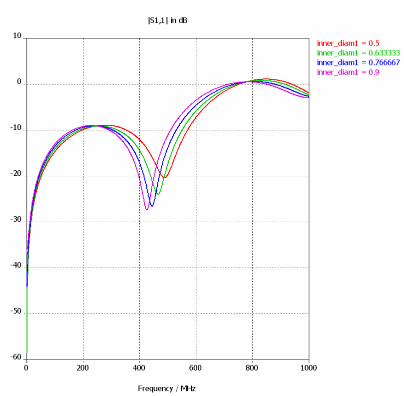
example of a coaxial-like HOM coupler
using a notch filter to reject the fundamental



# Physics Design Environment

- Fundamental Power Couplers need to:
  - deliver enough RF power to maintain fields in the cavity with beam
  - operate below arcing thresholds
  - avoid multipacting near the operation point
  - avoid lower order (<6-7th) multipacting in general
  - be reasonably matched to decrease standing waves
  - avoid excess evolved and condensed gas
  - account for HOM power field stress






- Extracting HOM Couplers need to:
  - adequately reject fundamental power
  - couple to a multitude of modes
  - couple to degenerate orthogonal modes
  - sufficiently damp broadband HOM energy
  - minimally impact beam properties
  - avoid multipacting (sputtering)
  - convey power to a matched load

- Dissipating HOM Couplers need to:
  - do all the above, *plus…*
  - get dissipated power (heat) out of material
  - maintain a broadband match
  - maintain adequate cooling under load

*Once the physics specifications and RF engineering concept for the coupler is established, the design process continues*

# RF Coupler Engineering

- Thermal management - Ohmic
  - minimize heating due to RF losses
  - control temperature on window
  - heat removal / cooling
- Thermal management - Cryogenic
  - minimize conductive thermal heat leak
  - minimize radiative heat leak
  - minimize heat leak due to RF losses
- Coatings
  - plating for lower Rs
  - multipacting suppression
- Mechanical
  - account for thermal contraction/expansion
  - proper tolerancing
  - assembly and brazing
  - adequate vacuum pumping
  - clean room cleaning and assembly
  - clean mounting to the cavity

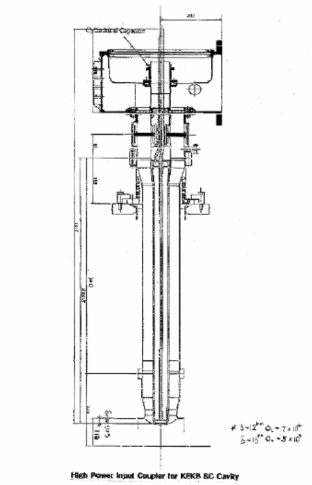
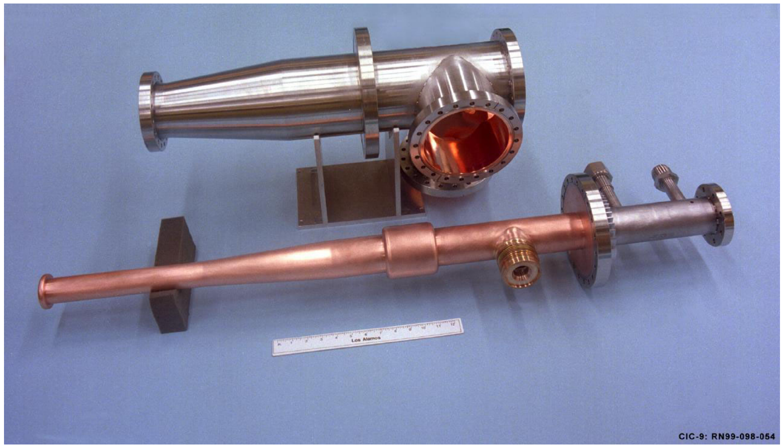



Figure 1. Input coupler for the KEKB

Fig. 5: the 75Ω fixed couplers. Note the two ports for the vacuum gauge and the electron monitor close to the ceramic.



# System Impact - Cryogenics and Operational

- System impact
  - intercept temperature
  - intercept stream (gHe, LHe, LN…)
  - dynamic vs static load
  - cryomodule design for clean assembly
  - overall RF architecture
  - cavity beam tubes for coupling
  - cryomodule fixed points
    related to contraction

- Operational
  - interlocks on coupler (essential vs wanted)
  - risk, setpoints and project schedule
  - coupler conditioning
  - high peak power processing in situ
  - abrupt vs graceful degradation
  - failure consequences

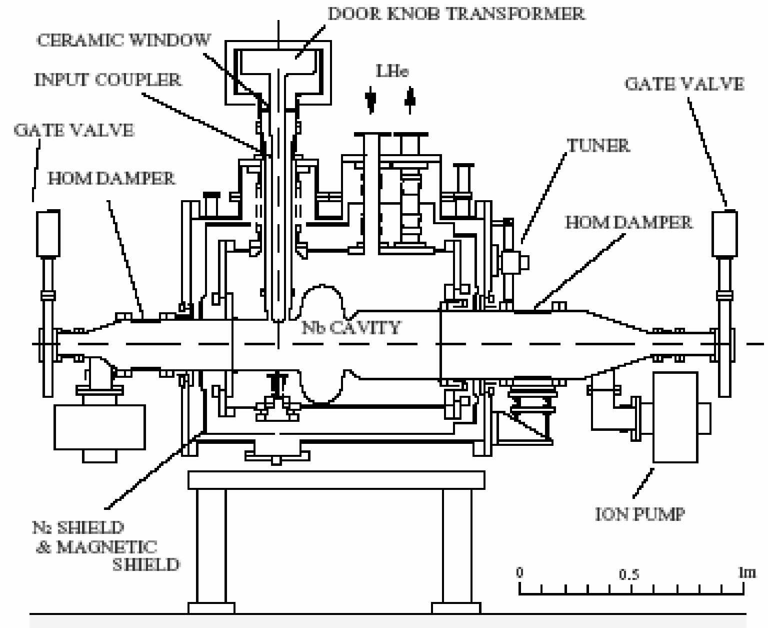



Figure 1: A sketch of the SC cavity module.

# The SRF High Power and HOM Coupler Design Envelop is Complex and Highly Interdisciplinary

- An SRF high power coupler is highly interdisciplinary – where RF power, cryogenics, contamination control, mechanical engineering, vacuum, and materials technology all come together
- While perhaps less visible, it is no less important than SRF cavity performance, target lifetime, or cryoplant reliability
- A broken or failed window is a major failure costing substantial money to fix
- A malfunctioning window impacts machine performance for the long term, which can also impact cost and availability

- However, being too conservative in coupler design or RF architecture can make a coupler excessively expensive
- Finding the right design balance is challenging since we tend to have areas of technical interest which can bias the process

# RF Coupler Constraint Space Compared to Emphasis

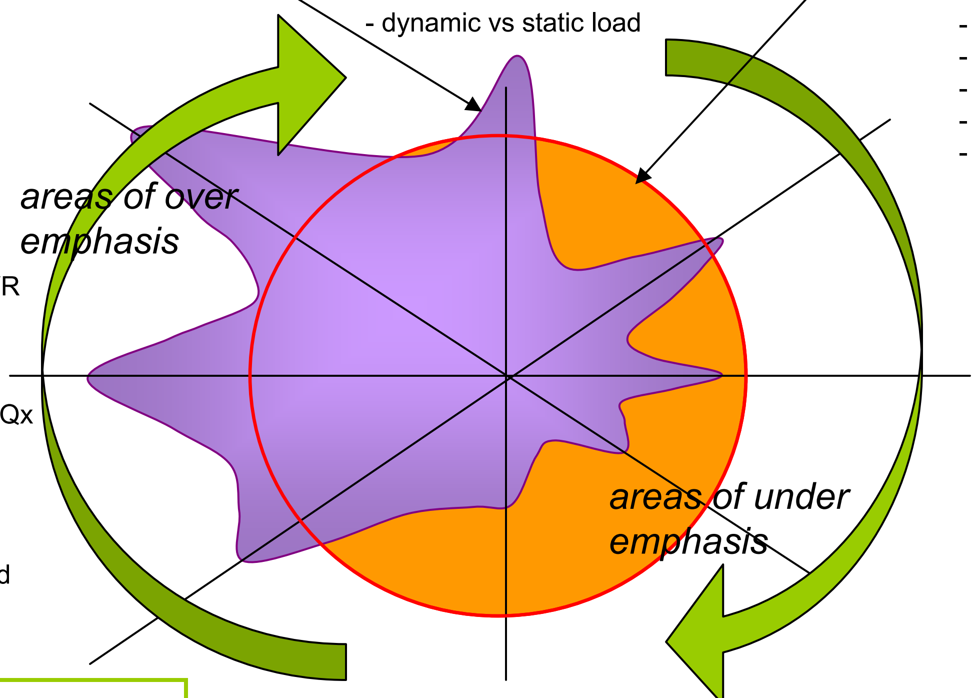
**Design Emphasis**

**Balanced Constraints**

**Cryogenics**
- heat loads
- intercept temperature
- operating temperature
- heat leak
- dynamic vs static load

**SRF Cavity Technology**
- cleanliness
- port size
- coupling and Qx
- RF conditioning

**Mechanical**
- alignment
- stresses
- mechanical modes
- vacuum levels
- pumping conductance
- ohmic heating removal




**RF Engineering**
- matching and VSWR
- band pass width
- power levels
- tuning
- adjustable vs fixed Qx
- variability in Qx
- multipacting
- HOM influences
- parasitic moding
- conditioning method

**Cryomodule**
- mechanical assembly
- clean assembly
- assembly complexity
- alignment
- cooldown and contraction
- compliance and fixed points

**Accelerator Physics Design**
- beam dynamics, cavity fields
- overall efficiency, gradient
- focusing lattice
- design defensibility

**START**

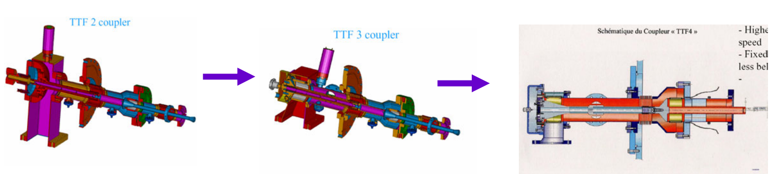
**System Engineering**
- reliability, efficiency
- margin management
- cost
- manufacturing
- spares
- fault modes and response
- cost reduction exercises
- repair

**Materials/Manufacturing**
- ceramic fab process
- defect distribution
- metal coating technology
- process control and QA

# Constraints Often Impact the Design Process and Performance of an RF Coupler

- Ideally, a balanced design effort is desired to ensure all critical areas are addressed
- Realistically, as the process evolves from accelerator physics to final design, an unbalancing of the process often occurs that can compromise performance and reliability
- While developing a balanced and multidisciplinary design team is important, it is not always possible to the extent desired
- For these reasons, extensive modeling, prototyping and testing is important for realizing a high performance RF coupler

- And, even with good design practices, it is helpful to remember that RF coupler development is an evolutionary, as opposed to immaculate, process

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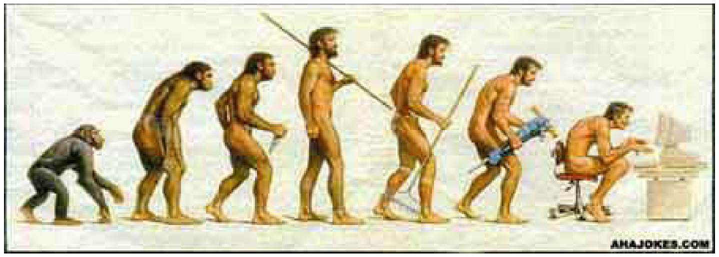


# Ample Tools and Techniques are Available to Aid the Design Process and Improve Performance

- Physics and RF Modeling Codes
  (Microwave Studio, MAFIA, URMEL…)
  - Electromagnetic modeling
  - Multipacting
  - Voltage biasing
  - HOM coupling
  - Beam effects
- Engineering Design Modeling
  (ANSYS, COSMOS…)
  - RF optimization
  - Thermal and heat transfer
  - Stress and strain
  - Vibration and modal response
  - Thermal expansion/contraction
  - Vacuum pumping
- Analytic analysis and scaling past designs
  - Maintain parameter space
  - Build upon what works
- Materials knowledge
  - Plating technology
  - Ceramic manufacture
  - Ceramic behavior (μcracking)
  - Coating technology (TiN)
- Process knowledge
  - Vacuum bakeout
  - High pressure rinsing
  - Plating adhesion testing
  - Clean assembly
  - Conditioning methods
  - High power test benches

*Since successful RF coupler design has a large empirical aspect to it, community experience is (at least) as important as good modeling*

# Experienced-Based Design Philosophies for Achieving Higher Performance

- Protect the window
  - don’t allow the window to be in tension or shear
  - avoid anisotropic heating due to higher order modes
  - allow for expansion with compliant features brazed to the window
  - don’t subject the window to longitudinal or rotating forces
  - don’t let the window see the cavity walls or electrons from the cavity
  - “guard” the braze areas with chokes to avoid high localized fields
  - keep close track of feedstock control on materials
  - try to not put the peak of a standing wave right on top of the window
- Avoid multipacting bands
  - work to keep low-order multipacting bands above operating point
  - keep coupler clean and baked
- Control the temperature
  - provide adequate cooling to cover expected AND unexpected heating due to MP, electron emission, HOMs, and mismatch
  - understand the impacts of prolonged operation and shutdown (condensed gas)
- Maintain excellent vacuum
  - poor vacuum pumping in the coupler leads to window problems and prolongs conditioning times
  - poor vacuum can also lead to greater condensate formation and enhanced MP

*All these aspects need to be addressed to realize a reliable RF coupler*

# Use a Design Approach that Uses Tools, Techniques, and Experience Base for Realizing a High-Performance Coupler

- Begin with as multidisciplinary of a team as possible
- Physics and RF design
  - Establish a reasonable and defensible operating power relative to accelerator requirements
  - Evaluate design compared to what has succeeded before, incorporate best practices
  - Run EM models to determine field and power levels
  - Evaluate multipacting characteristics of transmission lines
  - Apply margin on power for the design:  4x power (handles SW condition)
  - Determine Qx variance coverage and adjustability requirement
- Engineering design
  - Apply adequate margin:  200% x Ohmic thermal load for cooling, 50% of yield stress for metal
  - Analyze mechanical characteristics of the design and iterate
  - Analyze the cryo/thermal characteristics of the design, choose intercept temperature
  - Maximize vacuum pumping for transmission line size
  - Determine and qualify processes for plating, ceramic, other materials (BeCu)
  - Allow for vacuum bakeout of assembly

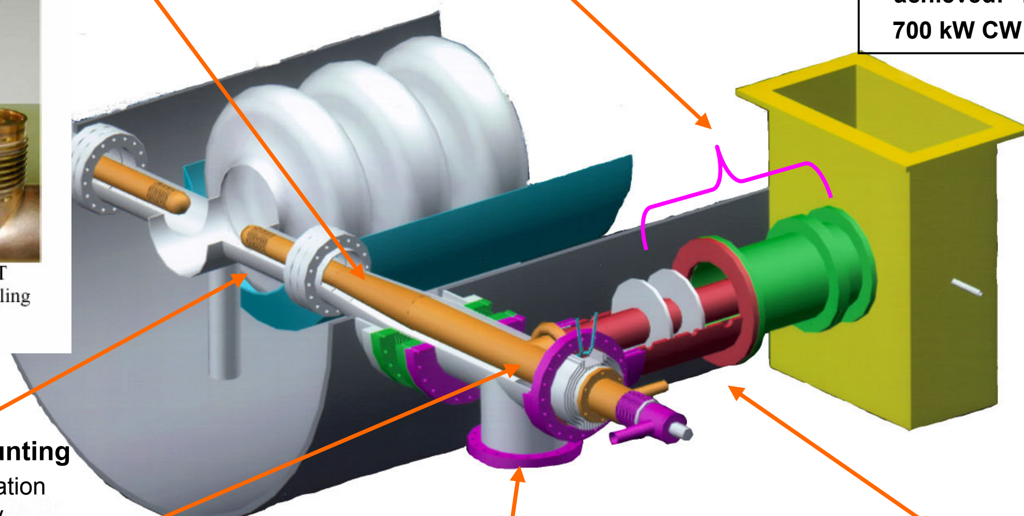
# The Design Process for a CW Power Coupler on APT Incorporated Many Experience-Based Features to Improve Performance

**4" - 6-1/8" 50 Ω coax for 700 MHz**
- MP bands at higher power
- lower power densities
- no outer conductor coax (fixed point)

**~ λ spacing**
- allows xsition HOM's to damp
- keeps RF fields on window uniform

**<u>700 MHz coaxial coupler:</u>**
- **250 kW CW TW power (oper)**
- **1 MW CW TW (RF design)**
- **500 kW CW (thermal design)**
- **achieved: 1,000 kW CW TW, 700 kW CW SW**

Figure 3. Details of the center conductor of the APT coupler, with the BeCu bellows, which allow the coupling variation (upper left). [8]



**Horizontal mounting**
- keeps contamination away from cavity

**λ/4 supporting stub**
- provides mechanical support
- gives good access for cooling
- allows mechanical adjustability
- complicates biasing if needed
- helps keep cavity HOMs off window

**6-1/8" diam open pipe for vacuum**
- no grill - fundamental freq. won't propagate
- Large vacuum conductance
- Serves as HOM "pump" for higher frequencies

**Planar coaxial windows at room temp**
- allows for convective cooling
- minimize thermal contraction/expansion
- non line-of-site to cavity

# Testing and Conditioning are Critical for Success

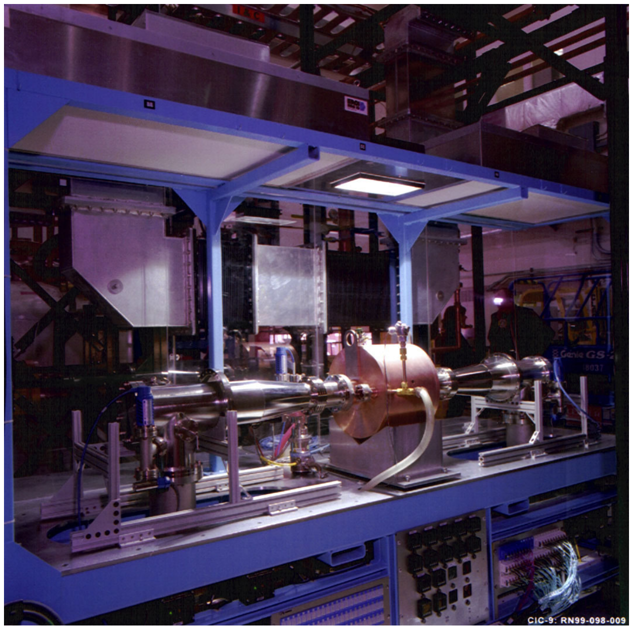



Figure 2: High power test stand

Room Temperature Testing and Conditioning:

- Room temperature test stands are an essential step in validating a design and conditioning a coupler
- It is important that the right RF power generators are available early in a project to allow testing

Cold Testing:

- Cold testing FPC's is very desirable, but is often cost prohibitive
- First cold tests are often done as part of the first cryomodule tests (which can be too late to affect major changes)
- Watch for long-term condensed gas buildup

Testing HOM couplers:

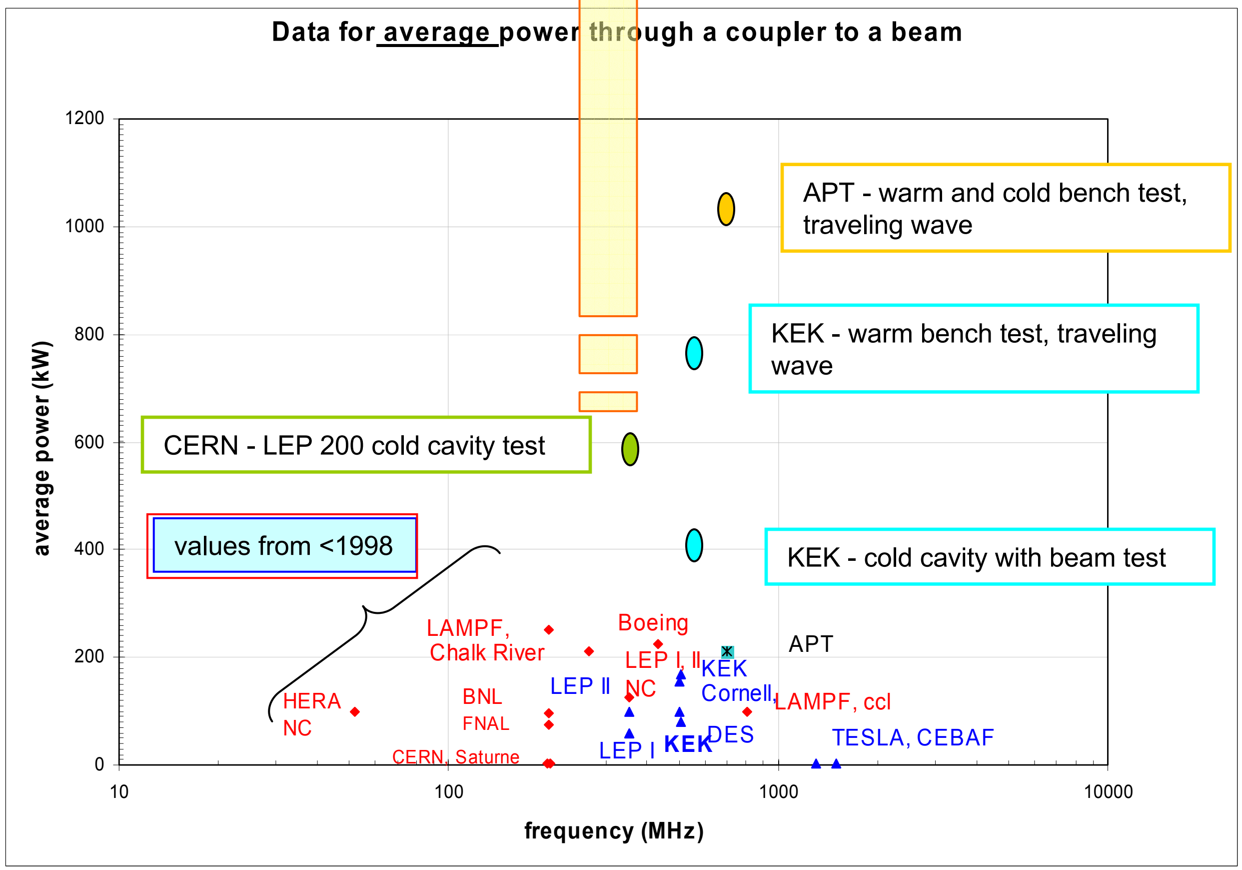
- Testing HOM couplers is more complex, as broadband excitation of the cavity is needed (best done with beam)
- Extensive bench testing and modeling are necessary
- Cold testing is also important to ensure bandpass and loss characteristics are preserved under cooldown

APT - warm and cold bench test, traveling wave equivalent for SW power achieved (>700 kW CW)

# These Techniques Have Worked to Improve Coupler Performance Worldwide in the Past 5 Years

Techniques applied to advance performance:

- engineering margin
- voltage biasing
- vacuum pumping
- bakeout
- process control on coatings

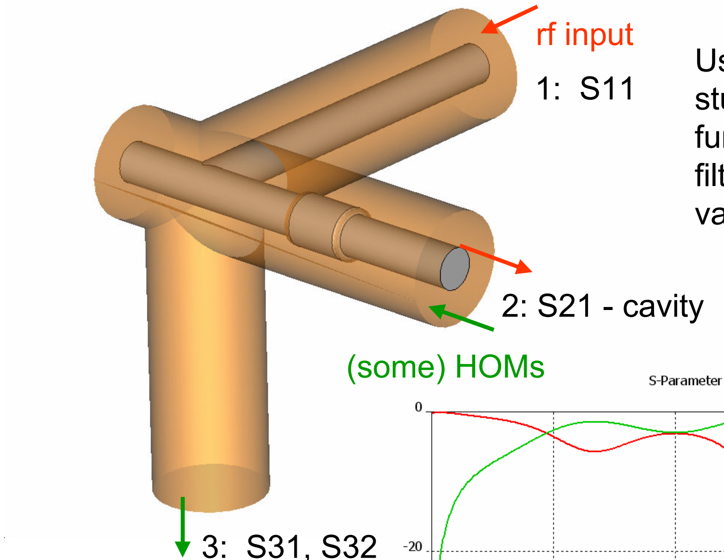


# While RF Coupler Work is Still a Development Area, a Recipe of “Basic Ingredients” for FPC’s is Evolving

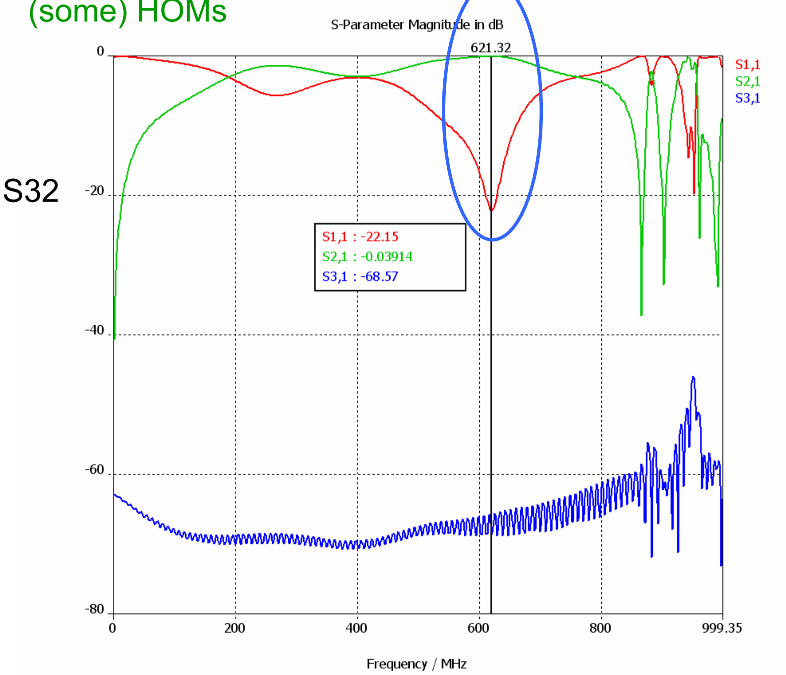
1. Coaxial line couplers are preferred for operation below 1-1.5 GHz
2. Go with as large a coax as possible
   - Stay reasonably proportioned to the cavity
   - Avoid overmoding the coax azimuthally
3. Planar coaxial windows are preferred geometrically for transmitting high power
   - Right cylinders are also good
4. Go with room temperature windows:
   - Avoids large thermal contraction, condensation, and conduction cooling issues
   - If gradient is state-of-the-art, a cold window may be necessary
5. For the RF design, try to maintain a minimum of ~ $\lambda$ spacing between the window and transitions
6. Vacuum bake coatings to outgas and improve adhesion
7. Vacuum bake windows to outgas
8. Clean assemble coupler using high pressure water rinsing in clean room
9. Apply generous design margins (2x thermal, 4x power)
10. Keep the DC biasing options “close at hand” in the design process, especially if MP is nearby
11. Use a big, open port for vacuum pumping and HOM damping
12. If the design process permits, employ a $\lambda/4$ stub to facilitate the mechanical and RF design

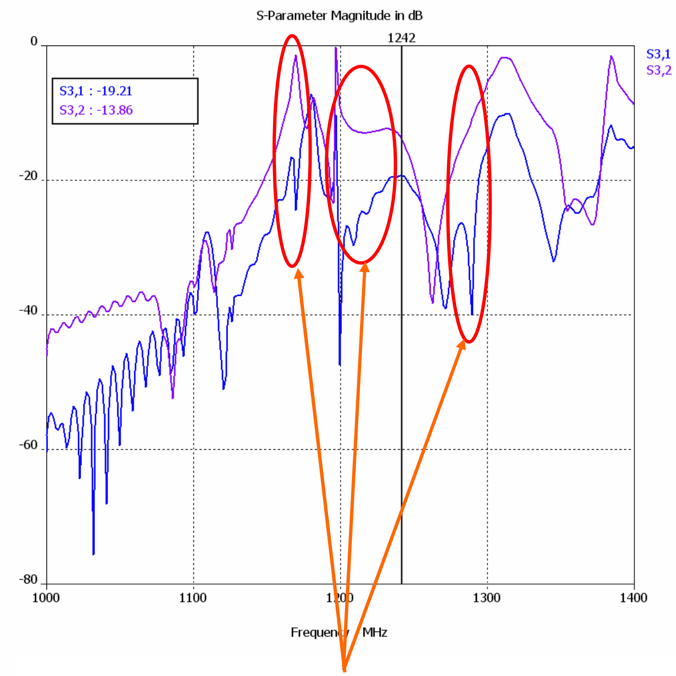
*As the operating experience of HOM couplers is highly beam and machine dependent, a recipe list for these devices is less obvious…*

# While a General Recipe Exists, R&D is Still Important to Improve Performance, Reliability, and Reduce Cost




Using a 3 way tee with a $\lambda/4$ stub on a coax line provides fundamental bandpass filtering and improved vacuum conductance




It also offers some intriguing possibilities for coupling to higher frequency HOM power, thereby better protecting the window

# Conclusions

- Fundamental power and HOM couplers are critical components on major accelerator projects
- Their lack of performance and/or failure impacts the entire facility, user group, and community
- RF coupler work is both exciting and challenging due to the highly interdisciplinary nature of the endeavor
- Because of this, interdisciplinary teams can be more effective in developing and advancing coupler designs
- We need to be aware of, and resist the tendency to overemphasize front-end design activities (physics, RF engineering, EM modeling) over other important aspects (materials considerations, system engineering, cryomodule integration)
- While it may be tempting to offer cost saving strategies in the coupler area, they should occur only after a proven design has been developed and evaluated

and

# Input on This Subject has Come from Many Sources Over the Years

- Many people and laboratories (and industries) worldwide have contributed to RF coupler development:

- Acknowledging those who have (unwittingly) contributed to this talk:

H.P Kindermann, J. Teuckmantel, B. Dwersteg, J. Sekutowicz, E. Haebel, A. Mosnier, M. Champion, R. Rimmer, M. Ono, S. Noguchi, L. Phillips, L. Doolittle, H. Padamsee, H. Safa, P. Balleyguier, D. Proch, I. Campisi, F. Krawczyk, W. B. Haynes, E. Schmierer, J. Waynert, P. Kelley, D. Schrage, K. Cummings, D. Rees…and many other scientists, engineers, designers, and technicians