RF Power and HOM Coupler Tutorial*

Brian Rusnak

Lawrence Livermore National Laboratory, Livermore, CA 94550

Abstract

Radio frequency (RF) couplers are used on superconducting cavities to deliver RF power for creating accelerating fields and to remove unwanted higher-order mode power for reducing emittance growth and cryogenic load. RF couplers in superconducting applications present a number of interdisciplinary design challenges that need to be addressed, since poor performance in these devices can profoundly impact accelerator operations and the overall success of a major facility. This paper will focus on critical design issues for fundamental and higher order mode (HOM) power couplers, highlight a sampling of reliability-related problems observed in couplers, and discuss some design strategies for improving performance.

Introduction

Superconducting accelerator research in the past three decades has enabled superconducting RF (SRF) cavities to achieve accelerating gradients in excess of 30 MV/m, well within a factor of two of the theoretical limit for elliptical high-β niobium cavities. As cavity gradients have improved to accelerate increasingly higher beam currents in modern machines, the power handling requirements placed on couplers for moving power in to and out of these cavities have gone up dramatically. Adding in requirements like high reliability, bridging ambient and liquid helium temperatures, low cryogenic heat leak, reasonable cost, and preserving extreme cavity cleanliness, and the complex nature of the engineering and physics design challenge inherent in these devices becomes apparent.

RF couplers are, in a most general sense, the assemblage of hardware and components needed to couple RF energy into or out of a resonant accelerating cavity. Fundamental power couplers (FPC) deliver energy to a cavity, and HOM couplers are used to extract or dissipate RF energy present in the cavity due to the radiative excitation of the cavity by the particle beam. The technological development of these devices has followed, and at times set the pace, for applications using SRF cavities.

Superconducting cavity power couplers not only need to handle up to megawatts of power spanning frequencies from 300 – 2000 MHz and duty factors from 1 – 100 %, they need to do it while simultaneously appeasing multiple and often conflicting constraints. Additionally, if a coupler fails to meet its performance objectives and the scientific output of the facility is compromised, the adverse consequences would be significant. The potential fallout between machine designers, funding agencies, and the community at large would be appreciable. For these reasons, it is vitally important proper diligence is applied to the RF coupler design process.

Another complication comes from the operational range of SRF accelerators being so broad and the RF design approaches being so varied that no one coupler design suits all applications. At best, there are general guidelines one can follow. At worst, the paths lead in all directions, and a fog is rolling in. To assist the SRF community in their need for reliable RF coupler technology, this tutorial is offered to help designers get a clearer, albeit more qualitative picture of the challenges involved, what the issues are, what approaches and solutions have been used by others in the field, and what concepts and strategies work. For additional information, the reader is encouraged to review two excellent coupler technology review papers written by Champion [1] and Campisi [2].

Background

There can be two types of RF power couplers on a given superconducting accelerator. The fundamental power coupler is used to excite the resonant structure to build up stored energy in the fundamental acceleration mode of the cavity. Higher order mode couplers are used to extract RF power from the cavity at frequencies above the fundamental, thereby damping the modes and decreasing their ability to degrade the beam quality and increase cryogenic load of the system.

Fundamental Power Couplers
The fundamental power coupler is used to deliver RF energy to the cavity at the fundamental frequency of the accelerator system. While this is very close to the resonant frequency of the cavity, it is not necessarily identical. Depending on the level of detuning due to microphonics, beam loading, and the synchronous phase set point, a FPC will need to efficiently transmit power over a range of RF frequencies. Fortunately for most applications, the bandwidth of these detuning effects is modest, and most RF transmission line systems and components can easily accommodate it.

As the losses in a superconducting cavity are so low, the amount of RF power the coupler needs to deliver is in the range of tens to hundreds of kilowatts in either continuous wave (CW) or pulsed operation.

FPCs tend to be based on either waveguide or coaxial RF transmission lines. How one type is chosen depends on a number of factors ranging from operational frequency to personal preference. Figures 1 and 2 shows examples of different types of coaxial and waveguide couplers.

Higher Order Mode Couplers
Higher order mode couplers are devices that remove or dissipate unwanted, higher frequency RF energy in a cavity. There are two types of HOM couplers – those that extract and transport HOM power to a dissipative load mounted outside the cavity vacuum, and those that have the dissipative medium contiguous with the cavity vacuum. The two types of HOM couplers are shown in Figure 3.
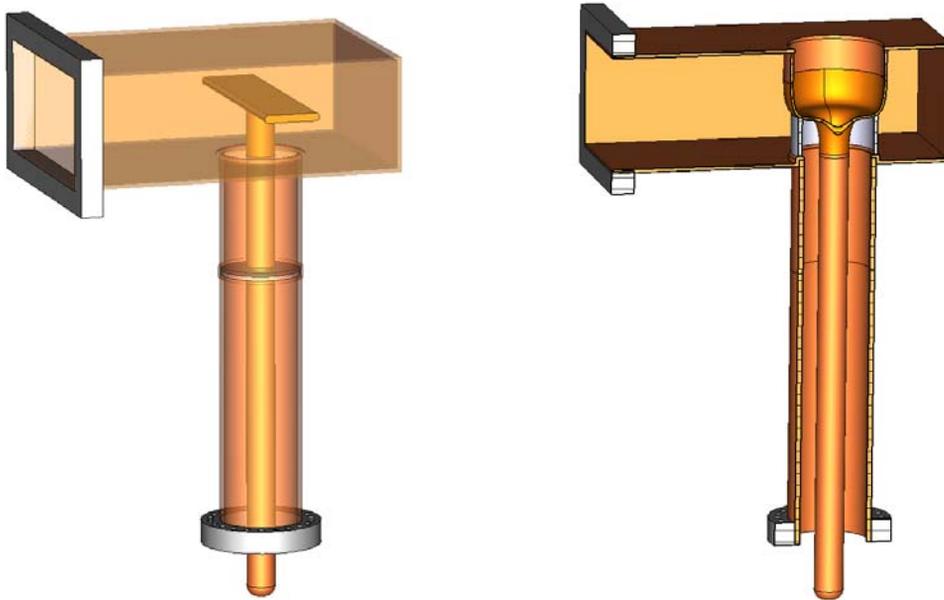
Figure 1. Drawings of some generic coaxial coupler geometries. On the left is a planar coax window with a T-bar transition to rectangular waveguide. On the right is a doorknob transition coupled to a right cylindrical window.
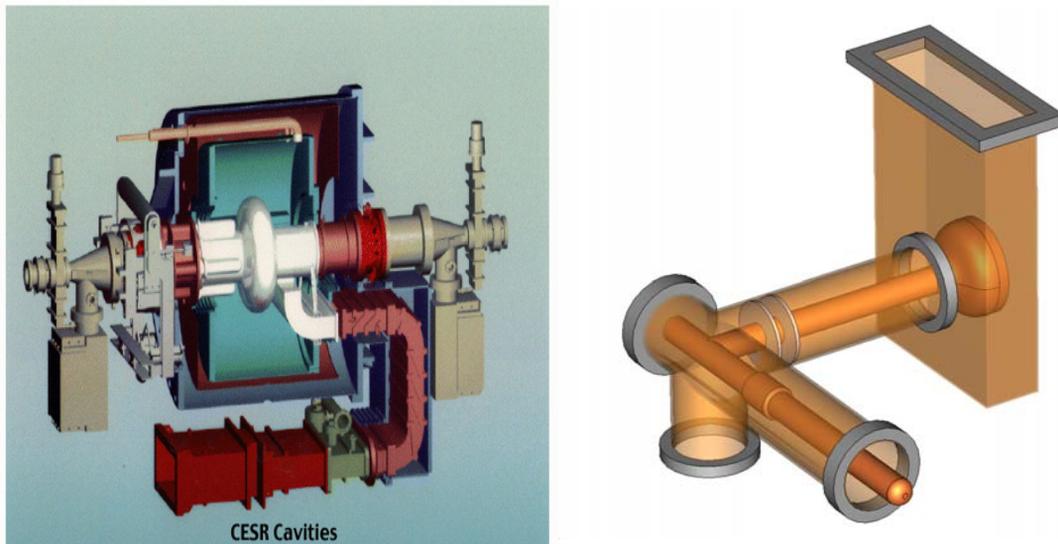
Figure 2. On the left is a drawing of a 500 MHz waveguide coupler with a warm window used on the CESR storage ring. This cavity also uses a fluted beam tube as an HOM coupler to deliver higher order power to lossy ferrite loads. On the right is a drawing of a coaxial dual planar window on a quarter wave stub. Using dual windows provides added mechanical stability, and the stub provides additional rigidity, high vacuum conductance, and some HOM filtering.
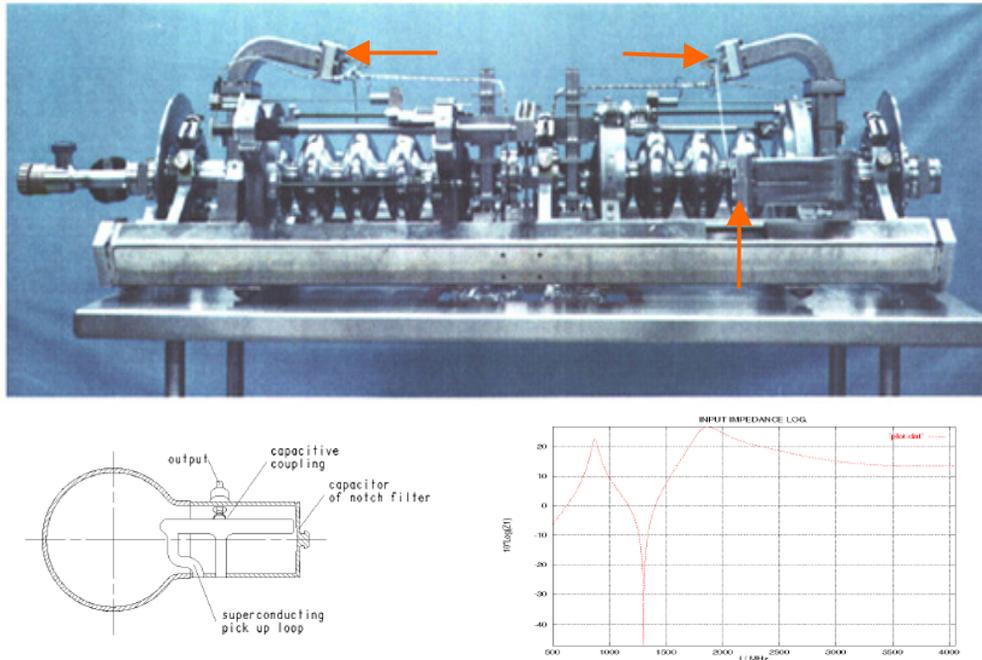
Figure 3. On the top is a photo of a JLab SRF cavity. The HOM coupler loads are highlighted with arrows. Specially shaped dissipating ferrites are mounted on flanges on the end of the waveguides. Both FPC and HOM couplers on these cavities are iris-coupled waveguides. The bottom shows a sketch of a coaxial-like transmission-type HOM coupler for TESLA.

The major difference between an HOM and a fundamental power coupler is the FPC needs to efficiently transmit RF power at the fundamental accelerator frequency f_0, where an HOM coupler needs to efficiently transmit *only* frequencies higher than f_0. An HOM coupler that extracts fundamental power out of a cavity is a serious problem.

Coupler Experience Base

As laboratories world wide have turned to superconducting accelerators for a variety of nuclear and high energy particle physics endeavors, each has had the opportunity to develop a power coupler suitable to their accelerator design and frequency choice. This has resulted in a wide range of designs that have been developed, tested, and evaluated over time which provides a good knowledge base.

Pioneering work at KEK, CERN, and DESY prior to 1995 on high power couplers for TRISTAN, LEPII, and HERA helped establish a basic understanding of the design issues and performance limitation mechanisms in high power applications at 50-150 kW [3][4][5]. Since then, design efforts for the KEK-B Factory at KEK[6], the CESR upgrade at Cornell[7], the LHC at CERN[8], the APT project at LANL[9], and the TESLA Test Facility at DESY[10] have advanced the technology of superconducting RF couplers to power levels exceeding 500 – 1000 kW. As all these efforts have spanned

varying breadths of the parameter space, it is valuable for the new designer to understand the breadth of these experiences.

This collective experience base has highlighted a number of areas that span most coupler applications and helps characterize coupler performance limitations and failure modes. In general, a coupler is considered failed when it no longer performs the functions it was intended to do. This can be separated into two broad categories:

Barrier Faults – The coupler allows ambient air or gas into a cavity, resulting in gas and particulate contamination in the SRF cavity in the cryomodule. These faults are cover:
- window rupture
- window cracking
- window puncture
- brazement leaks
- bellow leaks
- compliant feature or vacuum seal leaks

Transmissive Faults – The coupler maintains the vacuum barrier, but doesn't transmit RF power as designed. Faults of this type cover:
- multipacting barriers leading to heating or arcing
- condensed gas leading to multipacting or arcing over time
- passband shift due to thermal contraction or expansion
- Q_x (external Q) change off match condition due to temperature changes

As these are couplers used in SRF applications, the consequences of a potential failure are very high. A catastrophic barrier fault will result in the loss of at least one cavity due to condensed gas and particulate contamination, and perhaps an entire cryomodule or more worth of cavities. While the probability of this occurring is decreasing due to advances in operational interlocks, diagnostics, and experience, the severity of the outcome still makes it a concern. Minor barrier faults due to pinhole leakage are more manageable, but can still erode performance over time. Transmissive faults won't generally contaminate and compromise a cryomodule, but they can render a cryomodule sub- or inoperable. To restore operation in either case, the cryomodule will usually need to be removed from the linac and warmed up.   At a minimum for a transmissive-fault, the coupler will need to be removed and replaced with a new unit while maintaining clean conditions in the cavity, if possible. In the case of a contaminated module due to a barrier fault, the entire module would need to be reprocessed.

The cost of recovering the effects a failed coupler are significant. If a cryomodule needs to be refurbished, hundreds of hours of work are needed, as well as hundreds of thousands of dollars of for personnel, parts, and lost beam time. If additional effort is needed to study the failure and implement modifications, the cost impact of a substandard coupler design can approach millions of dollars for a large machine. For an accelerator with hundreds of couplers, having even a small fraction fail can be highly problematic.

These failure modes can usually be traced to four categories of underlying causes:

Manufacturing Errors – Something goes awry in the manufacturing which results in:
   - leaking or sloppy brazes
   - sharp edges
   - using improper materials
   - variations in plating procedures leading to poor adhesion
   - variations in brazing procedures leading to inconsistencies
   - improper surface preparation affecting coating adhesion

Materials Mishaps – Something is wrong with the materials and feedstock used in manufacturing which leads to:
   - higher losses from variations in ceramic properties
   - leaks from improperly manufactured and assembled components
   - improper chemical makeup of plating solutions
   - variations in critical mechanical properties like yield strength and loss tangent

Design Errors – Some aspect of the design was improperly done or didn't account for the entire effective operational envelop, resulting in:
   - excessive cryogenic load
   - excessive heating and material failure from inadequate cooling
   - leaking seals
   - arcing from excessive voltage
   - insufficient vacuum pumping

System Integration Effects – Performance is compromised by a combination of effects that result from the overall system configuration, and can lead to:
   - electron impingement due to field emission from a cavity
   - metallization of a ceramic due to sputtering from a cavity
   - electronic effects stimulated by beam-induced radiation

The extent of these underlying causes stems from the highly constrained and interdisciplinary nature of SRF power couplers. Understanding and appreciating the failure modes and their underlying causes early on allows for developing a design process that can address the challenges.

Design Environment

The design environment for a power coupler spans a number of disciplines, which are grouped into the areas of physics and RF, engineering, and system impact.

Physics and RF
The physics design process involves understanding the interactions and establishing the interfaces between the coupler, the RF accelerator, and beam dynamics design. As this activity happens at the earliest stages of a project, it is important to recognize that the coupler is a key component in the overall accelerator system and it needs strong advocacy

at the design table early on. The constraints endured by the coupler present enough of a challenge without the added complexity that comes from accommodating unnecessary compromises.

As the design process begins, a churning of ideas, concepts, constraints, and knowledge occurs to produce a basic design concept. Some of the aspects that need to be considered for designing a reliable, high power coupler include:

- Thoroughly determining the desired operating power range for maintaining RF fields in the cavity. This should include control system margin and estimations of mismatch due to external Q variations and cavity tune. Determining the normal and off-normal operating conditions for the coupler is also important, as these are often the conditions that maximally stress the coupler design.

- RF window type. This is the choice of window geometry, and includes coaxial planar, right cylinder, or planar concepts. Choosing a window type is based on a combination of what the operating power range for the coupler will be, and what the experience base locally and in the community has been at operating similar windows at similar conditions.
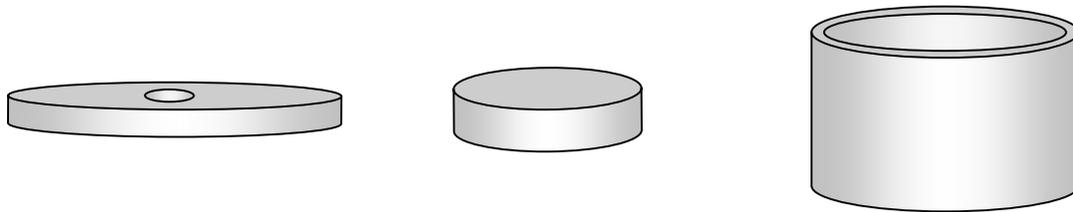

Figure 4. Graphical representations of three of the most common window geometries used today, showing from the left: coaxial planar, planar, and right cylinder windows.

- RF window temperature. The next choice involves weighing the operating conditions against the cleanliness requirements needed for the SRF cavity. Traditionally, concern about contamination in very high gradient cavities has encouraged designers to place windows close to the cavity in hopes of decreasing the risk of contamination. While this rationale is sound, having a cold window necessitates having vacuum on both sides of the ceramic surface which introduces a number of problems mainly related to cooling the ceramic. More recently, as clean room techniques have improved and experience has shown that large subsystems can be assembled cleanly, this strategy of opting for a cold window is becoming less desirable due to the limitations it imposes on coupler performance. Today, the emphasis is shifting toward utilizing warm windows and adapting the cryomodule design and clean room infrastructure to accommodate the impact.

- RF coupler type. This is the choice of waveguide or coaxial delivery approach, and is driven by a combination of operating power level, a survey of what coupler types

have worked best so far in a similar frequency and power regime, and if one has a personal preference or experience with a given type. A summary of some of the design considerations that go into making this choice is published elsewhere in this proceedings [11]. The choice of coupler is also constrained to some extent by the choice of window, and while it is possible to conceive of configurations that could use any window type, some are more amenable to coaxial or waveguide systems.

- Frequency and diameter considerations. Once the preferred window and coupler approach have been identified, some effort should be applied to system tradeoff studies regarding frequency and couplers diameter. While this is fairly constrained for waveguide couplers due to cutoff, coaxial couplers offer a broader design range. For coaxial couplers, one can vary the diameter and the impedance of the coax to accommodate cavity geometry, vacuum conductance, thermal loads and heating, mechanical stiffness, and multipacting. In general for coaxial couplers, larger coaxial diameter lines are better for avoiding multipacting, for being stiffer, and for better vacuum conductance, but may allow higher thermal radiation heat leak into the cryostat as well as interface problems on the beam tube. One should also not increase the diameter to such an extent that the line can support azimuthal overmoding.

- Multipacting conditions. Evacuated structures containing RF fields are prone to multipacting, a resonant coupling between the fields and emitted electrons where the electrons are accelerated by the RF fields and follow closed orbital paths that result in the buildup of substantial currents over multiple RF cycles due to secondary electron emission [12]. These currents can be very problematic and can lead to excessive heating, punctures, arcing, window charging, and outgassing. In general, the lower the order of the multipacting resonance, the more problematic since it is spatially broader and more stable. Overall, it is highly desirable to avoid lower-order multipacting (less than 6th or 7th cycle) for the entire operating range, and to avoid any multipacting resonances that coincide with operating power level of the coupler. To evaluate a design for multipacting susceptibility, scaling the multipacting behavior of a known design to a new one regarding the power levels of the multipacting thresholds can be done using the following relations for frequency (f), coax diameter (D), and impedance (Z) [13]:

   - Two point multipacting: power thresholds scale as $\sim f^4$, $\sim D^4$, $\sim Z^2$
   - One point multipacting: power thresholds scale as $\sim f^4$, $\sim D^4$, $\sim Z^1$.

- Adequacy of external Q. It is important to ensure that the chosen coupler type will be able to sufficiently couple to cavity fields to allow transferring power to sustain the stored energy for accelerating beam. For beam tube couplers, the fields need to couple through a beam pipe that is below cutoff, so spacing and beam pipe diameter need to be sufficient so the antenna does not have to penetrate (too far) into the beamline, where it may become activated by beam halo. Waveguide couplers, depending on how they are configured, have other challenges related to localized iris heating, or manufacturing complexity to achieve sufficient field intensity.

- Accommodating HOM power. A given power coupler on an accelerator is prone to higher order mode RF power from two sources. The first is from fields excited by the accelerated beam in the cavity. Depending on the mode and its orientation, sufficient power may couple out the FPC resulting in higher field stresses and heating. The second source is from transmission line transitions. When a high power transmission line has a bend, a waveguide-to-coaxial transition, or some other discontinuity, localized higher order modes can be excited by the geometry change which can propagate as much of a wavelength in distance downstream. This has been known to cause asymmetric heating on RF windows that can lead to failure.

- Finally, it is necessary to ensure that the evolving design will not adversely affect the performance of the superconducting cavity by introducing contamination. This is usually addressed by having the cryomodule design allow for clean room assembly of the couplers to the cavity no matter the scale, and thinking about cleaning and conditioning methods for the coupler and window early in the design process.

The design environment for HOM couplers generally has to meet the same basic requirements as power couplers. The primary distinction between an HOM and fundamental power coupler is their operating frequency. Where a FPC needs to transmit RF power at the main accelerator frequency (f_0), the HOM needs to *not* transmit power at f_0, but needs to broadband couple to frequencies higher. This passband characteristic of HOM couplers dominates the design characteristics of these devices. Another differences has to do with the amount of power that the HOM needs to convey. Depending on the current and energy of the particle beam, HOM power levels may be modest or very high. For HOM couplers that dissipate power locally, the heat produced by the lossy material needs to be removed either by the cavity cryogen or another coolant stream.

Engineering

Once the overall physics design has been established, extensive engineering evaluation should be used to develop the design into a working prototype. Engineering covers five basic areas:

- RF engineering. RF engineering involves iterating the design to achieve the desired operating characteristics. For broadband couplers, the design needs to be well matched to prevent the unnecessary buildup of standing waves and transition HOM modes. For coupler approaches that have narrow ($< 0.5\%$) passband characteristics, it is also necessary to generate a design that maintains good transmission over possible variations in temperature and assembly tolerance.

- Ohmic thermal management. High power couplers need to control heating due to Ohmic dissipation of RF currents in the walls of the coupler to a depth of a few RF skindepths. Ohmic heating in coaxial couplers is shared between the inner and outer conductor, and depending on the chosen impedance, the ratio between losses on the inner to the outer conductors can vary substantially. It is important to adequately deal with RF heating by applying sufficient cooling. A window or coupler that is allowed to change temperature dramatically will be prone to high stresses due to thermal

expansion and contraction that can compromise performance. Cooling should also be designed to take the largest possible anticipated thermal load due to operating the window and coupler in a full standing wave condition swept through 180 degrees. This requirement may need to be relaxed if the chosen cooling systems becomes a cost driver due to a large number of couplers. It is generally preferred that the coupler be designed to handle the worst cast scenario, thereby allowing it to gracefully handle normal operating conditions reliably. Depending on the temperature of the windows, coolants that have been evaluated and used on couplers have spanned air, gaseous helium, water, and liquid nitrogen.

- Cryogenic thermal management. Cryogenic thermal management refers to minimizing the coupler's contribution to the overall thermal heat load of the cryostat. Since heat and electricity are both conducted the same way in metals, a compromise is needed in establishing the right balance of achieving good electrical conductivity and low thermal conductivity. This is generally done by taking advantage of the skin depth effect to judiciously use thin high conductivity coatings (copper) on thicker, lower conductivity metals (stainless steel). A system tradeoff is needed to determine the a thickness that takes into account RF losses, cryogenic heat leak due to conduction, duty factor, and static and dynamic heat loads in the cryostat. Analysis is also needed to determine the proper location, size, temperature, and coolant stream characteristics of the thermal intercepts on the coupler. In addition, for very high average power couplers, one needs to analyze the thermal behavior around the niobium superconducting cavity coupler port, since it may be possible to achieve operational modes that support a stable localized quench region in the coupler port area that would increase cryogenic loads substantially.

- Coatings. There are two types of coatings typically used on RF couplers and windows. Titanium-based coatings (titanium nitride, thin titanium metal films) have been used to suppress multipacting in window/coupler assemblies. The difficulty in making, then measuring the applied films has contributed to a certain level of inconclusiveness regarding their effectiveness. Some labs have seen dramatic improvements in coupler and window performance with anti-multipacting coatings, where others have seen little benefit for the added complexity. Another difficulty is that titanium dioxide, which readily forms when titanium metal is exposed to oxygen, does little to suppress multipacting.

The other coating used is copper plating in the thermal break region. As the goal is to achieve a film of an optimum and uniform thickness to minimize both RF heating and cryogenic heat leak, being able to consistently apply then measure the film thickness on actual coupler parts is a challenge due to the geometry. In addition, the entire process of wet chemistry plating is prone to variability due to complexities associated with assaying and controlling large volumes of chemical mixtures in a manufacturing environment. Finally, ensuring there is a solid bond between the film and substrate is extremely important for couplers for SRF applications, since the bond not only thermally stabilizes the film, it prevents particulates from being generated from film particles sloughing off the surface and making their way to the cavity. Successful

films have also been accomplished using sputtering techniques, but this approach can be expensive to implement if in house or local capability is not available.

- Mechanical design. Mechanical design covers the process of bringing all the pieces of a window and coupler assembly together into a working unit. It is important that the design have a high vacuum conductance and pumping speed for the window; that the coupler is cleanable, is clean assembled, and is clean mounted on a (clean) cavity; that there is proper tolerancing on the parts to allow easy assembly; that stress analyses have been done for thermal expansion and contraction and adequate compliance has been designed in; that all brazing is done to minimize blushing onto the ceramic; and that all joining techniques are not only reliable, but leave good surfaces that can be plated and don't promote breakdown. Special care needs to be exercises when joining assemblies that have plating on one side to guarantee the plating quality is not compromised by the joining process.

System Impact

To realize a reliable, high-performance coupler, other accelerator subsystems need to accommodate the extensive constraints space occupied by the RF coupler. Areas that are affected include the cryomodule design, the RF amplifier and delivery system, the SRF cavity design, and the accelerator vacuum pumping system. Operationally, couplers also impact the interlock and control system on the overall machine, as well as the overall operability of the facility. As part of the coupler design process, one needs to understand and adequately address the impacts the power coupler has on the overall system. Issues related to consequences of coupler failure and/or degradation should also be evaluated.

Design Process

Designing a reliable high power coupler within this constrained and highly complex design environment requires contributions from many disciplines. Forming an interdisciplinary design team from the start is an ideal way to cover all the physics, engineering, SRF , cryogenic, mechanical, cryomodule, materials and manufacturing, and system engineering aspects that go into making a good coupler. However, since any given design needs to evolve over time, it is often the case that certain lead activity areas like physics, SRF, and RF engineering tend to dominate the design process to the detriment of the other areas. This unbalancing of emphases can open vulnerabilities in a coupler design that can ultimately lead to performance and reliability problems. While having such a multidisciplinary team is important, it is not always possible to mount such an effort on the desired time scales and budgets of a project. To partially offset this, it is crucial that sensitivity for the issues be combined with extensive modeling, prototyping, and testing in any development plan for fundamental power and HOM couplers. It is also important to realize and to communicate to customers and sponsors that coupler development is often more of an evolutionary, than an immaculate, process.

Tools
Ample design tools and techniques are available to aid in the coupler design process. One of the more important techniques that has been successfully used is to scale designs that have proven to be successful in other applications to the power level and frequency needed for a new application. This is useful for establishing and scoping a new design, and is attractive due to the soundness of its rationale and subsequent defensibility. Scaling also has its limitations if large extrapolations are needed in terms of voltage, average power, or beam power, or if a new coupler or window design architecture is being explored. An additional downside is it tends to impede exploration into alternative concepts when they may be better suited to the application at hand.

Software modeling tools have advanced significantly in recent years, and capability now exists to evaluate with models many aspects of couplers that have historically led to failure. Commercial RF modeling codes (e.g., Microwave Studio, MAFIA, HFSS) can now do full 3D simulations to relatively high accuracy to predict and optimize RF transmission, voltage, current, and power densities in a design. This information can be exported into sophisticated commercial mechanical analysis codes (e.g., ANSYS, COSMOS) to calculate motion, stress, and heating. Mechanical codes can also be used to evaluate thermal response, cryogenic loading, and modal response. The exact codes that are used are not as important as the fact that modeling is done and that the codes that are used be adequately benchmarked to ensure proper physics fidelity. Developmental-type codes are also available in the community to simulate multipacting [13][14], but the complex nature of the multipacting phenomena and its high dependence on surface preparation and material properties makes the results of these studies more open to interpretation than other modeling results.

Another tool to realizing a high performance coupler is the extensive materials and process knowledge bases that exists in the SRF and normal conducting RF accelerator community. The efforts of literally hundreds of researchers on as many coupler and window designs has created a wealth of technical knowledge about copper plating and adhesion, ceramic behavior, brazing, fabrication, anti-multipacting coatings, vacuum bakeout, cleaning and clean assembly, and conditioning methods. While modeling is essential, tapping into the community experience base is needed to help offset the more semi-empirical aspects that impact power coupler performance which are not addressed by modeling.

Philosophies
To this point, this paper has focused on the challenges associated with designing a reliable, high power coupler and what tools are available. Now, the emphasis will shift toward trying to distill some philosophies and approaches for realizing a successful design. Information from many individuals and laboratories who have achieved an appreciable increase in coupler performance in the past seven years has been coalesced to a generalized set of "principles and guidelines" to assist other researchers in the field.

The experience-based design philosophies for achieving higher performance in power couplers can be summarized into four general strategies:

- Protect the window. As the window is the critical component for separating gas from the cavity vacuum, it needs to be accommodated to a high degree in the design. To realize this, a number of aspects need to be addressed. The window ceramic should not be allowed to be in tension or shear over its anticipated temperature range. There should be minimal RF fields due to higher order modes on the window to avoid anisotropic heating. The window should be designed with ample compliant features to allow for thermal expansion and contraction. Longitudinal and rotational forces on the window should be avoided, especially in cases where the window is an assembly that mates to a coupler. Windows should not be in too close a proximity to the cavity, to avoid electrons emitted from the cavity during operation that can lead to window charging. Braze regions on the window should be shielded to decrease the impact of braze "blushing" onto the ceramic. Ceramic feedstock control and pedigree should be closely tracked. Try not to place a standing wave maximum on top of the window during operating conditions. Be careful in using and applying antimultipacting coatings to ensure they are not too thick or uneven, which can lead to undesirable heating.

- Avoid multipacting bands. While it is impossible to avoid multipacting through the entire power range a coupler sees on an accelerator, it is necessary to avoid them around the operating power level for the coupler, especially lower-order bands. This can be done by properly choosing the coupler diameter and impedance relative to the operating power level. In cases where a band does lie close to the operating point, voltage or magnetic biasing should be applied to disrupt the multipacting resonance condition. Baking the coupler and keeping it free of dust and contamination will decrease the amount of electron activity that can feed a nearby multipacting resonance. Bellows should also be avoided in couplers or at least evaluated very carefully, since the variation in electric fields across an undulation of the bellows shape greatly expands the operating voltage range of the surface which can then support multipacting.

- Control the temperature. Extensive analysis and design work is only valuable over the temperature range the analysis was done for. If the coupler or window operates at a significantly different temperature due to inadequate cooling, mechanical response and subsequent reliability become less predictable. To control the temperature, adequate cooling is needed on the coupler that accounts for expected (Ohmic heating due to traveling waves, anticipated mismatch standing waves) and unexpected (multipacting, electron emission, glow discharge, HOMs, and unexpected mismatch) heat sources.

- Maintain excellent vacuum. In general, couplers that have better vacuum and higher pumping speeds available at the window seem to condition and to perform better than those with more modest pumping. Decreasing the gas load in the coupler has a number of benefits spanning minimizing condensed gas that can lead to reduced multipacting, improving conditioning times, and decreasing electrons due to ionization. Part of understanding the impacts of temperature is related to the buildup,

release, and migration of any condensed gas that may be present in the thermal transition region of the coupler.

Approach

First, an adequately multidisciplinary design team needs to be identified and equipped with the proper software tools to do a full design. Once this is in place, the following list provides a framework of the main task areas that need to be addressed as part of the design process. By thoroughly understanding the operational parameters, by applying adequate to comfortable design margins, and by evolving the coupler design along these guidelines of "best practices" based on community experience, a higher performance coupler design can be achieved.

- Establish a reasonable and defensible operating power level in support of the accelerator design process.
- Evaluate the design choices and compare them with designs that have succeeded before, and incorporate best practices when possible.
- Evaluate multipacting susceptibility of transmission line system over the operating range.
- Run extensive electromagnetic models to determine voltages, currents, field levels, power densities, and parametric sensitivity for manufacturing and tuning purposes.
- Apply adequate margin to the electrical power handling (voltage breakdown) of the window and coupler for the design. For most cases, *four times* the operational traveling wave power is encouraged to accommodate full standing wave operation without sparking.
- Estimate Q_x variations along the linac due to geometry differences and evaluate the system impact. Determine what level of standing wave and/or adjustability is acceptable or desirable.
- Apply adequate margin on cooling for maximum sustained thermal loading. Cooling that can handle up to *twice* the thermal power dissipation at the operating point with an acceptable temperature rise in the window and coupler is suggested as a starting point.
- Do analyses on the mechanical design regarding static and thermal/dynamic stresses as well as vibrational moding, and iterate the design to minimize stress and movement.
- Do analyses on the cryogenic impact of the design from both a static and dynamic loading standpoint. Choose an intercept temperature and coolant parameter state for iteration with the cryoplant design team.
- Maximize the vacuum pumping conductance to optimize pumping speed at the window and plated areas.
- Determine and qualify processes for plating solutions, coatings, ceramics, and other materials.
- Ensure the design can accommodate vacuum bakeout of the entire assembly, and preferably of the coupler and window on the cryomodule.

The development of the APT power coupler at LANL used many of the tools, philosophies, and approaches presented to address many of the constraints cataloged in

the beginning of the paper. The design that evolved was one example of how the information presented could be combined to achieve a high performance, high power coupler. A graphic image of the coupler is shown in Figure 5.

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

700 MHz coaxial coupler:
- **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

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
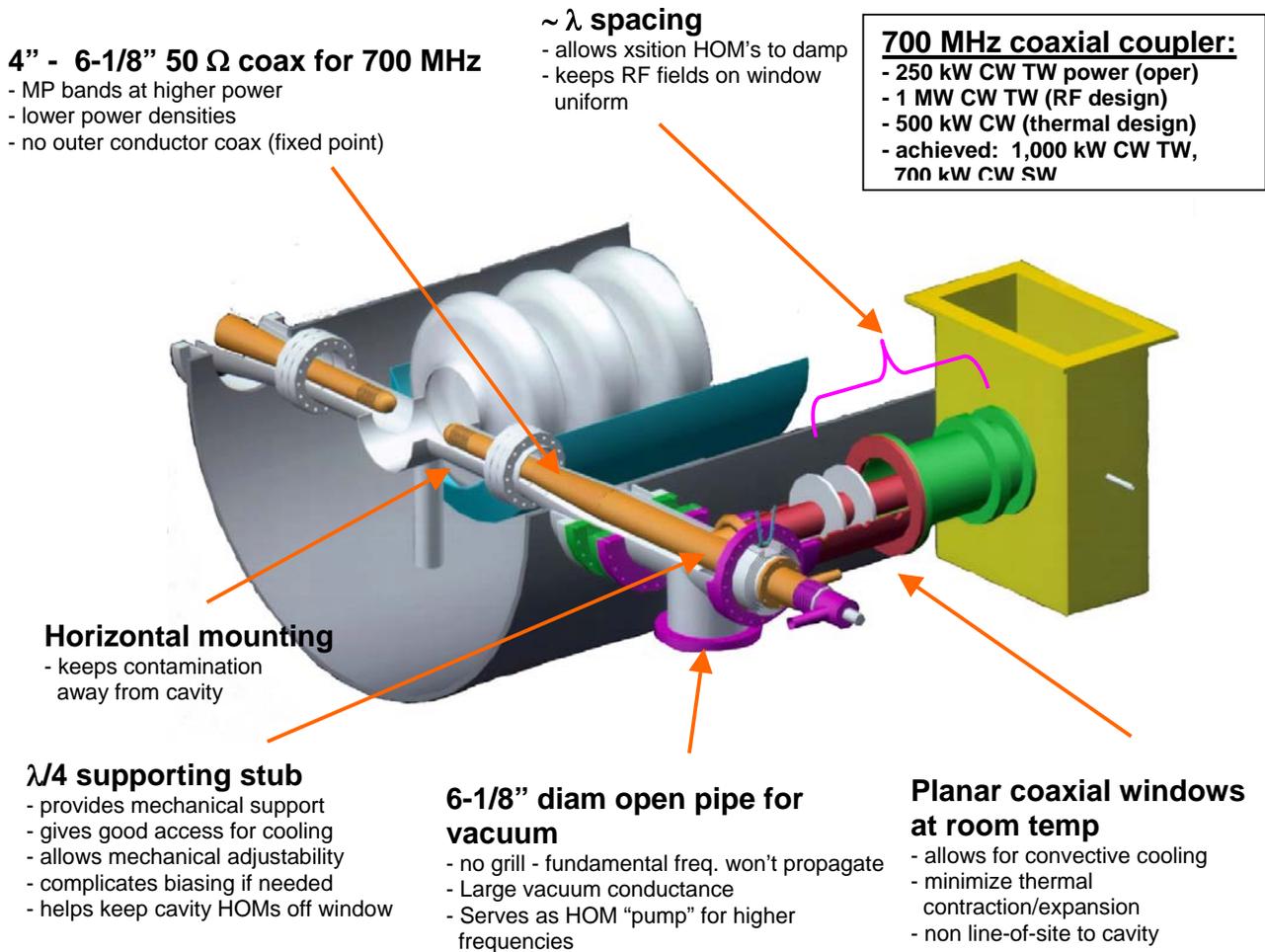- non line-of-site to cavity

Figure 5. Graphic showing the APT power coupler concept that incorporated many of the design approaches and philosophies considered to be important for realizing a high-performance coupler. In testing, this coupler achieved 1,000 kW CW operation at 700 MHz for traveling wave operation, and 700 kW CW operation for a full standing wave.

Evaluation Process

Testing

Room temperature testing and conditioning are essential for realizing a properly functioning high power coupler. Testing is necessary to evaluate and validate the design and conditioning is necessary to outgas the coupler components and "condition" the RF surface to make it more robust against breakdown and electron emission. Figure 6. shows two types of conditioning benches.
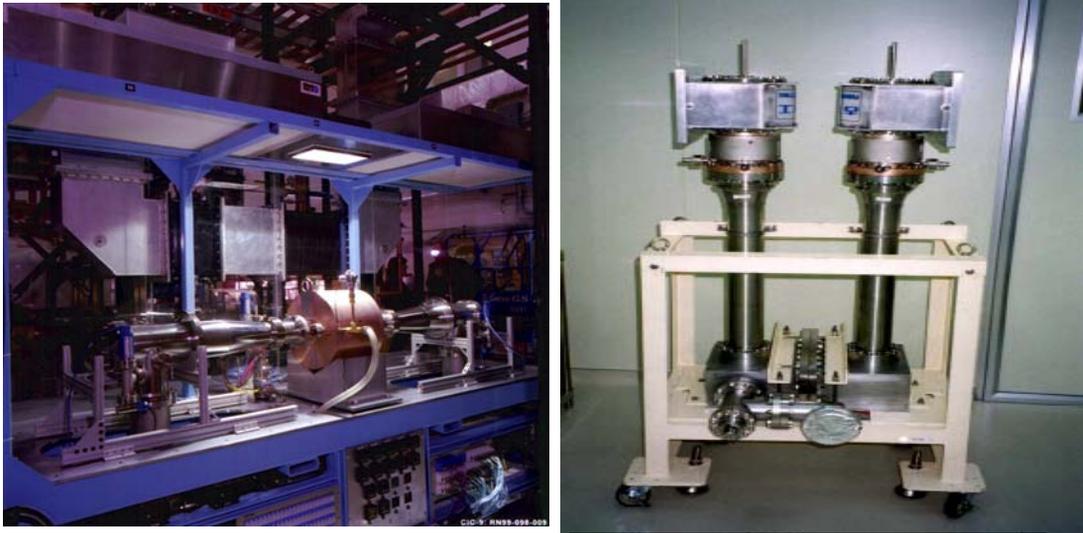
Figure 6. Photos showing examples of two RF coupler test/conditioning stands. On the left is the LANL/APT testing and production conditioning stand, on the right is the JLab/SNS test stand.

Performance Improvement

Window and power coupler designs in the past decade that have implemented various aspects of the guidelines outlined in this tutorial have demonstrated an increased level of performance, as shown in Figure 7. As the RF power needs in the SRF community have risen to accommodate higher gradients along with higher current beams, coupler technology has advanced as well to meet the requirements.

Figure 7. Plot showing how the application of techniques including ample engineering margin, voltage biasing, high vacuum pumping rates, bakeout, and process control on coatings has helped increase the average power handling of SRF couplers built in the past decade.

Basis Ingredients

While RF coupler work is still a developing area, it is possible to assemble a list of "basic ingredients" that, when properly combined, should result in improved performance of a prototype coupler. Performance here is defined as being able to handle very high peak and average power, as in a CW application, with high reliability. As such, the offered list is suited to this approach. Other interpretations of performance would likely produce a somewhat different selection. This list is also not intended to be absolute as much as to illuminate one path forward. Other paths certainly exist, and can very likely also lead to a successful design. While the list basically holds for HOM couplers as well, they tend to be more application specific, and a similarly detailed recipe for them is not as readily developed.

1. Use room-temperature windows instead of cold windows.
2. The order of preferences for window geometry for transmitting very high power is planar coax, right cylinder, then planar disk. If planar coaxial windows are used, use two windows closely spaced with air in between. This helps mechanically stabilize the windows and does provide a little higher level of (at least perceived) protection.
3. Use coaxial transmission lines over waveguides, unless there is a solid technical benefit for using guides.
4. Use as large a coaxial line as possible without circumferentially overmoding the guide.
5. Maintain a minimum of one wavelength spacing between transitions and the window.
6. Clean all coupler parts thoroughly using ultrasonic baths and high pressure water rinsing.
7. Ensure the design allows vacuum baking of assemblies to outgas windows and coatings as well as to improve adhesion of plating.
8. Avoid bellows whenever possible on the outer wall of the coupler, and carefully evaluate and weigh the need if they are to be used on an inner conductor.
9. Apply generous design margins (2x for thermal, 4x for power/voltage).
10. Use a large open port for vacuum pumping to improve pump speeds and HOM damping, and use modeling to manage the power dissipation in the port.
11. Keep the design open to either voltage biasing or magnetic suppression techniques to handle potential multipacting problems if low lying resonances are nearby.
12. If the application permits, employ a quarter wave stub to facilitate mechanical stability, adjustability, and RF isolation.

Conclusions

Fundamental power and HOM couplers are critical components on major accelerator projects. Their lack of performance and/or failure impacts the entire facility, the science user group, and the SRF community. Past performance difficulties have arisen partially because of the highly interdisciplinary nature of the power coupler in SRF applications. The extent that a coupler spans physics, engineering, cryogenics, SRF technology, materials, and system engineering makes them challenging, yet rewarding, development efforts. Interdisciplinary teams using a combination of modern tools, a thorough awareness of the issues at hand, and the experience base of the community, stand a very good chance of realizing a successful coupler development effort. By balancing the many disparate disciplines that tend to meet at the coupler in an SRF application, the evolving design stands a much better chance of proving to be reliable. And, while it may be tempting to explore cost savings strategies in this critical area, they should only occur after a proven design has been realized and thoroughly evaluated.

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