RF Coupler Working Group Report*

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Introduction

As part of the program for the 11th Workshop on RF Superconductivity, four working groups were organized to facilitate an exchange of information on topics of interest to the community. The working group on RF Couplers met for two hours and discussed topics primarily related RF power couplers, as well as slow and fast tuners and HOM couplers, on superconducting cavities. Approximately 80 people attended and contributed to the session.

During the discussions, varying degrees of consensus occurred depending on the topics being discussed. Where possible, a sense of the level of consensus will be conveyed to provide additional insight into the topic.

RF Power Couplers

For the discussion, RF power couplers were taken to be the RF assembly that conveys RF energy from room temperature to the cryogenic environment of the SRF cavity. These devices also seal the cavity under ultra-clean conditions, need to be reliable, need to have low insertion losses, and should have a modest impact on the cryogenic load of the cryomodule. The highly multidisciplinary nature of these devices makes them a design and development challenge for the SRF community. The issues that were discussed spanned conditioning and bakeout, warm vs. cold windows, single vs. dual windows, waveguide vs. coaxial couplers, adjustability, cleaning recipes, vacuum, coatings, and DC biasing.

Conditioning and Bakeout

High power RF conditioning of a coupler is important to ensure reliable operation on an SRF cavity. Conditioning not only “conditions” the electrical surface by reducing localized areas of field enhancement that can lead to arcing and multipacting, it also heats the window and metal surfaces thereby improving gas desorption. The range in experiences related to coupler conditioning was broad. Many newer coaxial coupler designs managed to condition to well above their operating points of several hundred kilowatts of power in 10-12 hours, where some older couplers could take days or longer. This range is attributed to a combination of pumping efficiency and gas load. In couplers with conductance-limited pumping combined with large gas loads, long times are needed to recover vacuum after a conditioning event. In couplers that have high conductance and have been baked, conditioning times drop dramatically.

Vacuum bakeout of a coupler assembly is generally seen as a necessary step to achieving a reliable coupler. The presence of copper plated surfaces and ceramic materials makes

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the potential gas load of a coupler very high. Baking helps to rapidly degas these parts to allow faster conditioning times, and, depending on the temperature of the bake, may improve the adhesion of the copper plating. It also leads to more reliable operation on line as the coupler is less likely to evolve gases that can condense on the cold outer wall of the coupler and lead to breakdowns and multipacting. While there were variations, it was generally reported that a bakeout above 155 ^{o}C was needed to release water. Some labs baked windows to 200 ^{o}C and platings to 400 ^{o}C. After bakeout and conditioning, different labs reported various degrees of deconditioning that occurred if the coupler was let up to air. Some saw substantial loss of conditioning effect that needed to be recovered, while others saw virtually none. There was speculation this may have been due to humidity in the air.

With the recent increases in cavity gradients that have come in recent years, in-situ bakeout and processing is looking more attractive. By designing a coupler with adequate pumping and power handling to allow in-situ conditioning, flexibility is gained in cryomodule assembly and conditioning. In-situ baking in a cryomodule would not only improve production efficiency, it could provide more options for cryomodule tune ups to get rid of condensed gas buildup over time.

Warm vs. Cold Windows

The debate between warm and cold windows has historically been centered around hermetically sealing the ultraclean environment of the SRF cavity. Placing a window near the cavity allows for a smaller cavity assembly to be handled and sealed in the clean room, but being near the cavity means the window is necessarily cold. This requires the window have vacuum on both sides, which not only opens the window to multipacting and arcing problems on both sides, it also necessitates the window be cooled only by radial conduction. While this was workable for lower power windows, today's higher power levels make this approach less attractive.

Having a warm window means the window can be convection cooled on one side by air. This not only provides much better cooling of the window, it also reduces the potential electronic heat load on it. The downside to warm windows is they necessarily are further away from the cavity cold mass, in order to keep both conductive and radiative heat leaks into the 2 or 4 K liquid helium bath low. This means the cavity/coupler assembly that needs to be cleanly assembled gets larger, and the cryomodule design gets more complicated.

The general consensus of the working group for this area is that it appears the need for cold windows is fading. As people gain experience achieving very high gradients in long cavity strings and in larger, lower frequency cavities, the notion of dealing with a warm-window coupler is less onerous. Provided the cryomodule design accommodates a warm-window coupler up front, using a warm window is the preferred approach for accommodating high power handling, high reliability, and ultraclean conditions.

Single vs. Dual Windows

There are two distinct reasons regarding the need to dual windows. In the case where a cold window is used, a second window is needed to provide a vacuum-to-air break in the warm part of the coupler to preserve vacuum on both sides of the cold window. The other situation is when a second window is used to “back up” a primary warm window in case the air/vacuum window catastrophically breaks. In this case, there is usually air or gas between the two windows. As the second window is essential if a cold window is employed, the discussion surrounded the need for a second window backing up a warm window.

The high power coupler for TRISTAN at KEK used a Teflon® disk to help impede gas flow toward the cold cavity in the event of a window rupture. The APT coupler design at LANL employed a dual window to provide a contained volume of gas in the event the air/vacuum window broke. By having a contained volume, calculations indicated that this approach could contain contamination due to a window break to one or two cavities, instead of disabling an entire cryostat. Another benefit of dual windows is it helps stabilize a planar coaxial window to torques during handling and assembly which could result in microcracking and premature failure. The main downsides are it makes the window assembly more complicated and expensive.

Discussion focused on whether a second window is needed at all. In at least the last 15 years, the community has not seen a warm window catastrophically fail where an inrush of air was let into a cold cavity. Advances in operating experience, instrumentation, and interlocks have allowed detection and neutralization of a potentially problematic window well before it is stressed to failure. Alternatively, as gradients are going higher and the effects of contamination become more acute, the prospect of losing one or two cryomodules worth of cavities due to a fast-leaking window is a serious concern, and if a 10-20% cost increase buys somewhat higher reliability by being able to contain and localize the effects of a break, perhaps it is worth it. On the other hand, higher part counts and systems to close off the air volume add complexity which can decrease reliability.

Overall, there was not a strong consensus on the question. While everyone agreed that reliable couplers and windows are important, it was not clear that the added cost and complexity warranted a dual warm window approach. Perhaps the assurance one gets by having a dual warm window may alternatively be accessible by better diagnostics and protection algorithms.

Waveguide vs. Coaxial Couplers

The RF accelerator community has extensive experience with coupling RF power into resonant cavities. Whether a given accelerator, be it normal conducting or super-conducting, chooses a waveguide or coaxial coupler depends on a large number of factors. Operating frequency, power level, previous experience, commercial availability, RF structure design, operating temperature and heat leak, vacuum conductance, and window performance data base are a sample of some of the aspects that influence the choice.

In general, while people had their preferences, there appears to be no strong technical advantage of one approach over the other. It appears there is a preference for coaxial couplers in the overall SRF community (CERN, KEK, DESY, LANL, ANL), but there is also a significant number of waveguide designs in use as well (Cornell, JLab).

There was also some discussion on the pros and cons of each approach:

Frequency and size. Coaxial becomes attractive for lower frequencies (<500 MHz) due to the cutoff characteristics of the guide.

Power handling. Only for very high average power (>500 kW) does the coaxial window approach appear to have an advantage. On the other hand, coaxial transmission lines have higher attenuation than waveguides. For pulsed power applications, waveguide and coaxial windows have both performed well handling over 1 MW of power.

Multipacting suppression. Coaxial guides can employ DC biasing between the inner and outer conductor. Waveguides can use magnetic field coils to suppress the resonances entirely. Coaxial guides also have a greater opportunity to support one and two point multipacting, especially at lower frequencies, but waveguides are not immune from local multipacting either.

Vacuum conductance. Waveguides generally have a higher vacuum pumping conductance over a coaxial line, depending on the frequency and impedance choice.

Thermal heat leak. Coaxial couplers generally have a lower heat leak due to overall size, but this is partially offset if the antenna tip is at room temperature in the cryogenic environment. Heat leak in waveguides can be handled by good design, but larger guides can be problematic.

Adjustability. It is generally accepted that a coaxial line is more amenable to physical adjustability by moving the center conductor antenna with respect to the cavity fields. Some physical adjustability is possible with circumferential-iris coupled waveguides (used on the JLab cavities) by deforming the gap distance. Both types can be electrically adjusted using a 3 stub tuner, though the additional field stress and heating due to the standing way may become problematic at higher average power levels.

Simplicity. A waveguide coupler is generally seen as simpler, due to the lack of a center conductor and fewer piece parts. On the other hand, plating a rectangular guide and using large rectangular, ultra-high vacuum, cryogenically cycling seals can be challenging. While some labs (Cornell) have been successful using rectangular Helicoflex® seals, others have had substantial reliability and process control problems.

Conditioning. Conditioning does not appear to strongly favor one approach over the other. It appears the test stand design, vacuum conductances, and bakeout regimen all strongly influence the conditioning experience.

Adjustability

Discussion around adjustability was fairly limited. In general, people like the idea of having an adjustable coupler on their machine. The more versatile a machine needs to be (a heavy ion linac vs. the proton linac for SNS), the more important an adjustable coupler becomes. However, the added complexity, cost, and reliability impact of having an adjustable system can dampen the enthusiasm.

Cleaning Recipes

The importance of meticulously cleaning the power coupler before it is installed on a clean SRF cavity is widely accepted. Most labs use a combination of ultrasonic cleaning and deionized water rinsing with some high pressure water rinsing.

Vacuum

The general trend in developing higher power couplers is to go to lower operating vacuum in the area of the window (especially a warm window). This is accomplished through improved pumping capacity and conductances near the window. Improved pumping significantly reduces conditioning times and should result in longer operational lifetimes before condensed gases become problematic.

Coatings

Coatings are used to help suppress multipacting on the window and coupler components as well as to reduce charge buildup on the ceramic. The challenge is getting bona fide TiN is not particularly easy. Often, titanium metal or titanium dioxide are deposited instead. Discussion seemed to embrace the idea of using TiN or some form of anti-multipacting coating on windows, but it was not clear that there was overwhelming experience saying these coatings were universally needed. In some instances, the coatings made a huge difference in conditioning and power handling, in others, it made little to no difference.

DC Biasing / Magnetic Field Multipacting Suppression

Coaxial couplers that have DC biasing find it useful for conditioning and avoiding multipacting. The lower the application frequency, the more important biasing becomes as more lower order multipacting resonances are accessible. It is important that the design of the insulation approach for biasing be done well, as arcing may adversely affect performance. Using a solenoidal magnetic field has also proved effective in suppressing multipacting in waveguide couplers. It may be possible that this approach could be successfully applied to coaxial geometries as well, though it doesn’t appear this has been attempted in an application so far.

Coupler Summary

As there is such a range of experience of power couplers on SRF (and normal conducting) cavities, Table 1 was assembled to provide a sampling of the breadth of this technology.

lab		**Cornell**	**CERN**	**CERN**	**JLab**	**LANL**	**SLAC**	**DESY**	**DESY**
machine		**CESR III**	**LEPII**	**LHC**	**SNS**	**APT**	**PEPII**	**test cryo**	**TTF linac**
frequency	(MHz)	500	352	400	805	700	476	1300	1300
normal/SRF coupler		SRF	SRF	SRF	SRF	SRF	norm	SRF	SRF
number of tested cplrs			> 300	4 so far	40	4			
window type		planar disk	Cylin.	cylin.	planar coax	planar coax	planar disk	cylin.	cylin.
coupler type		fixed	fixed	fixed	fixed	variable	fixed	variable	variable
pulsed or CW		CW	CW	pulsed	pulsed	CW	CW	pulsed	pulsed
cold window	(y/n)	no	No	no	no	no	no	yes	yes
TiN coating ceramic	(y/n)	yes	Yes	yes	yes	no	yes	yes	yes
copper plating	(y/n)	yes	Yes	yes	yes	yes	yes	yes	yes
on beam/test stand		beam	beam	test	test	test	beam	test	beam
operting peak power	(kW)	360	125	120	550	420	500	650	250
operating ave power	(kW)	360	125	120		420		8.45	1.6
operating pulse width	(msec)			50	1.3			1.3	1.3
operating rep rate	(Hz)				60			10	5
operating duty factor	(%)	100	100	10		100	100		
condit pwr -travelling	(kW)	450	600	180	1000	1000	600	1000/500	350
condit pwr -standing	(kW)	125	500		600	850			
travelling wave equiv	(kW)				2400	3400			
condit pulse width	(msec)	1		50	1.3			0.5/1.3	1.3
condit rep rate	(Hz)	10/100			60			10	5
condit duty factor	(%)			10		100	100		
condit time (test stand)	(hrs)	60	72-100	100-150	35-40	16-24	8	80	
condit time (on cavity)	(hrs)						50	40-60	120/cplr
max condit. vac	(mbar)	1.E-07	5.E-07	5.E-07	5.E-07	1.E-06	1.E-07	1.E-06	1.E-06
baking temp	(C)	130-160	200	none	200	150	155	150	none
ramp up time	(hrs)	24	18		18	24	24	24	
hold time window	(hrs)	240-330	24		24	48	72	24	
hold time parts	(hrs)	72-125				24	120 cav		
ramp down time	(hrs)	24	18		18		24	24	
DC biasing	(y/n)	no	yes	yes	yes	No	no	yes	yes
mag field sup.	(y/n)	yes	no	no	no	No	no	no	no
cleaning recipe									
degreasing			yes						
ultrasonic bath		yes	yes		yes		yes	yes	yes
DI rinse		yes			yes	yes			
high pressure rinsing			yes					yes	yes
alcohol rinse		yes	yes				yes		
dry nitrogen drying					yes				
CR drying		yes	yes						

Table 1. Sample of a variety of high power coupler parameters spanning multiple labs and applications (both NC and SRF).

Slow Tuners

The mechanical designs for slow tuners tends to vary widely across the SRF community. As the tuner is strongly constrained by the cavity geometry, the cryomodule design, and the tuning requirements of the machine, this variety is understandable. A main point that came out in the discussion was that the tuners should be tunnel-serviceable as much as possible. Losing operability of a cryomodule due to a stuck tuner is not good. Having to vent warm a cryomodule to repair a tuner is also not as desirable as being able to fix a unit while the cryomodule remains cold. While there was consensus that this was a good idea in general, most recognized that accomplishing it would greatly complicate the cryomodule design process. Another point was that flexures were superior to gears not only for reducing backlash, but also for being more reliable and reproducible.

Another discussion area was in testing and qualifying units for service. As tuners need to operate reliably, they should be thoroughly engineered and tested, not only as prototypes, but as production units. Some labs have had the experience that even with rigorous testing, problems still arose from vendors changing procedures in the middle of a production run. Testing and design rigor should be based on the anticipated number of cycles the tuner is likely to see in its lifetime. Another point that came up was in some applications where extensive tuner adjustment occurs, it may be necessary to have a program of scheduled maintenance on the tuners to keep them lubricated and running properly.

Fast Tuners

Fast tuners are usually short-stroke tuners that can actuate rapidly (up to 10’s of kHz). They are used in conjunction with slow tuners, and are usually used to fine tune a cavity and make it run more efficiently with less RF power. Fast tuners are becoming more important for SRF cavity applications that are either lightly beam loaded, or are pulsed. For lightly beam loaded machines, the beam loaded Q of the cavity is sufficiently narrow that microphonic excitations can disrupt cavity phase lock. In this case, fast tuners are used to reduce the frequency excursion of the cavity due to the excitation. In pulsed machines, fast tuners are useful for offsetting the effects of Lorentz force detuning, which helps improve efficiency. It was noted in the discussion that piezo fast tuners work much better at canceling Lorentz detuning than canceling microphonic detuning, since the action of trying to cancel one mechanical mode can lead to the excitation of multiple other modes. Work today is advancing piezoelectric tuners. Tests have shown them to be effective and reliable, provided they are properly pre loaded. One test at DESY has cycled a piezo stack for 1 year at liquid nitrogen temperatures without degradation.

Magnetostrictive tuners hold promise as an alternative, but the approach lags behind piezo technology since less engineering development has been done. Voltage-controlled reactive fast tuners have also proved to be reliable and effective for fast tuning lower frequency heavy ion resonators with stored energies at gradient of less than 10 Joules.

While fast tuner technology is advancing in reducing the effects of detuning on a cavity, there are also important gains to be made in both damping the sources of detuning and in stiffening cavities so the response is smaller.

HOM Couplers

Higher Order Mode couplers are devices that are used to couple beam-induced RF power out of a cavity to prevent it from building up fields that can either disrupt the beam and/or can add to the cryogenic load. Discussion on HOM couplers was limited due to time constraints, but a few points were made. First, the TTF coax-style HOM coupler was good for fairly low HOM power levels corresponding to TESLA-like beam currents. For much higher beam current applications, like B-factories, either waveguide HOM couplers or in-vacuum beamline ferrites were needed to handle the power. It is important to instrument these couplers to monitor how well they are working and to see if any changes are occurring over time. Also the potential of HOM couplers that take the power signal out of the cryogenic environment as beam diagnostics equipment was acknowledged.

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