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RF Couplers for High-Power Superconducting Ion Linacs

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RF COUPLERS FOR HIGH-POWER SUPERCONDUCTING ION LINACS*

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INTRODUCTION

Superconducting Radio Frequency (SRF) accelerating structures present a unique design environment for the high-power radio frequency (RF) antennas that deliver power to the cavity to establish the electromagnetic fields and ultimately accelerate beam. These RF couplers need to reliably transmit high power RF with low reflection and insertion loss, while simultaneously maintaining cavity vacuum, minimizing heat leak into the cryomodule, and not adversely affecting the RF cavity or cryomodule mechanics upon cool down. While a majority of research and development (R&D) on SRF couplers have been focused on electron accelerators, advances made in high-power ion accelerator design for the Spallation Neutron Source (SNS), the Japan Proton Accelerator Research Complex (J-PARC), and the Rare Isotope Accelerator (RIA) have necessitated developing high-power RF couplers for these applications as well. This paper examines the present state of RF coupler development and R&D for superconducting ion accelerator applications.

TECHNICAL OVERVIEW

High-power RF couplers in SRF applications are a significant engineering challenge. The technical requirements on RF transmission, power handling, multipacting susceptibility, coupling to the cavity, Ohmic heating, field asymmetry influencing the beam, cryogenic heat leak, and mechanical stability upon cool down are a complex set that are often competing. In addition, the knowledge base for building robust RF couplers can be difficult to embrace, as the experience base on how to build high performance couplers is spread throughout the globe. Technology summary papers often amass results and data but usually won't go as far as distilling best practices since different applications have widely varying requirements.

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When considering power couplers for superconducting ion linacs, an obvious question is whether the coupler technology for an ion accelerator is intrinsically different than what is needed for an electron machine. As shown in Table 1, while minor differences in couplers exist for each type of machine, overall, a power coupler design is driven more by accelerator physics design considerations than species. This allows for a greater breadth of design knowledge and operational experience to draw on for making new designs for either application.

	electrons	**ions**
peak power	same	same
average power	lower	higher
synchronous phase	0^o	-25^o to -40^o
vacuum levels	UHV	UHV for H^-
particle velocity	~ c	variable
beam potential well	negative	negative or positive
HOM power	high	lower

Table 1. A comparison of the operating conditions for a coupler in an electron or ion linac.

DESIGN ENVIRONMENT

Successfully designing an SRF power coupler for reliable operation requires balancing a number of disparate constraints related to the engineering, physics, and system integration aspects of the machine. As a number of highly detailed papers exist on this technology and possible design strategies for high-power SRF couplers [1] [2] [3] [4], only a brief summary will be presented here.

The primary objective of a power coupler is to deliver electromagnetic energy to a superconducting resonator without degrading the performance of the SRF cavity or the cryomodule and without having the cavity or cryomodule adversely affect the mechanical and RF design of the coupler such that cost, manufacturability, or reliability are compromised. The technical issues that need to be reconciled by a successful coupler design are numerous.

Physics Issues

Physics considerations for a coupler relate to how the coupler interacts with RF power and how it will interface to the cavity to couple in the power. The main issues are:

- RF power handling and arcing thresholds for air, gas, and evacuated transmission lines. Though seemingly trivial, an arcing coupler is a failed unit, and field levels need to accommodate up to full standing wave voltages.
- Electric versus magnetic field coupling to the cavity. While most $\beta\sim1$ elliptical cavities rely exclusively on electric field coupling on the beam tube, lower velocity structures for heavy ion acceleration often rely on magnetic field coupling.
- Avoiding lower-order multipacting levels near and below the operating power levels.
- Assuring the coupler also accommodates the HOM power emitted from the cavity due to beam excitation. This power can lead to additional and anisotropic window heating as well as arcing in the transmission line.

Engineering Issues

Once the physics issues are adequately addressed by a design concept, thorough engineering analysis is needed to evaluate and advance the design. The engineering issues are:

- Hermetically sealing the cleaned SRF cavity and maintaining cavity cleanliness once sealed.
- Dissipating heat due to Ohmic losses on the transmission line including mismatch operation from, for example, conditioning without beam.
- Managing cryogenic heat leak at an acceptably low level.
- Applying high-quality titanium nitride coatings to suppress multipacting on windows and parts.
- Applying high-quality copper coatings to reduce Ohmic losses on stainless steel parts.
- Creating a sound overall mechanical design that accommodates thermally induced movement and contraction; has adequate vacuum pumping, vacuum joints and sealing, vacuum joining and brazing; and can be cleaned and clean assembled.
- Ensuring the design allows for coupler preparation and processing related to in-situ baking, minimizing gas evolution, and high-power RF processing.
- Maintaining rigorous material quality assurance (QA), as minor changes in material properties or preparation can significantly affect the performance of the finished coupler.

System Integration Issues

System integration issues are related to aspects of the coupler design that interface with the cavity and cryomodule. While a well-designed coupler may have the potential to work well, its performance may be hampered by limitations from integration into the cryomodule. The main system integration points to consider are:

- Selecting the right thermal intercept temperature and coolant stream choice. This entails matching the coupler coolant design needs to the optimum cooling circuit temperature and flow characteristics for the cryogenics system.
- Balancing the dynamic and static heat loads in the cryomodule based on the operating scenarios.
- Ensuring the coupler window will not be subject to field emitted electrons from the cavity.
- Choosing the fixed points on the cryomodule to not stress the coupler upon cool down.
- Choosing the proper level of interlocks and protective diagnostics for the coupler—enough to prevent catastrophic failure but not so many to impede operation or drive up cost.
- Accommodating in-situ coupler conditioning and bake-out.
- Determining if the coupler degrades gracefully or abruptly over time.
- Evaluating the fault modes, consequences, and recovery strategies for the coupler.
- Achieving an optimized management of design margin across the entire machine to increase the overall reliability.

Obtaining the right balance between these aspects will determine how well a given design will perform and how reliable it will be over the lifetime of the machine. This large number of considerations is also why there is not a universally accepted “best” approach to power couplers for SRF cavities. The breadth of issues suggests that adapting others’ designs to new projects with the idea of saving non-recurrent engineering effort and reducing manufacturing risk may come at the price of performance and reliability. Given the critical role a coupler plays in the overall performance of an SRF linac, designers should be aware of the benefits and limitations of scaling others' designs, and be prepared to apply an appropriate level of engineering analysis and design rigor.

HISTORIC PERFORMANCE DATA

As gradients in SRF cavities have increased, the RF power couplers have had to keep pace to deliver the power needed to support them. Therefore, it is natural that SRF coupler performance has improved in the past 20 years. Figures 1 and 2 show how the peak and average power transmitted through couplers has improved over time.

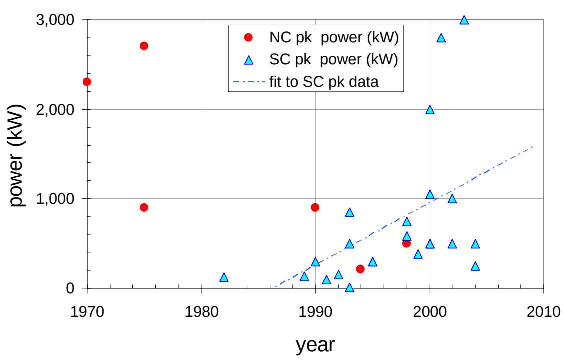

Figure 1. Plot showing peak power through power couplers for the past 30 years. Red data are for normal conducting (NC) machines and blue are for SRF. The line is a linear fits to the data.

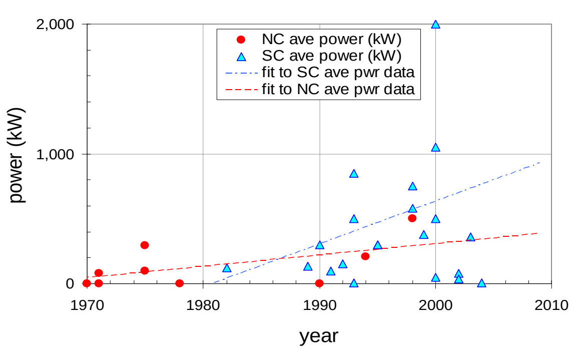

Figure 2. Plot showing the average power through power couplers for the past 30 years. Red data are for NC machines and blue are for SRF. The lines are linear fits to the data.

As shown in Figure 2, the average power being transmitted through SRF power couplers has increased more rapidly than it has for normal conducting machine couplers, suggesting SRF is becoming the preferred technology for high-power, high-duty-factor accelerators.

The data were also evaluated to investigate the role frequency plays in coupler performance. In Figure 3, peak and average powers for SRF couplers were plotted against frequency.

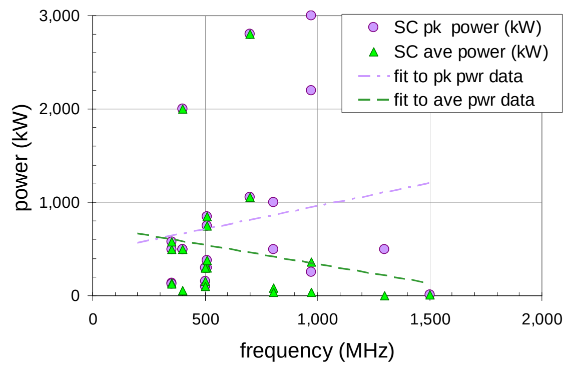

Figure 3. Plot showing peak and average powers through SRF power couplers versus frequency. The linear fits show opposing trends between the peak power data (purple dash-dot) and average power data (green dash).

The data in Figure 3 are not easily interpreted regarding performance and frequency, and trying to gain insight is further complicated by how frequency and power levels for couplers are specified on a machine.

As an example, based on the single-point multipacting scaling of

$$P_{MP} \propto f^4 D^4 \quad [5],$$

one might expect strong performance gains in going to higher frequency. However, the data do not obviously support this. One reason is that SRF coupler designs are driven largely by the greater project parameters.

In the design of a large machine, a myriad of parameters are evaluated and a baseline concept is established. Usually, the machine frequency, beam current, cavity shape, gradient, Q, machine length, cryogenic load, and focusing lattice are all worked within the context of good beam dynamics. Of these parameters, the first four are critical for the coupler as they not only establish the operating power level, they bound the coupler diameter by setting the cavity diameter which then limits the beam tube diameter.

Other parameters further define and constrain the performance envelope for the coupler. In this way, coupler performance usually does not drive machine parameters as much as respond to them.

TECHNOLOGY AND APPROACH ASSESSMENT

As coupler development has been active for the past 20-plus years, significant progress has been achieved in understanding how to build a robust high-power coupler for SRF accelerators. A number of successful designs have been realized spanning various machines. As part of this process, it becomes clear which areas of the technology work well and which areas could use further development.

What Works Well

Areas of coupler design that work well in SRF applications include:

- Couplers hermetically sealing the cavity and supporting the cleanliness levels needed. Cold windows have achieved operation compatible with accelerating gradients of 20–30 MV/m at TESLA Test Facility (TTF), and warm windows have achieved gradients of 15–17 MV/m on SNS [6].
- Couplers are achieving low heat leak into the cryomodules.
- RF engineering designs tend to be reasonably good, as the availability of modeling and measurement systems makes this relatively straightforward to achieve.
- Couplers are operating with good reliability at or near specification power levels. However, in many cases, couplers have also played a major role in limiting overall machine performance and have required special attention and caretaking to maintain reliable operating conditions.

Areas for Improvement

Although couplers are supporting reliable operation at major SRF facilities such as Jefferson Lab and TTF, couplers, in general, would benefit from improvements in of the following areas:

- Multipacting susceptibility of couplers is still a significant concern. Although a fix exists in using DC biasing, it complicates the design and adds cost.
- Present-day coupler designs work, but they tend to be complicated and over-constrained, leading to higher manufacturing costs.
- Coating technology for multipacting (MP) suppression tends to not be reliable or commercially available.
- Coating technology for copper plating to reduce Ohmic heating is available commercially but tends to be finicky. Consistency is problematic as well.
- Conditioning time for SRF couplers is wide ranging, depending on the design and conditioning procedures. For a machine the scale of the International Linear Collider (ILC), long conditioning times will adversely impact project costs and schedule. Understanding which design features increase coupler conditioning times would be beneficial.

On Design Strategies

As designing a high-power RF coupler from scratch can be both technically risky and costly, taking advantage of successful development work from other projects and adapting these designs to new applications is a reasonable strategy. This technique of scaling proved to be highly successful for the SNS coupler design [7]. It is also the development route for the design evolution of the TTF-class of couplers. While this approach works, a downside is that these development efforts tend to be incremental improvements on a single design concept. To counter this, a certain amount of exploratory design work is beneficial to better understand the operational parameter space and to best optimize a solution set for a specific coupler application. In addition, while the scaling approach is highly defensible, augmenting it with developmental R&D on new coupler approaches helps ensure continued progress toward the next generation of higher performance coupler designs.

RECENT DEVELOPMENT EFFORTS

Coupler development is being actively pursued at a number of laboratories in support of various electron and ion accelerator applications.

Couplers for Electron Accelerators

SRF electron accelerators are being built for either high-energy physics or photon-related science. For these applications, extensive development work is underway at DESY and Orsay on couplers for the XFEL project, eventually providing an important technology base for the ILC [6]. This effort is focused on improving the processing and manufacturability aspects of the TTFIII coupler for the XFEL to reduce cost, as well as advancing the concept with new designs such as the TTF-IV, TTF-V, and TW60 couplers. These alternative designs are being pursued to explore improvement routes for the TTFIII design. As an example, a drawing of the TW60 coupler is shown in Figure 4.

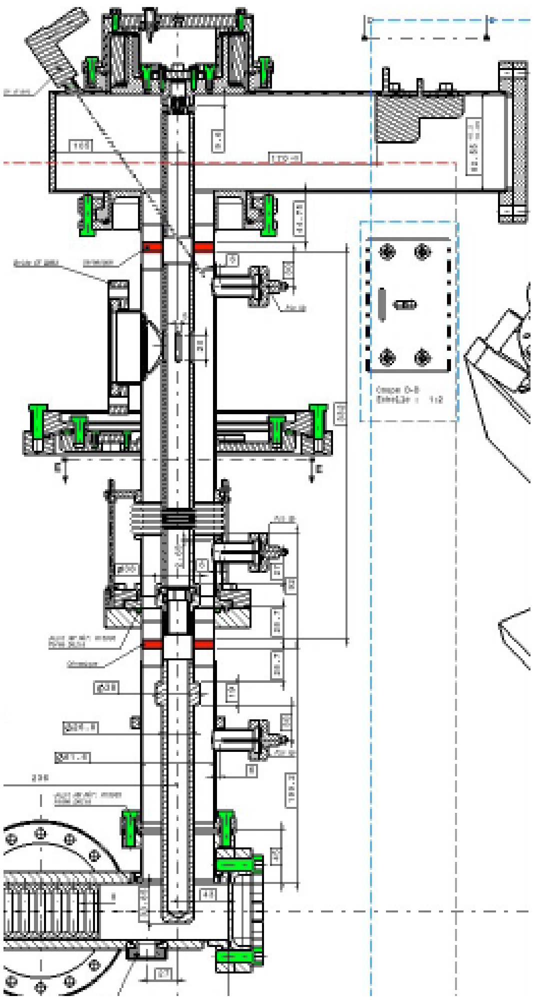

Figure 4. A drawing of the Orsay TW60 coupler design, which incorporates planar coaxial disk windows.

Another development area for electron-machine SRF couplers is for energy recovery linacs (ERLs). Recent work at Cornell focused on modifying the TTFIII coupler design for continuous wave (CW) operating conditions [8]. As the original TTFIII design was for a 1.3 percent duty factor, the modified design is an appreciable departure from the original, requiring additional cooling on bellows and other components. A model of the Cornell design is shown in Figure 5.

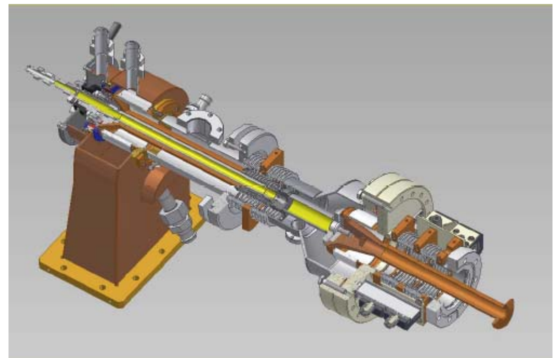

Figure 5. A model of the Cornell ERL coupler. Design changes were made to allow this TTFIII-based design to operate at CW conditions.

To summarize, Table 2 shows some select parameters for electron-related coupler work.

	freq (MHz)	Ppk (kW)	d.f. (%)	lab
TTF-III	1300	250–500	1.3	DESY
TTF-V	1300	250–500	1.3	Orsay
TW60	1300	250–500	1.3	Orsay
TTF-IV	1300	250–500	1.3	Orsay
XFEL	1300	150	1.3	Orsay
ILC	1300	250–500	1.3	many
ERC	1300	150	100	Cornell

Table 2. Electron-machine coupler-related development efforts listed by coupler design.

Couplers for Ion Accelerators

SRF ion accelerators are being envisioned for either nuclear physics or as spallation production drivers for neutron-related science. The proposed Rare Isotope Accelerator for nuclear physics research would be a highly versatile machine that could accelerate all stable isotopes and needs reliable, adjustable RF couplers. While these couplers will be at relatively low power compared to those used in spallation-neutron driver linacs, their need to operate at CW conditions over a wide frequency range makes them a design challenge as well.

Couplers for spallation neutron driver machines tend to be high power and run at high duty factors ranging from 10 percent up to CW. Recent commissioning experience on the SNS linac shows encouraging results in rapid coupler reconditioning after cryomodule installation. A photo of the SNS couplers on a test stand is shown in Figure 6.

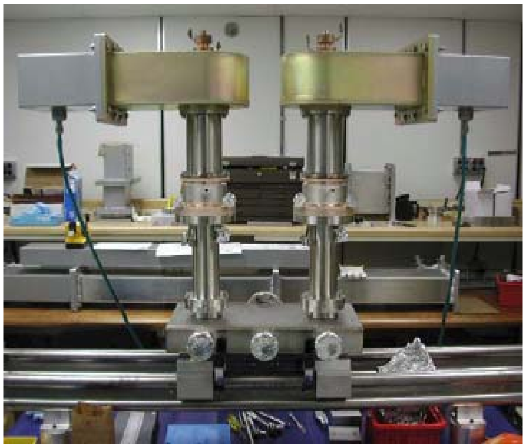

Figure 6. A pair of SNS couplers on a conditioning test stand showing the waveguide to coax transitions and the evacuated coupling waveguide (bottom).

To summarize, an overview of ion-related coupler development work is provided in Table 3.

	freq (MHz)	Ppk (kW)	d.f. (%)	lab
SNS	805	550–650	8	JLab/ ORNL
RIA lo β	57–345	2–5	100	ANL
RIA hi β	805	20–50	100	JLab/ MSU
J-PARC	972	2200	12.5	KEK
LHC	400	500	100	CERN
ADTF	350	135	100	LANL
APT	700	250–450	100	LANL

Table 3. Ongoing or recent ion machine coupler development work. Note the higher duty factors needed for the ion versus electron machines.

EXAMPLES OF R&D AREAS

Advancing coupler technology further will require R&D in a number of areas. One example of R&D being pursued is the capacitively-coupled planar disk window being pursued by KEK [9]. This approach is based on capacitively coupling across a planar barrier window in a cylindrical TEM guide, as shown if Figure 7, and is a radical departure from conventional planar coaxial or right-cylindrical window designs.

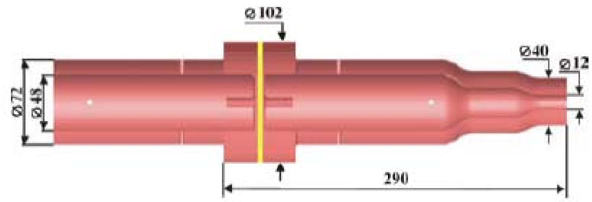

Figure 7. Model of the KEK capacitively-coupled planar disk window concept.

Another example of coupler R&D is an evaluation of multipacting susceptibility and enhancement due to outer conductor bellows in coaxial coupler transmission lines being performed by SLAC and LLNL. Looking at field levels on the bellows region of a TTFIII-style coupler shows how the geometry of the bellows causes field enhancement and de-enhancement zones that effectively support a much broader range of multipacting resonances than a flat wall, as shown in Figure 8.

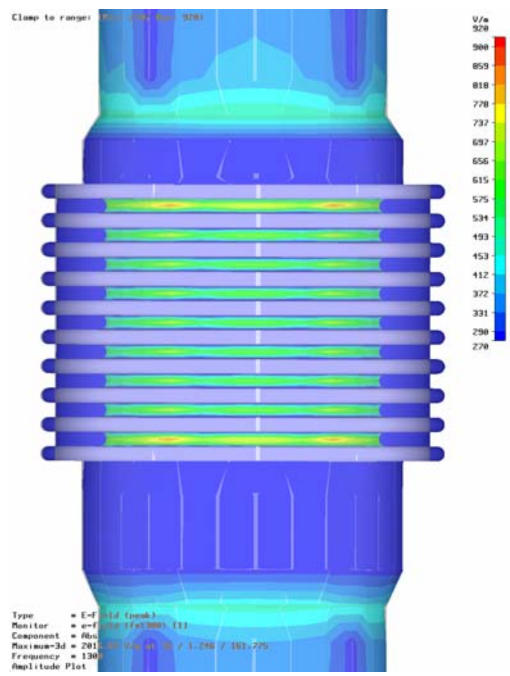

Figure 8. Model showing field-enhanced regions (yellow-green) due to bellows geometry that can support a number of lower-order, higher-field multipacting modes than exist on the flat wall (dark blue).

This enhancement results in a much larger effective surface area that needs to be conditioned against MP breakdown, as shown in Figure 9.

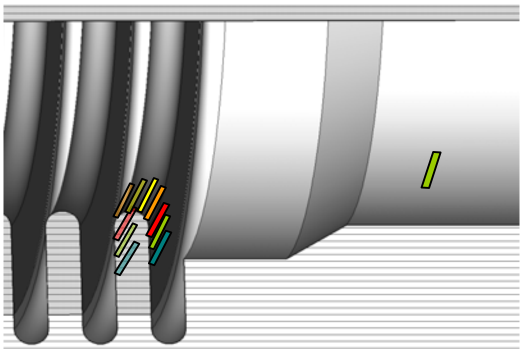

Figure 9. A graphic showing how a given higher order multipacting resonance supported on a straight coax outer wall (green patch on the right) is accompanied by additional lower-order resonances due to field enhancement caused by the bellows.

Other areas being pursued include more detailed multipacting calculations, alternative windows, and RF conditioning studies of coupler piece parts to better understand their role in gas evolution and RF conditioning.

CONCLUSIONS

RF couplers in SRF applications present significant technical challenges for machine designers. The combined physics, engineering, and system integration design envelope is complex, and a detailed, thorough, and balanced design effort is needed to realize a reliable coupler. A number of active development efforts on couplers for both electron and ion machines have pushed the performance of couplers higher over the past two decades, and R&D in the field hold the promise of further understanding to enable higher power, higher reliability coupler technology at lower costs.

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