STATE OF THE ART POWER COUPLERS FOR SUPERCONDUCTING RF CAVITIES *

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Abstract

Fundamental power couplers for RF particle accelerators are the most important components that interface with the accelerating structures.

In the case of superconducting cavities, the main function of providing appropriate power to the cavity's fields and to the beams is dwarfed by the requirements the couplers must meet to blend harmoniously into the vacuum, cryogenic, and electromagnetic environment.

Recently, a lot of progress has been made in the areas critical to the successful design, construction and operation of fundamental power couplers. Simulations are now routinely performed that allow the prediction of electromagnetic, multipacting, thermal, and mechanical properties of couplers. From these studies, better designs have been conceived which can minimize potential problems ahead of construction. Judicious use of materials and the implementation of clean practices and of careful conditioning have gradually increased the power levels at which couplers can safely operate.

Machine operation at hundreds of kilowatts has been achieved in CW at KEK and Cornell, and in a pulse mode at the TESLA Test Facility (TTF). Test stand operations in CW have been achieved at the megawatt level (Accelerator for the Production of Tritium) and in pulse mode at a peak power of 2 MW (Spallation Neutron Source, TTF version II).

The recent progress indicates that understanding of fundamental power coupler behavior is rapidly increasing and that optimal designs are being developed which will allow routine attainment of the megawatt power levels necessary for high-beam-power machines under construction and under study.

1 INTRODUCTION

In the past two decades RF superconductivity has evolved from a highly complicated curiosity into a mature, reliable technology underlying diverse machines for electron, positron, and proton acceleration—with more ideas and applications on the horizon. As superconducting cavity gradients have gradually approached theoretical field limits (at least for niobium), more demanding requirements have been placed on auxiliary components which, in a cohesive way, must make up the cryogenic accelerator unit, the cryomodule. No component associated with superconducting cavities is being put to the test by the increasing demands as much as RF power couplers.

From the original idea that the usefulness of superconducting cavities consists in their ability to build up fields even with a small incident power, one has gradually passed to applications in which high beam currents require strong coupling and large traveling wave power to be fed to the cavities via the couplers. With the higher gradients, situations in which large standing and traveling waves must coexist have complicated coupler design, and with the advent of pulsed machines, transient fields and large input power variations have put new demands on them. Whereas for superconducting cavities there is always the mythical goal of reaching the theoretical maximum field allowed by a given material, expectations for power couplers are that they must always perform better than needed for a specific application, without adversely affecting cavity performance.

Recent progress has led to megawatt-capable couplers. The progress results from computational tools used in designing combined aspects of the couplers and from painstaking care in constructing and preparing couplers for installation. However, this progress also demonstrates the complexity of the coupler challenge. Coupler construction and preparation costs now match those of the cavities themselves. For RF superconductivity to be more widely applied, power coupler costs must be carefully re-evaluated, and new manufacturing methods devised, as has been done for the cavities.

This paper attempts to give an idea of the properties and design characteristics of power couplers for superconducting cavities and to point out the areas where improvements will be needed. Ref. [1] contains an exhaustive bibliography on power couplers for superconducting cavities.

2 THE FUNCTIONS OF POWER COUPLERS

2.1 Electromagnetic

Couplers exist, obviously, to transfer energy from an RF generator to a superconducting cavity at a rate suitable for the specific application. The basic ways of coupling the power are via a waveguide or through coaxial lines terminated capacitively or inductively into the evanescent cavity fields. Of the coaxial type, capacitive coupling has

* Supported by US DOE Contracts Nos. DE-AC05-00OR22725 and DE-AC05-84-ER40150
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the widest application, because magnetic field coupling creates additional design complications.

In recent years the study of electromagnetic coupling has been enormously aided by computer codes allowing complete modeling of the field distribution of the coupler/cavity fields' interfaces and guaranteeing that the proper coupling is achieved, thus minimizing the cut-and-try tedium that formerly slowed development of a coupler. Figure 1 presents an example such calculations' results. Codes such as MAFIA and HFSS are routinely used to evaluate the coupling and to minimize the reflections and insertion losses introduced by various elements in the transmission line and the coupler proper.

The proper coupling to a cavity implies that no power is wasted unnecessarily, either because of a lack of matching to the beam or because some components in the transmission line are not properly matched. One possible way of dealing with this issue is to make the coupler variable, so as to minimize wasted power. However, variable couplers have a very complicated mechanical structure, and the materials used can add to possible failure modes, thus decreasing the structure's reliability.

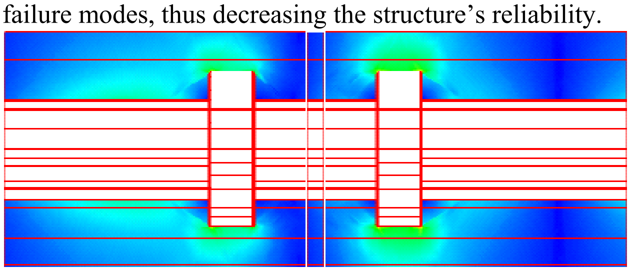

Figure 1. Example of field configuration calculated for a traveling wave window. [2]

2.2 Vacuum barrier

The next function that a coupler must perform is to provide a barrier to the gases that would be otherwise cryopumped into the cavity. Obviously these barriers must be permeable to the electromagnetic radiation without introducing significant losses or reflections. In normal conducting accelerator structures the same is true, but the demands on the quality of the vacuum and the reliability of the windows are less stringent. The failure of a window in superconducting accelerator structures can necessitate very costly and lengthy repairs.

This additional function introduces the single most complex aspect of coupler design. The window constitutes the most sophisticated and technologically challenging component of the whole cryomodule. In it the technologies of materials, surfaces, vacuum, electromagnetic design, gas dynamics, and manufacturing methods must converge harmoniously. [3]

Depending on the transmission line interfacing the cavity, windows can come in a planar waveguide configuration or in a variety of geometries adapted for coaxial lines. Figure 2 shows a recent application of the coaxial geometry with cylindrical windows. [4]

In some cases, double windows guarantee vacuum integrity even if one window fails. Such designs (CEBAF for waveguide with one cold window; APT with both windows at room temperature; TTF with one window at 70 K) tend to complicate the structure, adding parts that must be carefully quality-controlled. Moreover, a failure does not eliminate the need for immediate replacement of the coupler and possibly the cryomodule.

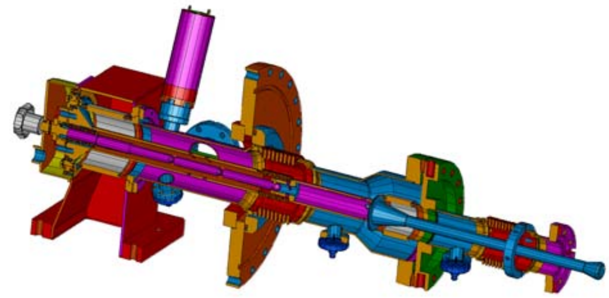

Figure 2. A recent version of the TESLA coupler. Variable coupling and a warm and a cold cylindrical window illustrate the complexity of couplers for superconducting cavities. [4]

2.3 Thermal barrier

As the RF power must be fed into the cold superconducting cavity, the final parts of the transmission line must cross the boundary between room temperature and the low-temperature environment, usually 2–4.5 K. This aspect of coupler design imposes very tight requirements on geometries and very delicate balances between static and dynamic heat loads placed on the refrigeration system.

The penetrations must be short due to the limited radial space available in most cryostat designs. Thus they must employ materials that provide large thermal resistance to sustain the large thermal gradients without introducing additional RF losses.

Balancing these aspects imposes tight requirements on the design of the thermal transition, which must be tailored to the specific configuration. In modern cavities, in which only the cells themselves are cooled directly by liquid helium, the presence of heating terms deriving form the couplers can push the temperatures of superconducting components dangerously close to the threshold for transition to the normal state. In addition, this delicate balance must not introduce thermal instabilities into the cavity proper, which needs already to be pushed to the limit of the thermal magnetic instability without introducing other perturbing factors that could lead to loss of superconductivity. Nowadays complete simulations of coupler thermal behavior are available to guide design and to preclude lengthy experimental cycles (see, e.g. [5]).

3 OTHER DESIGN CONSIDERATIONS

3.1 Multipacting

Multipacting is an unavoidable characteristic of RF systems operating under vacuum. Whereas it is practically impossible to eliminate for all the possible geometries and modes of operation of RF systems, a great deal of progress has been made in identifying the critical areas which contribute to it and in greatly decreasing its incidence and its negative effects on RF structures.

A great understanding of this phenomenon has been achieved by computational methods. Nowadays it would be inconceivable to start designing a power coupler structure without first performing a thorough study of its multipacting behavior. Several codes can guide such study. Results point to the fact that multipacting can exist in couplers at nearly any power level, due to the complexity and variety of the geometries usually involved, and also to the fact that, unlike in cavities, mixed waves with all sorts of relative amplitudes and phases can exist at one time or another [6], [7].

The choices of geometry and line impedance should be made to minimize the incidence of multipacting. If unavoidable, multipacting should be shifted away from locations likely to give catastrophic problems, like near windows. Processes and materials should be implemented to decrease the secondary electron emission coefficient. Conditioning activities should be included in the planning for coupler development. Finally, most importantly, careful handling and conservative ultra-high vacuum practices cannot be substituted for by even careful choices of geometry.

3.2 Peak power versus average power

Increasing power demands are being placed on couplers for superconducting cavities. Either because of the structure of the beam itself or to lower the cryogenic plant requirements, some new machines are being designed to require pulsed power, which therefore constitutes a new issue in the use of couplers for superconducting cavities.

To first order, pulsed power systems have the beneficial effect of lowering the average power requirements on components, thus alleviating some of the dissipated power removal demands. However, little experience exists in the operation of power couplers in real pulsed superconducting accelerators. So far, only in the TTF has a real accelerator and cryogenic environment been achieved, albeit for only a limited period.

The transient nature of pulsed power can introduce thermal and mechanical stresses in critical components that are difficult to predict and evaluate. In addition, the large fluctuations of traveling and standing waves in the coupler at each pulse can cause transient desorption of gases and higher likelihood that some multipacting barrier might be encountered at some time during the pulse in some location in the coupler. It is very difficult to predict how these and other effects, due to the pulse nature of the operation of these accelerators, will affect the lifetime of couplers and therefore of cryomodules in the future. No real accelerator will come online with these characteristics over the next few years (SNS is expected to begin beam operations in about three years), and it would be desirable to conduct more detailed studies of this aspect.

3.3 Manufacturing methods

Substantial progress in the ability of couplers to handle high power has been achieved in the last few years in several laboratories and with the help of a few industries working together. The manufacturing methods have relied upon the refinement of existing techniques, such as binding of ceramic to metals, careful machining of components, and coating of surfaces. All of these methods have been placed under high scrutiny in order to achieve levels of quality control necessary for the reliable operation of large superconducting accelerators.

Whereas in recent years efforts have been mounted in the cavity manufacturing areas in order to achieve lower fabrication costs, the complexity of the coupler assemblies and the inherently large number of operations necessary in their fabrication have prevented the development of new, and possibly revolutionary, techniques for the manufacturing and assembly of power couplers. Traditional methods of brazing complicated window assemblies have provided a reliable method for a long time, but simplification of bonding methods will be necessary in the future in order to decrease the costs associated with this operation.

As large applications of RF superconductivity are being planned, the need emerges more clearly for a reduction of costs and for simplification of manufacturing methods. This issue will have to be addressed by the community in the immediate future, so that this technology can be more widely applied.

3.4 Design integration

Because of the high power handling of recent couplers, due to the strong coupling that makes the cavity/coupler fields perturb each other, and because of the stronger influence of ponderomotive effects on cavities, it is no longer possible to design these components separately and then merge them into a cryomodule environment. The coupler/cavity entity must be considered as a unity from the beginning, and the two components designed in all aspects as a whole. In this sense, good progress is being recently made [8] and the path to total integration is being pursued.

3.5 Preparation, conditioning, and assembly

Since couplers must be assembled onto cavities, the stringent vacuum requirements demand that the surfaces be treated with the utmost care. But whereas superconducting cavities are processed with relatively drastic methods (chemical treatments, electropolishing, high-pressure water rinsing, high-temperature heat treatments) in order to provide pristine surfaces, couplers cannot be subjected to the same degree of treatment. Each of the several materials that compose a coupler (metals, ceramics, films, coatings, braze alloys, etc.) is often treated with compounds that are incompatible with the others. Thus a key element of the success of the coupler is to maintain cleanliness and tight processing from the early stages of assembly, so that, later on, only mild rinsing methods need to be applied before installation.

Since not all of the handling and treatment is always completely under control, it is customary to condition couplers before installation onto superconducting cavities in order to remove surface contaminants though RF processing. This process is very useful also to evaluate the performance of couplers ahead of their final assembly. It is, however, a rather lengthy and complicated process and for large-scale applications there might be need to re-evaluate its necessity, in order to decrease installation costs. Careful processing is in any case necessary at the time of turn-on when couplers are installed in cryomodules.

3.6 Testing and cryomodule integration

Even with the advent of sophisticated simulation and design tools that enable one to eliminate a lot of the cut-and-try processes of early days and to predict most of the behavior of the couplers under high-power conditions, it is still necessary to verify the performance of couplers under real power conditions.

Most of the testing that is performed for preliminary studies is done at room temperature in special test stands, which typically test two couplers at a time, since two windows are necessary to define the vacuum space in the transmission line [9]. Typical tests include the use of traveling and standing waves with arbitrary phase and of electric DC bias of the center conductor (for coaxial couplers) [10], or magnetic bias (for waveguides) [7].

Whereas this type of testing reveals a great deal of the properties of couplers, it cannot disclose the subtle influence of adsorbed gases with graded density and composition, typical of the thermal gradients that characterize couplers installed in a cryomodule. Partial cooling with liquid nitrogen or superconducting transmission cavities has been implemented, but so far most of the testing of couplers in the final cryostat configuration has been done in the real cryomodule. Due to the long design and assembly times involved in this process, the reliability of couplers is always questioned till the very last moment, much more so than for superconducting cavities, the performance of which is generally accepted to be satisfactory via vertical cryostat tests.

A notable effort has been done for TESLA from Saclay and recently at Orsay, where rapidly cycling cryostats have been used [11]. This is a very laudable effort, since it enables one to test the complete performance of coupler/cavity systems (even though without the beam loading characteristics) in a very short time after the development of prototypes. In the future, it is desirable that similar cryostats be built for the main frequencies at which cavities and couplers are being designed, and that through worldwide collaborations the testing of new couplers designs be carried out well in advance of their permanent installation into accelerator systems.

The integration into actual operating systems for accelerators requires several protection interlocks to be implemented in order to avoid catastrophic failures of couplers (notably windows), which could eventually result in serious operational consequences for the whole accelerator system. Nowadays, early detection of arcs near windows, of vacuum excursions, of electronic currents, and of heating in the vicinity of windows is a necessity, given the increasing power levels that couplers and windows must handle. Temperatures of the cryogenic part of the transmission lines are also monitored to avoid thermal quenches in parts of the couplers close to the cavities, to prevent the cavities themselves from turning normal [12].

4 COUPLERS IN OPERATION AND UNDER DEVELOPMENT

Presently, only a handful of couplers are being used in actual operation with superconducting cavities. With the decommissioning of LEP (where 288 couplers were operating at 352 MHz in CW at about 125 kW), only HERA operates multi-cell cavities in a storage ring with CW couplers with powers up to 100 kW CW. At CEBAF the main accelerator requires modest power levels at 1.5 GHz for operation of the waveguide couplers (5 kW). The Jefferson Lab IR FEL, with waveguide couplers operating up to 50 kW CW, has been disassembled for upgrading.

However, single-cell superconducting cavities are being powered at 500 MHz under real accelerator conditions at Cornell's CESR-B, with waveguide couplers running close to 300 kW CW, and at the KEK B factory, where coaxial couplers with planar windows have reached the highest operating CW level so far: 380 kW. Operation at the megawatt level during testing has been achieved.

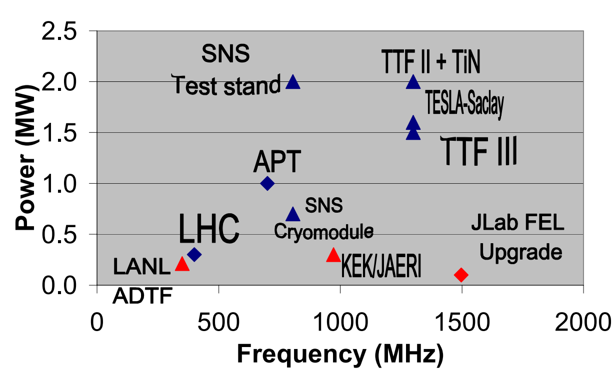

Figure 3. Couplers for superconducting cavities recently developed. Red shows couplers designed but not yet tested. In blue are couplers tested without beam. Triangles are pulsed couplers, diamonds CW.

The TTF, not yet a fully operating machine, has used coaxial couplers of various designs, and pushed the peak operating power under pulse conditions up to about 225 kW. Bench tests of various potential candidates for the final design, incorporating double windows and variable coupling, have gradually reached peak power levels under millisecond pulses close to 2 MW at 1.3 GHz.

A host of accelerators requiring couplers for superconducting cavities are being studied or are under development in several parts of the world. The 400 MHz LHC couplers (of a particularly demanding design which requires rapid coupling variations) have reached about 300 kW in bench tests.

Of particular interest is the design study for a machine that was recently studied but not funded, the APT. Those 700 MHz couplers have exceeded expectations, and during tests at room temperature have sustained power levels in excess of 1 MW CW. The techniques used in designing those couplers and some of the specific solutions adopted have been of great benefit to the whole field of superconducting cavity accelerator design.

5 A CASE STUDY: THE SPALLATION NEUTRON SOURCE (SNS) COUPLERS

SNS adopted superconducting cavities for the main part of the linac in early 2000. The short time available for the development of couplers specific to this frequency (805 MHz) did not allow detailed studies of new solutions. The necessity of reaching relatively large peak power levels (550 kW in the machine) but modest average powers led to the choice of a reliable existing design and to scaling it to the appropriate frequency. The support and collaboration of colleagues from all over the world who helped in realizing this design allowed for an extremely short development time. Nine months after the beginning of the effort to build prototypes, couplers were ready for testing and three months later tests at LANL confirmed that the simple planar window design was capable of withstanding peak pulsed power level of over 2 MW in a test stand. To this date, due to the unavailability of a proper RF source above 2 MW, the couplers have not shown a hard limit.

Recently, tests in the SNS prototype cryomodule have confirmed, under realistic conditions, that the couplers are capable of sustaining at least 700 kW peak incident power under a variety of mixed-waves conditions [12].

This process showed that simple and proven designs are capable of being adapted rapidly to new applications, and that careful execution of the preparation and processing are essential in providing an edge in successful development and testing of couplers [13].

The design in question, inherited from the KEK-B couplers, has been used in klystrons and coupler windows for a long time and it is now being considered also for other proposed accelerators [14].

6 CONCLUSIONS

Beyond the specific properties of the design of one coupler or another, it is clear that the time has come for a new approach to the design and construction of couplers. Now that megawatt levels are reachable both in pulse and CW for a few different designs, it is imperative that cooperation among laboratories be implemented in order to minimize development time and to access the best facilities for construction, preparation, assembly, and processing of couplers. But most of all, now is the time to re-evaluate basic design solutions and to question the basic methods for coupler assembly. There is a need to simplify both design and manufacturing methods in order to make the cost of couplers acceptable for large-scale adoption of this technology.

7 ACKNOWLEDGMENTS

The author would like to thank the many colleagues in laboratories all over the world and at Jefferson Lab who have provided information presented in this paper and who cannot be individually acknowledged.

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