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REVIEW OF HIGH POWER CW COUPLERS FOR SUPERCONDUCTING CAVITIES*

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Abstract

A number of high power fundamental input couplers for superconducting cavities operating in CW mode have been developed in recent years around the world. Some couplers have already been in service for many years delivering hundreds of kilowatts of RF power to beams. In this paper we will summarize experience accumulated in different laboratories and review design options and technical issues associated with R&D, testing and operation of the CW high power couplers. Several future projects will be discussed to highlight new requirements and design challenges.

1 INTRODUCTION

There are two primary function associated with the RF power couplers: i) efficiently couple RF power to a load thus providing an impedance matching network and ii) serve as an RF-transparent vacuum barrier between an air- or gas-filled transmission line and an evacuated volume of the cavity. The klystron output power couplers perform similar functions and very high power CW klystrons (with output power up to 1.3 MW) have been manufactured for quite a long time already [1]. But a typical klystron output coupler has fixed coupling and is able to efficiently transfer specified RF power to a load with VSWR up to only 1:1.2. On the other hand, a fundamental input power coupler for a superconducting cavity (SC) is a much more demanding device than the klystron output coupler though ceramic windows developed for klystrons were used in several coupler designs. The SC cavity couplers must operate in a much wider range of the load impedance: from a matched condition when the cavity is beam loaded to a full reflection at an arbitrary phase w/o beam load. In addition to the primary functions mentioned above, the cavity coupler has to satisfy requirements related to the nature of its load:

- Serve as a thermal transition from the room temperature to the cryogenic temperature (2 to 4.5 K) environment with low static and dynamic heat leaks.
- Support clean assembly procedures to minimize the risk of contaminating the superconducting cavity.
- Minimize cavity field perturbations that can affect beam or cavity performance.
- Provide adjustable coupling to accommodate different operating modes of an accelerator (when necessary).
- Be multipactor-free or provide means (such as bias voltage) to counter multipacting phenomenon.

These additional design challenges were overcome at different laboratories around the world using different technical approaches. Table 1 lists high average power RF couplers developed for superconducting cavities that were tested at high RF power. While compiling the table we had assumed that it is reasonable to call an input coupler a high average power one if it has reached power level of at least $100\times(500/f_{\mathrm{MHz}})^2$ kW during testing or in operation, where f_{MHz} is the operating frequency of the coupler in MHz.

HERA, LEP2 and TRISTAN couplers represent the first generation of high-power couplers. These couplers demonstrated during testing that they are capable to transfer hundreds of kilowatts of RF power. However, due to mainly accelerator/cavity specifics, they were limited in operation to 100 kW power level. Nevertheless, these couplers provided invaluable experience of fabricating, testing, operating and maintaining large-scale systems (288 couplers in LEP2). Of the first generation only the HERA couplers are still in operation.

The couplers of the second generation were designed with accumulated experience and knowledge in mind and in some cases were improved versions of the old couplers (LHC, KEKB, JLAB FEL), while in other cases were new designs (APT, CESR). These couplers reached impressive power levels of 1 MW on a test stand (APT) and 380 kW in operation (KEKB).

Many aspects of the high-power coupler design, fabrication, preparation, conditioning, integration in cryomodules, etc. will be discussed in presentations at this workshop. The goal of this paper is to review high average power coupler designs and technical approaches used in different laboratories, summarize testing and operating experience, and discuss several future applications. For a more comprehensive overview of the subject of fundamental power couplers for superconducting cavities and for an exhaustive bibliography we refer the readers to two recent papers by I. Campisi [2, 3].

2 DESIGN OPTIONS

There are two main options of a coupler design: a waveguide coupler or a coaxial coupler. Their major pros and cons are listed in Table 2. Though waveguide couplers can handle RF power better than coaxial ones,

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they become too large in lower frequency range. Also, coaxial couplers have in general smaller heat leak, and it is relatively easy to modify multipacting power levels by changing the diameter and/or impedance of a coaxial line. On the other hand, the larger size of a waveguide coupler means higher pumping speed and the absence of the center conductor makes the design simpler and cooling easier. So it seems that it is to a large extent a matter of machine/cavity specific requirements, availability of an acceptable prototype design, and laboratory traditions to decide which coupler/window option to choose. Waveguide couplers are represented in Table 1 by the two Cornell CESR couplers and the Jefferson Lab coupler for the FEL injector cryomodule. All other couplers are coaxial.

Table 1: High average power fundamental RF power couplers for superconducting cavities.

Facility	**Frequency**	**Coupler type**	**RF window**	Q_{ext}	**Max. power**	**Comments**
LEP2 [4,5,6]	352 MHz	Coax fixed	Cylindrical	2×10^6	Test: 565 kW 380 kW Oper: 100 kW	Traveling wave Stand. wave@ Γ=0.6
LHC [5,7]	400 MHz	Coax variable (60 mm stroke)	Cylindrical	2×10^4 to 3.5×10^5	Test: 500 kW 300 kW	Traveling wave Standing wave
HERA [8,9]	500 MHz	Coax fixed	Cylindrical	1.3×10^5	Test: 300 kW Oper: 65 kW	Traveling wave
CESR [10,11] (Beam test)	500 MHz	WG fixed	WG, 3 berillia disks	2×10^5	Test: 250 kW 125 kW Oper: 155 kW	Traveling wave Standing wave Beam test
CESR [12,13]	500 MHz	WG fixed	Disk WG	2×10^5	Test: 450 kW Oper: 300 kW 360 kW	Traveling wave Beam power Forward power
TRISTAN [14]	509 MHz	Coax fixed	Disk coax	1×10^6	Test: 200 kW Oper: 70 kW	
KEK-B [15,16]	509 MHz	Coax fixed	Disk coax	7×10^4	Test: 800 kW 300 kW Oper: 380 kW	Traveling wave Standing wave
APT [17]	700 MHz	Coax variable (±5 mm stroke)	Disk coax	2×10^5 to 6×10^5	Test: 1 MW 850 kW (fixed coupler)	Traveling wave Standing wave
JLAB FEL [18]	1500 MHz	WG fixed	Planar WG	2×10^6	Test: 50 kW Oper: 35 kW	Very low ΔT

Table 2: Pros and cons of waveguide and coaxial couplers.

	Pros	**Cons**
Waveguide	• Simpler design • Better power handling • Easier to cool • Higher pumping speed	• Larger size • Bigger heat leak • More difficult to make variable
Coaxial	• More compact • Smaller heat leak • Easier to make variable • Easy to modify multipacting power levels	• More complicated design • Worse power handling • More difficult to cool • Smaller pumping speed

Rectangular waveguides are used as transmission lines between RF power generators and cavities at high frequencies. Hence RF windows for waveguide couplers are usually planar inserts with one or more ceramics of different shapes and (sometimes) variable thickness. Windows utilizing simple round ceramic disks usually require matching posts (Figure 1a), while it is possible to design a self-matched window by choosing appropriate shape and thickness of the ceramics (Figure 1b).

Coaxial couplers require waveguide to coaxial transition. Most frequently a doorknob type transition is used. Windows of different shapes can be used in coaxial couplers: coaxial disk (APT, KEKB, TRISTAN), cylindrical (HERA, LEP2, LHC), conical. Cylindrical windows are often a part of the waveguide-coaxial transition while disk and conical windows are part of the coaxial line itself.

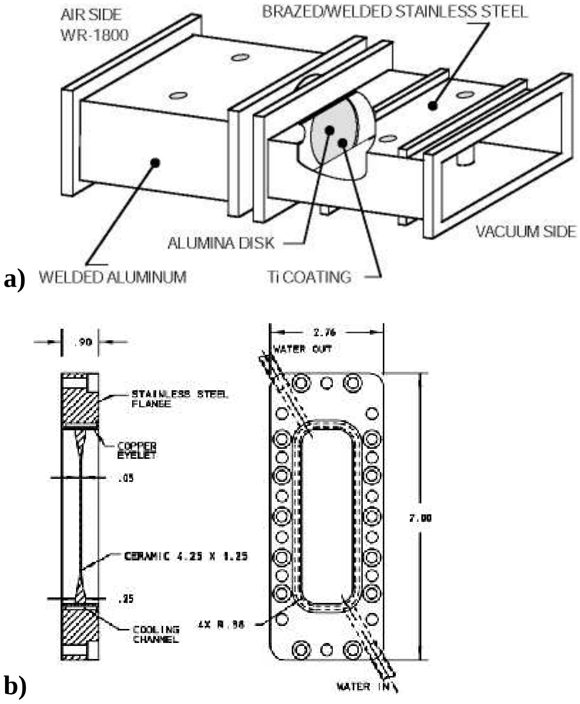

Figure 1: Waveguide windows: a) Thomson windows used in the CESR B-cell cryomodule [12], b) warm window of the JLAB FEL injector cryomodule [18].

The most commonly used ceramic material is alumina of different purity. In fact, only one coupler in Table 1, CESR waveguide coupler for the beam test, made use of different material (berillia). Though other materials were proposed, aluminum nitride for example, none of them has been used so far in high-power windows. Vacuum side of most windows is coated with a thin layer of titanium nitride or titanium oxide to suppress multipacting and prevent charging phenomenon. Two windows in series are used (APT, JLAB FEL) for added protection.

Most couplers have fixed coupling chosen so that matched conditions are reached at the maximum operating beam current to provide most efficient operation of the RF system. Auxiliary devices such as a 3-stub waveguide transformer can be used to adjust the coupling [19, 20]. In certain cases (LHC) variation of beam loading between different operating conditions is too large, so adjustable coupling is required. As testing of the APT and LHC couplers showed, designing variable coupler capable to handle high average power is not a trivial task.

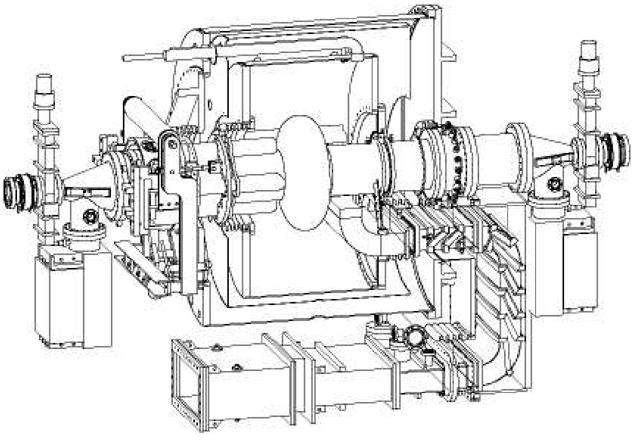

Figure 2: Cornell B-cell cavity equipped with a rectangular waveguide input coupler.

An example of the waveguide input coupler is the coupler of the Cornell B-cell cavity [13] (Figure 2) with fixed coupling at $Q_{\mathrm{ext}} = 2\times10^5$ via a coupling slot in the beam pipe (Figure 3). The coupling block with an attached waveguide elbow is part of the niobium cavity structure residing in the cryostat helium vessel. The 30 cm long waveguide feed immediate to the He vessel is cooled by 4.5 K helium gas through tracing welded to the waveguide walls. Next is a waveguide double-E bend similarly cooled by liquid nitrogen. Following is a short thermal transition to room temperature, a waveguide pumping section and finally the vacuum window. All waveguide parts between He vessel and room temperature environment are made of copper-plated stainless steel.

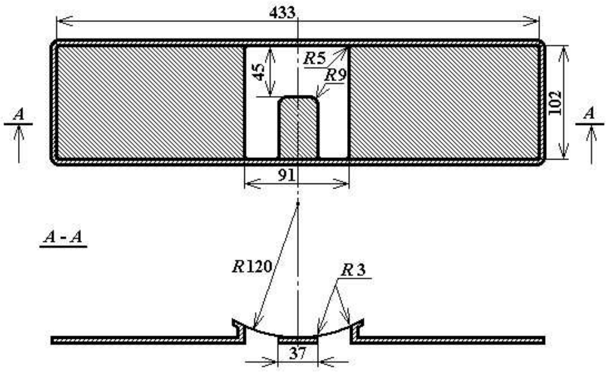

Figure 3: Coupling slot of the CESR coupler.

As multipacting in the cold sections of the vacuum waveguide presented some operating difficulties in CESR, solenoid coils were added to the waveguide outside of the cryostat magnetic shielding to provide DC magnetic bias. The bias field of about 10 Gauss proved to be useful to counter multipacting [21].

The KEKB input coupler [15, 16] is shown in Figure 4. It is an improved version of the TRISTAN coupler [14] and has fixed coupling at $Q_{ext} = 7\times10^4$. The ceramic window is a 10 mm thick coaxial disk made of 95% purity alumina. The surface of the window is coated with 100 Å of TiN_xO_{1-x} to reduce the secondary emission coefficient. The impedance of the 120 mm coaxial is 50 Ohm. The inner conductor made of electropolished copper and is cooled by water. The outer conductor is copper-plated stainless steel cooled by 8 l/min He gas at 4 K.

The doorknob transition section has a cylindrical capacitor around the inner conductor, which allows biasing up to ±2 kV to suppress multipacting or for bias aging.

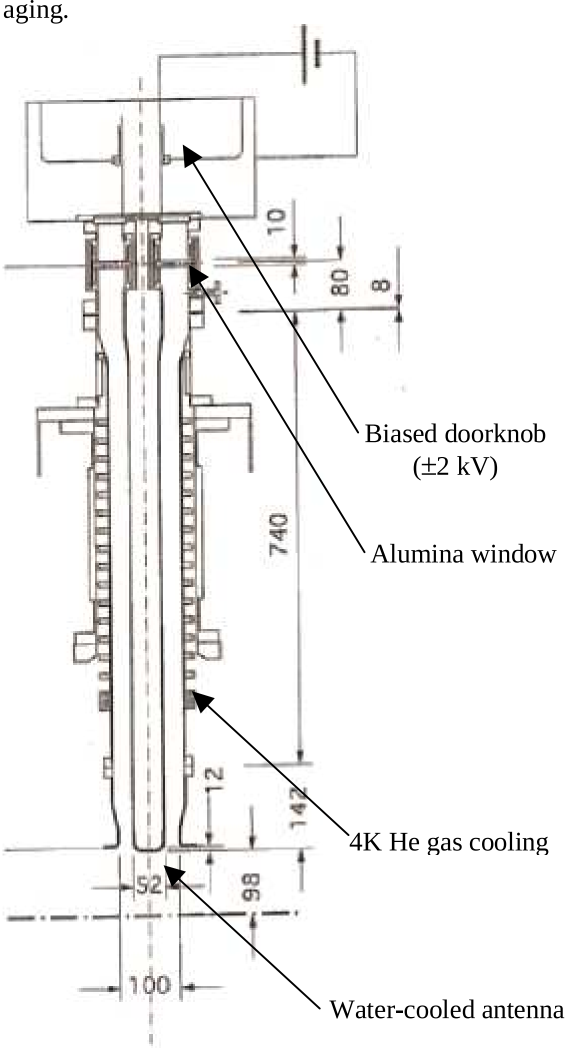

Figure 4: KEKB coaxial coupler.

The LHC variable coupler [5, 7] is based on the LEP2 coupler design. The cross-section of the coupler is shown in Figure 5. The waveguide height is reduced to permit a waveguide-coaxial transition without a doorknob. A Ti-coated cylindrical window is part of the transition. The main 145 mm coaxial line has impedance of 75 Ohm; its antenna is air-cooled. Cylindrical capacitor serves for DC bias of 3 kV. The most remarkable feature of this coupler is the coupling range. The external Q factor change from 2×10^4 to 3.5×10^5 is made by an axial movement of antenna (60 mm stroke), making use of bellows.

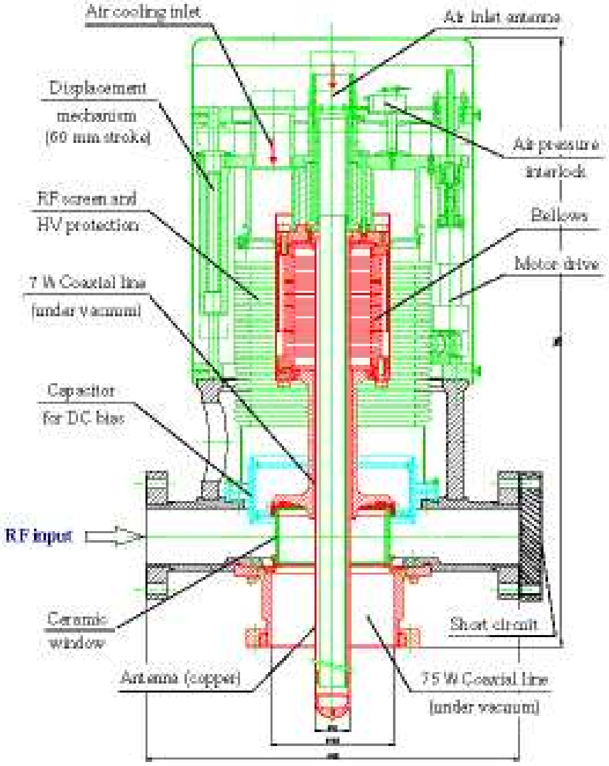

Figure 5: LHC variable coupler.

The APT coupler [17] is presented in Figure 6. Two primary functions of an input coupler are separated here into two distinct assemblies: the RF window assembly and the power coupler. The RF window assembly consists of a waveguide-coaxial (152 mm, 50 Ohm) tee-bar transition and a dual ceramic window section. The windows are similar to those used in high-power klystrons. The power coupler consists of the outer conductor, the inner conductor and the thermal intercept. The coupler provides external Q of 4×10^5 adjustable by ±50% with tip movement of ±5 mm.

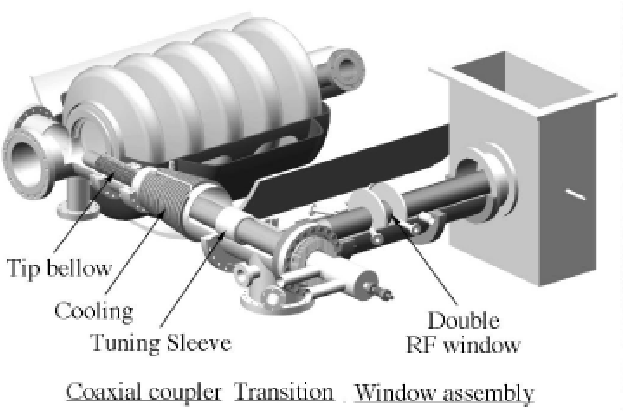

Figure 6: APT power coupler.

3 TESTING AND OPERATING EXPERIENCE

All input couplers are tested and processed separately at high RF power prior to the final cryomodule assembly. As waveguide couplers are an integral part of the cryostat, only windows are tested separately. Coaxial couplers are more portable and allow processing of a complete unit before installation. Two windows or couplers are connected together directly or via a coupling device, which can be an evacuated coupling waveguide (Figure 7) or a normal-conducting or superconducting cavity (Figure 8). Both traveling wave and standing wave mode of operations are checked. Sometimes a resonant ring setup is utilized [18], but it allows testing only in the traveling wave mode. In any case final processing is performed after complete cryomodule assembly.

Figure 7: Two 500 MHz waveguide windows assembled for RF processing [22].

Testing and operating of high power couplers must include adequate protection and monitoring. The instrumentation used on power couplers includes: vacuum gauges, residual gas analyzers, arc detectors, view ports for IR and/or video, electron current pick-ups, electron energy analyzers, temperature monitoring, and RF instrumentation.

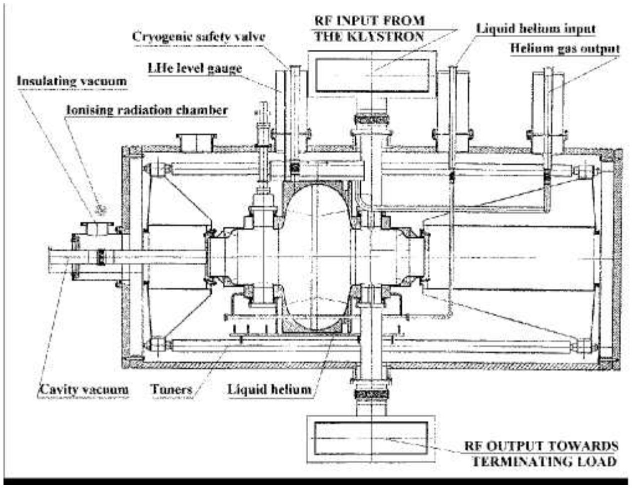

Figure 8: LEP2 input coupler test set-up using a single-cell superconducting cavity [6].

Typically, initial processing is performed in the traveling wave mode followed by testing in standing wave mode at different positions of reflection plane. Processing procedure employs both CW and pulsed regimes during power ramping. A so-called tickle processing [23] can be used to overcome especially hard multipacting barriers. It may take from several hours to several days to reach the maximum power level. In addition, *in situ* processing sometimes is required after cryomodule installation in the accelerator [24].

The maximum power reached to date is 1 MW in traveling wave and 850 kW in the standing wave. Both results were obtained at the APT test stand (Figure 9). 800 kW power has been reached in traveling wave by the KEKB input coupler [15, 16].

Figure 9: Test stand for APT couplers [25].

Only three accelerators have currently high power CW couplers in operation: CESR (4 couplers), HERA (16 couplers) and KEKB (8 couplers). TRISTAN (32 couplers) and LEP2 (288 couplers) have been decommissioned. Jefferson Lab FEL operation has been stopped for an upgrade. Commissioning of the upgraded JLAB FEL is scheduled to begin in late 2002.

Operation at high power is typically limited by the overall machine parameters and not by the input coupler performance. The maximum power delivered to the beam was 380 kW at KEKB. Figure 10 shows the typical loading curve during high-energy physics operation of KEKB.

4 FUTURE PROJECTS

In this section we review several new designs of high-power couplers that were presented recently. None of the new designs call for extremely high power levels. The emphasis is rather on a robust and reliable design, a good pumping speed and avoiding multipacting phenomena. In all cases previous experience in the laboratory proposing the new coupler, as well as in other laboratories, is well utilized.

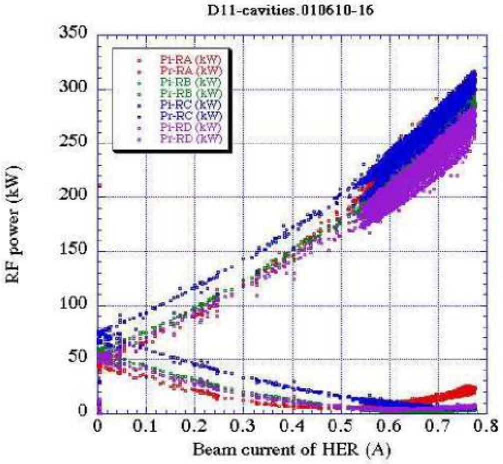

Figure 10: Typical forward and reflected power dependence on the beam current for D11 cavities at KEKB [26].

A coupler of the spoke cavity for the AAA project is shown in Figure 11 [27]. It is a 350 MHz, 212 kW coaxial coupler. Experience with the APT coupler was taken into account, but the design for the normal conducting APS cavity [28] was chosen as a prototype. The coupler consists of a half-height WR2300 waveguide section merged with a shorted coaxial conductor. A 4.8 mm thick cylindrical ceramic window is located at the waveguide to coaxial (103 mm, 75 Ohm) transition. A full diameter pumping port is located in the quarter-wave stub to facilitate good vacuum. The power acceptance test of the first couplers is anticipated in late 2002.

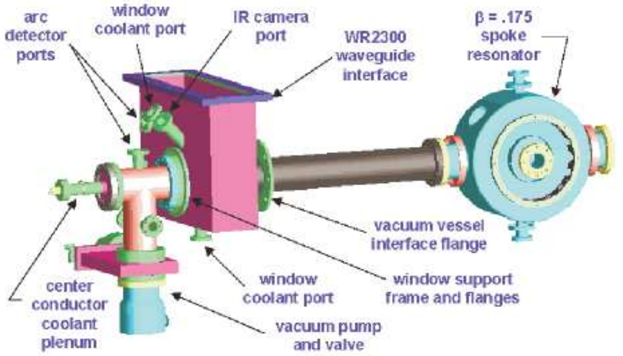

Figure 11: Schematic of the power coupler with a spoke cavity.

A preliminary design of a 704 MHz, 300 kW power coupler for a high intensity proton linac was proposed at Saclay [29]. This new development utilizes the Saclay group experience with work on TESLA couplers. The first iteration of the coupler design (shown in Figure 12) consists of a waveguide window, a waveguide vacuum valve as a SC cavity protection in case of the vacuum window failure, a doorknob type waveguide to coaxial transition, and a coaxial line. A scaled version of the Thomson windows used in CESR [12, 24] is considered as a possible solution. Computer simulations indicate that the multipactor should not be a problem in the coaxial line.

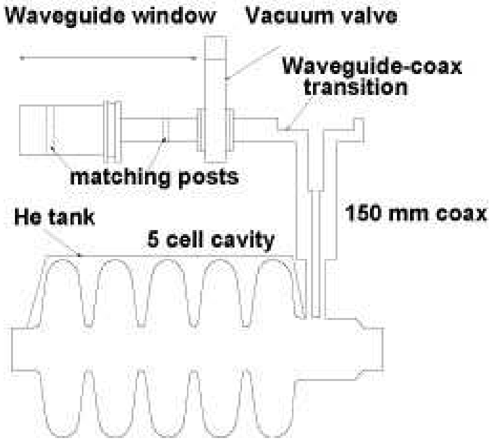

Figure 12: General layout of the Saclay coupler.

Development of a 100 MeV, 100 mA average current energy recovery linac (ERL) prototype is in progress at Cornell University [30]. A 1300 MHz superconducting cavity of the ERL injector has to provide 100 kW of RF power to the beam. Its input coupler is adjustable in the external *Q* factor range from $4.6 \cdot 10^4$ to $4.1 \cdot 10^5$. Additional challenge to this input coupler is a very strict requirement on the parasitic transverse kick to the beam. A low-kick twin-coaxial coupler (illustrated in Figure 13) was proposed as the design of choice [31]. It will be based on the TTF5 coupler and will adopt many features of that and other TTF input couplers [32]. The 60 mm, 60 Ohm coaxial line is multipactor-free up to 200 kW even in standing wave regime.

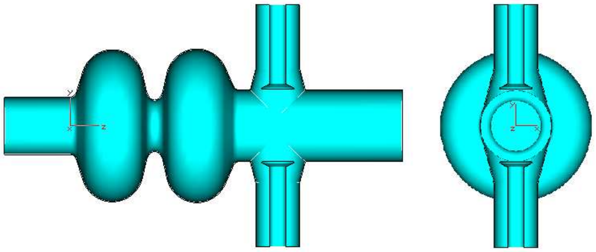

Figure 13: Symmetric twin-coaxial coupler with a two-cell cavity.

5 SUMMARY

High average power input couplers for superconducting cavities are complex technical devices that must perform simultaneously several difficult tasks, the primary of which are delivering RF power to the beam and separating an ultra-high vacuum, ultra-low temperature environment of cavities from an air-filled, room temperature transmission lines. Great progress has been made in achieving high power levels in operating conditions as well as in tests. Now, when the second generation of the couplers proved that multi-hundred kilowatt levels are reachable in operation, the new emphasis is on designing robust and reliable couplers with simplified manufacturing methods and reduced overall cost suitable for large-scale installations. If the second-generation designs were based to a large extent on the intra-laboratory experiences, it has become evident that new designs are based on the inter-laboratory experience and that cooperation between laboratories will benefit development of the next-generation high average power couplers.

6 REFERENCES

[1] H. P. Bohlen, "Advanced High-Power Microwave Vacuum Electron Device Development," *Proceedings of the 1999 Particle Accelerator Conference*, New York, NY, March 1999, Vol. 1, pp. 445-449.

[2] I. Campisi, "Fundamental Power Couplers for Superconducting Cavities," *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, September 2001.

[3] I. Campisi, "State of the Art Power Couplers for Superconducting RF Cavities," *Proceedings of the Eighth European Particle Accelerator Conference*, Paris, France, June 2002, pp. 144-148.

[4] C. Arnaud, et al., "Status Report on Superconducting Nb Cavities for LEP," *Proceedings of the 4th Workshop on RF Superconductivity*, August 1989, KEK, Tsukuba, Japan, Vol. 1, pp. 19-35, KEK Report 89-21.

[5] H.P. Kindermann, et al., "Status of RF Power Couplers for Superconducting Cavities at CERN," *Proceedings of the 5th European Particle Accelerator Conference*, Sitges, Barcelona, Spain, June 1996, pp. 2091-2093.

[6] H.P. Kindermann, M. Stirbet, "RF Power Tests of LEP2 Main Couplers on a Single Cell Superconducting Cavity," *Proceedings of the 8th Workshop on RF Superconductivity*, October 1997, Abano Terme (Padova), Italy, Vol. III, pp. 732-739.

[7] H. P. Kindermann, M. Stirbet, " The Variable Power Coupler for the LHC Superconducting Cavity," *Proceedings of the 9th Workshop on RF Superconductivity*, Santa Fe, NM, November 1999, pp. 566-569.

[8] B. Dwersteg, Qiao Yufang, "High Power Input Coupler Development at DESY," *Proceedings of the 4th Workshop on RF Superconductivity*, August 1989, KEK, Tsukuba, Japan, Vol. 2, pp. 605- 614, KEK Report 89-21.

[9] B. Dwersteg, "High Power Couplers," *Proceedings of the 4th Workshop on RF Superconductivity*, August 1989, KEK, Tsukuba, Japan, Vol. 1, pp. 351- 376, KEK Report 89-21.

[10] D. Metzger, et al., "Tests Results and Design Considerations for a 500 MHz, 500 kWatt Vacuum Window for CESR-B,"*Proceedings of the 1993 Particle Accelerator Conference*, Washington, DC, May 1993, pp. 1399-1401.

[11] H. Padamsee, et al., "Beam Test of a Superconducting Cavity for the CESR Luminosity Upgrade," *Proceedings of the 1995 Particle Accelerator Conference*, Dallas, TX, May 1995, pp. 1515-1517.

[12] E. Chojnacki, et al., "Tests and Designs of High-Power Waveguide Vacuum Windows at Cornell," *Particle Accelerators*, Vol. 61, pp. [309-319]/45-55, 1998.

[13] S. Belomestnykh and H. Padamsee, "Performance of the CESR Superconducting RF System and Future Plans," *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, September 2001.

[14] S. Noguchi, et al., "Couplers – Experience at KEK," *Proceedings of the 4th Workshop on RF Superconductivity*, August 1989, KEK, Tsukuba, Japan, Vol. 1, pp. 397-412, KEK Report 89-21.

[15] S. Mitsunobu, et al., "High Power Input Coupler for KEKB SC Cavity," *Proceedings of the 9th Workshop on RF Superconductivity*, Santa Fe, NM, November 1999.

[16] Y. Kijima et al., "Input Coupler of Superconducting Cavity for KEKB," *Proceedings of the 7th European Particle Accelerator Conference*, Vienna, Austria, June 2000, pp. 2040-2042.

[17] E. N. Schmierer et al., "Results of the APT RF Power Coupler Development for Superconducting Linacs," *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, September 2001.

[18] V. Nguyen et al., "Development of a 50 kW CW L-Band Rectangular Window for Jefferson Lab FEL Cryomodule," *Proceedings of the 1999 Particle Accelerator Conference*, New York, NY, March 1999, Vol. 2, pp. 1459-1461.

[19] B. Dwersteg, "SC-Cavity Operation via WG-Transformer," *Proceedings of the 4th Workshop on RF Superconductivity*, August 1989, KEK, Tsukuba, Japan, Vo2. 1, pp. 593-604, KEK Report 89-21.

[20] V. Veshcherevich and S. Belomestnykh, "Correction of the Coupling of CESR RF Cavities to Klystrons Using Three-Post Waveguide Transformers," Report SRF020220-02, Laboratory for Elementary-Particle Physics, Cornell University (2002).

[21] R.L. Geng, et al., "Experimental Studies of Electron Multipacting in CESR Type Rectangular Waveguide Couplers," *Proceedings of the Eighth European Particle Accelerator Conference*, Paris, France, June 2002, pp. 2238-2240.

[22] S. Bauer, et al., "Latest Results from the Production of 500 MHz SRF Modules for Light Sources and CESR Upgrade," *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, September 2001.

[23] M. Pisharody, et al., "High Power Window Test on a 500 MHz Planar Waveguide Window for the CESR Upgrade," *Proceedings of the 1995 Particle*

Accelerator Conference, Dallas, TX, May 1995, pp. 1720-1722.

[24] E. Chojnacki and S. Belomestnykh, "RF Power Coupler Performance at CESR and Study of a Multipactor Inhibited Coupler," *Proceedings of the 9th Workshop on RF Superconductivity*, Santa Fe, NM, November 1999.

[25] E. N. Schmierer, et al., "High-Power Testing of the APT Power Coupler," *Proceedings of the XX International Linac Conference (LINAC'2000),* Monterey, CA, August 2000, Vol. 2, pp. 944-946.

[26] T. Furuya, et al., "Operation Status of the KEKB Superconducting Damped Cavity," *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, September 2001.

[27] E. N. Schmierer, et al., "Design of the Spoke Cavity ED&D Input Coupler," *Proceedings of the 10th Workshop on RF Superconductivity*, Tsukuba, Japan, September 2001.

[28] M. Akemoto, et al., "High Power Input Coupler with a Cylindrical Alumina Window," *Proceedings of the 1991 Particle Accelerator Conference,* San Francisco, CA, 1991.

[29] G. Devanz, et al., "Preliminary Design of a 704 MHz Power Coupler for a High Intensity Proton Linear Accelerator," *Proceedings of the 7th European Particle Accelerator Conference*, Vienna, Austria, June 2000.

[30] I. Bazarov, et al., "Phase I Energy Recovery Linac at Cornell University," *Proceedings of the 8th European Particle Accelerator Conference*, Paris, France, June 2002, pp. 644-646.

[31] V. Shemelin, et al., "Low-Kick Twin-Coaxial and Waveguide-Coaxial Couplers for ERL," this workshop.

[32] W.-D. Moeller., "High Power Coupler for the TESLA Test Facility", *Proceedings of the 9th Workshop on Superconductivity,* New York, NY, March 1999, pp. 577-581.