OVERVIEW OF INPUT POWER COUPLER DEVELOPMENTS, PULSED AND CW*

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Abstract

While many successful high power fundamental input couplers have been developed over years for superconducting cavities, projects like the International Linear Collider (ILC), Energy Recovery Linacs (ERLs), Free Electron Lasers (FELs), and Superconducting RF (SRF) guns bring new challenges. As a result, a number of new coupler designs, both for pulsed and CW operation, was proposed and developed recently. In this paper a brief discussion of design options and technical issues associated with R&D, testing and operation of the high power couplers will be given first. Then we will review existing designs with an emphasis on new developments and summarize operational experience accumulated in different laboratories around the world.

INTRODUCTION

There are two primary functions of the RF input couplers for accelerating cavities:

i. RF input couplers are passive impedance matching networks designed to efficiently transfer power from an RF power source to a beam-loaded cavity operating under ultra-high vacuum conditions.
ii. As transmission lines, coaxial or waveguide, are usually filled with gas, couplers have to have RF-transparent vacuum barriers (RF windows).

In addition, input couplers have to fulfill several other requirements, some of which are specific to a particular machine or to use in superconducting cavities:

- An input coupler must serve as a low-heat-leak thermal transition between the room temperature environment outside and the cryogenic temperature (2 to 4.5 K) environment inside the cryomodule. Very extensive thermal simulations have to be performed during the design stage to minimize the heat leak and at the same time to avoid overheating of the input coupler components. Incorporating carefully placed thermal intercepts and/or active cooling in the coupler design might be necessary.
- The coupler design should conform to clean cryomodule assembly procedures to minimize the risk of contaminating superconducting cavities. Hence using two RF windows, warm and cold, is advisable for high accelerating gradient applications.
- In many cases input couplers are located on a cavity beam tube, in close proximity to the beam axis. This creates asymmetric cavity field perturbations, which can be detrimental to beam quality. Special measures, such as using double couplers or compensating stubs, may be required.
- If an accelerator has several different operating modes, an adjustable coupling may be required. This can be implemented either within the coupler envelope or by using an impedance matching device, e.g. a three-stub tuner, in the transmission line.
- Input couplers should be designed taking into consideration multipacting phenomenon.
- Minimizing RF conditioning time is very important and is still long in many cases. It is therefore mandatory to carefully plan handling, preparation, assembly and storage steps and procedures and to follow them.

Tables 1 and 2 list high-power CW and pulsed input couplers developed for superconducting cavities that are either already operational or have been tested at high RF power. While the tables do not include all existing couplers, they are representative of the field. The couplers listed are coaxial and waveguide, with RF windows of different shapes and sizes, operating at frequencies from 352 MHz to 1500 MHz.

HERA, LEP2, TRISTAN and CEBAF couplers are examples of the successful designs of the first generation of high-power couplers. They were part of the large superconducting cavity installations and demonstrated good performance. The subsequent generations were designed with the accumulated experience and knowledge in mind and in some cases were improved versions of the older designes. The input couplers have reached power levels of up to 1 MW CW and 2 MW pulsed.

Many aspects of the input coupler design, fabrication, preparation, RF conditioning, integration in cryomodules, interactions with beam, etc. have been discussed elsewhere and we refer the readers to previous overview papers [1 – 6]. Here we will review only most recent developments in the field.

FLASH / XFEL / ILC INPUT COUPLERS

FLASH (former TESLA Test Facility, TTF) is an FEL user facility based on the 1300 MHz superconducting TESLA technology. FLASH-type cryomodules will be used in the European XFEL project. Since a superconducting option was chosen for ILC, the TTF-III coupler was selected as a baseline. At the same time alternative coupler designs have been pursued as well.

TTF-III couplers

The TTF-III coupler [7], shown in Figure 1, is a more recent design in a series of couplers developed in the framework of TESLA collaboration. The coupler is of a coaxial antenna type with two cylindrical windows and adjustable coupling.

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Table 1: CW input couplers for superconducting cavities.

Facility	Frequency	Coupler type	RF window	Q_{ext}	Max. power	Comments
LEP2 / SOLEIL	352 MHz	Coax fixed	Cylindrical	2×10^6 / 1×10^5	Test: 565 kW 380 kW Oper: 150 kW	Traveling wave @ Γ=0.6
LHC	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	500 MHz	Coax fixed	Cylindrical	1.3×10^5	Test: 300 kW Oper: 65 kW	Traveling wave
CESR (Beam test)	500 MHz	WG fixed	WG, 3 disks	2×10^5	Test: 250 kW 125 kW Oper: 155 kW	Traveling wave Standing wave Beam test
CESR / 3rd generation light sources	500 MHz	WG fixed	WG disk	2×10^5 nominal	Test: 450 kW Oper: 300 kW 360 kW	Traveling wave Forward power
TRISTAN / KEKB / BEPC-II	509 MHz	Coax fixed	Disk, coax	1×10^6 / 7×10^4 / 1.7×10^5	Test: 800 kW 300 kW Oper: 400 kW	Traveling wave Standing wave
APT	700 MHz	Coax variable (±5 mm stroke)	Disk, coax	2×10^5 to 6×10^5	Test: 1 MW 850 kW	Traveling wave Standing wave
Cornell ERL injector	1300 MHz	Coax variable (15 mm stroke)	Cylindrical (cold and warm)	9×10^4 to 8×10^5	Test: 61 kW	Traveling wave
JLAB FEL	1500 MHz	WG fixed	WG planar	2×10^6	Test: 50 kW Oper: 35 kW	Traveling wave

Table 2: Pulsed input couplers for superconducting cavities.

Facility	Frequency	Coupler type	RF window	Q_{ext}	Max. power	Pulse length & rep. rate
SNS	805 MHz	Coax fixed	Disk, coax	7×10^5	Test: 2 MW Oper: 550 kW	1.3 msec, 60 Hz 1.3 msec, 60 Hz
J-PARC	972 MHz	Coax fixed	Disk, coax	5×10^5	Test: 2.2 MW 370 kW	0.6 msec, 25 Hz 3.0 msec, 25 Hz
FLASH	1300 MHz	Coax variable (FNAL)	Conical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 250 kW Oper: 250 kW	1.3 msec, 10 Hz 1.3 msec, 10 Hz
FLASH	1300 MHz	Coax variable (TTF-II)	Cylindrical (cold), WG planar (warm)	1×10^6 to 1×10^7	Test: 1 MW Oper: 250 kW	1.3 msec, 10 Hz 1.3 msec, 10 Hz
FLASH / XFEL/ ILC	1300 MHz	Coax variable (TTF-III)	Cylindrical (cold and warm)	1×10^6 to 1×10^7	Test: 1.5 MW 1 MW Oper: 250 kW	1.3 msec, 2 Hz 1.3 msec, 10 Hz 1.3 msec, 10 Hz
KEK STF	1300 MHz	Coax fixed (baseline ILC cavity)	Disks, coax (cold and warm)	2×10^6	Test: 1.9 MW 1 MW	10 μsec, 5 Hz 1.5 msec, 5 Hz
KEK STF	1300 MHz	Coax fixed (low loss ILC cavity)	Disk (cold), cylindrical (warm)	2×10^6	Test: 2 MW 1 MW	1.5 msec, 3 Hz 1.5 msec, 5 Hz

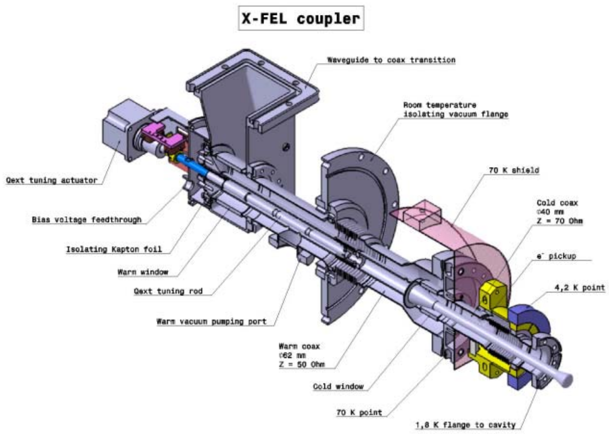

Figure 1: TTF-III input coupler for XFEL.

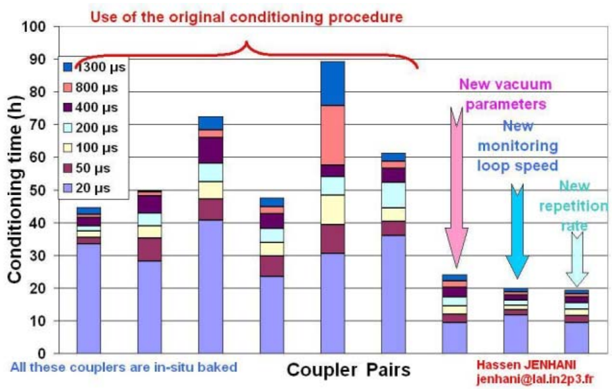

Figure 2: Improved RF conditioning time on the test stand at LAL-Orsay [8].

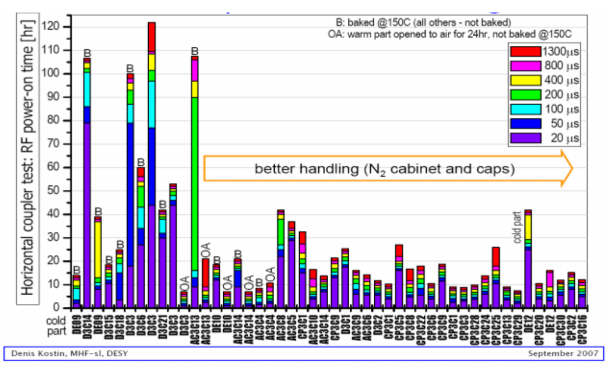

Figure 3: Re-conditioning time on cavities [9].

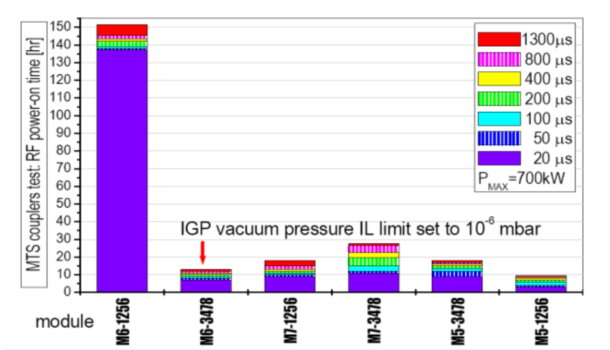

Figure 4: Re-conditioning on FLASH cryomodules [9].

While many TTF-III couplers operate reliably at FLASH, long RF conditioning time is an issue. A long experimental program has been carried out to reduce the conditioning time. An improved procedure, incorporating new vacuum parameters, monitoring loop speed and RF pulse repetition rate, was developed at LAL [8]. Implementing it led to reduction of the processing time on the input coupler tests stand to less than 20 hours (Figure 2). Further, improved handling of input couplers and adjusted RF conditioning parameters allowed significant reduction of the re-conditioning time on cavities and cryomodules (Figures 3 and 4) [9]. From Figure 3 one can make two important observations: 1) baking did not produce expected improvement of the conditioning time and 2) it was easy to re-process couplers after 24-hour air exposure.

At LAL-Orsay the XFEL team is performing industrialization study of input couplers' production [10]. Three companies were awarded study contracts to define the manufacturing processes and produce 2 prototypes in 2008. This study is a necessary and useful step toward the mass production (800 couplers for XFEL, 16000 couplers for ILC). Action plans, anticipation and organization will ensure fabrication, assembly and tests with minimum risks and at an optimized cost.

A call for tenders for the production of XFEL couplers will be initiated by LAL in the middle of 2008, based on functional specifications. There will be an extensive process control and close monitoring of the mass production, in order to guarantee a consistently good quality among the 800 couplers.

Input coupler for the KEK STF baseline cavities

A high power input coupler is designed for the STF baseline cavity system at KEK [11] as part of the ILC program. The coupler, which consists of a cold part and a warm part, has two TRISTAN-type coaxial disk RF windows. For simplicity and cost reduction it was designed with fixed coupling. Four couplers were fabricated and tested at high RF power from a 5 MW pulsed klystron. RF processing up to 1 MW with 1.5 msec long pulses and 5 Hz repetition rate (1.9 MW with short pulses) was successfully accomplished. One cavity for the STF Phase-0.5 was assembled with an input coupler and a tuning system. RF processing of the input coupler in the cryomodule was carried out at room temperature up to 250 kW with a 1.5 msec long pulse and 5 Hz repetition rate. First cool down and high power test of the cryomodule are scheduled for October 2007.

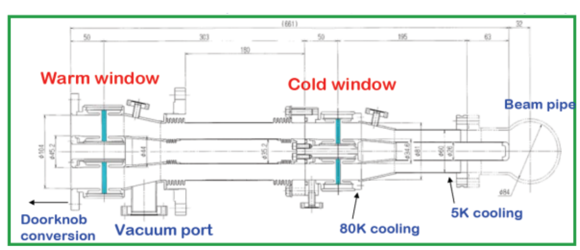

Figure 5: Drawing of the STF baseline cavity coupler.

Input coupler for the KEK STF LL cavities

An alternative ILC coupler design was developed at KEK for the Low-Loss (LL) shape cavity [12]. Main features of this so-called capacitive-coupling coupler, shown in Figure 6, are:

- Simple modular design.
- Capacitively coupled RF windows.
- Metal rod supported center conductor.
- Low static heat leak.

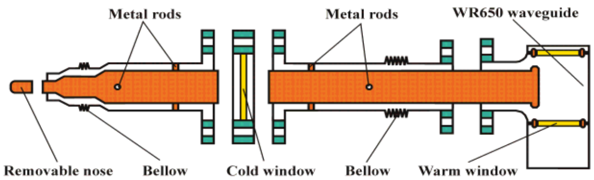

Figure 6: Conceptual drawing of the capacitive-coupling coupler.

High power test demonstrated that couplers of this design can successfully operate with 1.5 ms long pulses at power level up to 1 MW at 5 pps and 2 MW at 3 pps in the traveling wave mode and up to 500 kW at 5 pps in the standing wave mode. Like the coupler described in the previous subsection, a coupler of this design was assembled into a cryomodule and tested at room temperature up to 250 kW with a 1.5 msec long pulse and 5 Hz repetition rate [13].

COUPLERS FOR ERLS AND CW FELS

Several Energy Recovery Linacs and CW Free Electron Lasers projects, such as Cornell ERL, BESSY FEL, ERL in Japan, 4GLS, proposed to use TESLA technology in a modified form for CW operation. Higher thermal loads in this regime make modification of the input couplers mandatory. For example, CW tests of the TTF-III input coupler, performed by a collaboration of several laboratories, showed that while operation of up to 5 kW in the standing wave mode should be possible, the prudent way is to upgrade cooling of the coupler center conductor to lower its temperature and improve vacuum [14]. BESSY is pursuing this option [15].

Design of the input coupler for the ERL main linac in Japan is based on the input coupler design for the KEK STF baseline cavities (see above). For 20 kW CW operation the following modifications will be made: gas cooling of the center conductor will be added, the impedance will be changed from 50 Ohm to 60 Ohm, ceramics will be upgraded from 95% to 99.7% alumina. In addition, the coupler will be made adjustable [16].

Cornell ERL Injector Input Coupler

The design of the Cornell ERL Injector couplers (Figure 7) is based on the design of TTF III input coupler. It has, however, been significantly updated [17]:

- The cold part was completely redesigned using a 62 mm, 60 Ohm coaxial line (instead of a 40 mm, 70 Ohm line) for stronger coupling, better power handling and avoiding multipacting.
- The antenna tip was enlarged and shaped for stronger coupling.
- The “cold” window diameter was enlarged to that of the “warm” window.
- The outer conductor bellows design (both in warm and cold coaxial lines) was improved for better cooling: heat intercepts were added.
- Forced air cooling of the warm inner conductor bellows and “warm” ceramic window was added as well.

Recent high power test of the first production pair in a test cryostat demonstrated stable operation of couplers up to 61 kW CW in traveling mode [18]. These couplers (slightly modified) will be used in the ERL cryomodule developed by a collaboration of Daresbury, Cornell, LBNL, Rossendorf and Stanford [19].

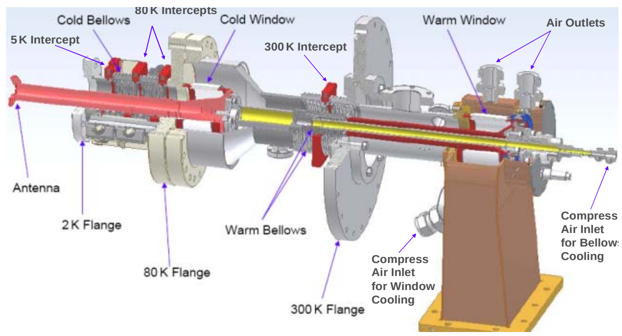

Figure 7: Cornell ERL injector input coupler.

INPUT COUPLERS FOR 3RD GENERATION LIGHT SOURCES

Operation of the third generation light sources requires delivery of hundreds of kilowatts of RF power to compensate particle beam energy losses to synchrotron dariation [20]. On the other hand, superconducting RF systems for these machines tend to be based on existing designs and technologies. This is why all these machines use high-power couplers reliability and robustness of which is proven by many years of operation in accelerators like CESR, LEP or KEKB. Couplers for light sources operate at frequencies from 352 MHz to 509 MHz and deliver RF power up to 270 kW CW.

EXPERIENS WITH SNS COUPLERS

The SNS coupler (Figure 8) is another successful variation of the TRISTAN input coupler, re-designed for 805 MHz. It is specified to deliver 550 kW peak / 48 kW average RF power. The SNS couplers were tested up to 2 MW peak power on a test stand and achieved over 500 kW in real cavity operation. While on the whole SNS couplers operate reliably, there are some operational difficulties [21]. A parasitic cavity-coupler interaction reveals itself in an electron current at the full traveling wave and is accompanied by radiation spikes. Vacuum cold cathode gauges, providing interlock signals for window protection, proved to be troublesome and unreliable in operation, often with an erratic signal character. It is difficult to adjust helium flow under changing average power and there is cryogenic cross-interaction between cavities in a cryomodule. Higher average power requirements for the SNS upgrade and more stable operation at 60 Hz repetition rate may require additional cooling.

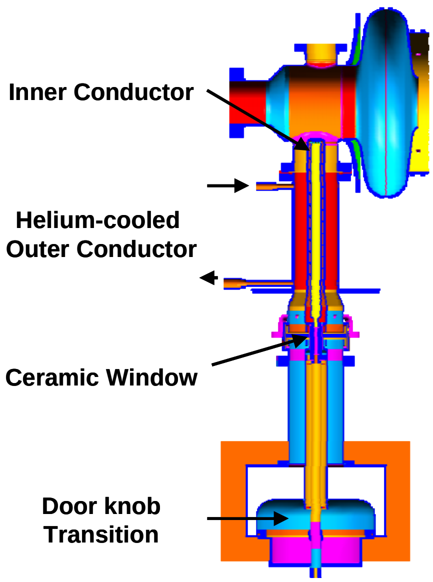

Figure 8: SNS input coupler.

SUMMARY

While new projects present ever more demanding requirements, new input coupler designs appear to be able to meet the challenges in terms of RF and thermal performance. Several new input coupler designs, both pulsed and CW, have been tested recently with very good results. In some cases the designs were based on successful existing couplers (TTF-III, TRISTAN) though often with significant upgrades and modifications. Progress is being made to improve coupler handling, preparation and RF conditioning time. Efforts to reduce the construction cost are under way, including industrialization study for XFEL couplers. In the era of large-scale projects like ILC and XFEL close cooperation between laboratories is extremely important.

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REFERENCES

[1] I. Campisi, “Fundamental Power Couplers for Superconducting Cavities,” *Proceedings of SRF’2001*, Tsukuba, Japan, p. 132.

[2] I. Campisi, “State of the Art Power Couplers for Superconducting RF Cavities,” *Proceedings of EPAC’02*, Paris, France, p. 144.

[3] S. Belomestnykh, “Review of High Power CW Couplers for Superconducting Cavities,” *Proceedings of the Workshop on High-Power Couplers for Superconducting Accelerators*, Newport News, VA, 2002.

[4] B. Rusnak, “RF Power and HOM Coupler Tutorial,” *Proceedings of SRF’2003*, Luebeck, Germany, 2003.

[5] T. Garvey, “The Design and Performance of CW and Pulsed Power Couplers – A Review,” *Proceedings of SRF’2005*, Ithaca, NY, p. 423.

[6] A. Variola, “High Power Couplers for Linear Accelerators,” *Proceedings of LINAC 2006*, Knoxville, TN, p. 531.

[7] B. Dwersteg, *et al.*, “TESLA RF Power Couplers Development at DESY,” *Proceedings of SRF’2001*, Tsukuba, Japan, p. 443.

[8] A. Variola, private communications, October 2007.

[9] D. Kostin, *et al.*, “Testing the FLASH Superconducting Accelerating Modules,” this workshop, WEP05.

[10] S. Prat and W.-D. Moeller, “Industrialization Process for XFEL Power Couplers and Volume Manufacturing,” this workshop, TH202.

[11] E. Kako, *et al.*, “High Power Input Coupler for the STF Baseline Cavity System,” this workshop, TUP60.

[12] H. Matsumoto, *et al.*, “A New Design for a Superconducting Cavity Input Coupler,” *Proceedings of PAC’05*, Knoxville, TN, p. 4141.

[13] T. Saeki, *et al.*, “The First Processing of Capacitive-coupling Coupler at Room Temperature in a Cryomodule at STF,” this workshop, WEP45.

[14] J. Knobloch, *et al.*, “CW Operation of the TTF-III Input Coupler,” *Proceedings of PAC’05*, Knoxville, TN, p. 3292.

[15] J. Knobloch, *et al.*, “CW Operation of Superconducting TESLA Cavities,” this workshop, TUP40.

[16] H. Sakai, *et al.*, “Design of the Input Coupler for the ERL Main Linac in Japan,” *Proceedings of ERL’07*, Daresbury, UK

[17] V. Veshcherevich, *et al.*, “Design of High Power Input Coupler for Cornell ERL Injector Cavities,” *Proceedings of SRF’2005*, Ithaca, NY, p. 590.

[18] V. Veshcherevich, *et al.*, “High Power Tests of Input Couplers for Cornell ERL Injector,” this workshop, WEP26.

[19] P. A. McIntosh, *et al.*, “Realisation of a Prototype Superconducting CW Cavity and Cryomodule for Energy Recovery,” this workshop, WEP26.

[20] S. Belomestnykh, “Superconducting RF in Storage-Ring-Based Light Sources,” this workshop, MO302.

[21] Sang-ho Kim, private communications, October 2007.