

THE DESIGN AND PERFORMANCE OF CW AND PULSED POWER COUPLERS – A REVIEW*

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Abstract

The design of input power couplers represents one of the most important challenges of accelerators that use super-conducting RF technology. These devices must fulfil several functions while being subject to mechanical, electromagnetic, vacuum and cryogenic constraints. The rapidly increasing number of projects, planned or under construction, which propose to use super-conducting cavities has prompted developments in power couplers for both CW and pulsed applications. Amongst the projects for which couplers have, or are being, developed one finds VUV and X-ray free electron lasers (based on self-amplified spontaneous emission), spallation neutron sources (SNS), energy recovery linacs, and high energy colliders. We will review the design requirements and performances obtained for several of these couplers. Particular attention will be paid to the couplers which have been used on the TESLA Test Facility at DESY, the variations of this coupler which are under consideration for future synchrotron light sources and the coupler chosen for use on the SNS.

INTRODUCTION

The rapid advance in the achievable gradients of superconducting cavities over the last two decades, along with the emergence of accelerator projects requiring high beam power, has meant that input power couplers must meet ever increasing performance requirements. Although the principal function of the power coupler is to optimally transfer energy from the RF source to the cavity, the coupler is faced with numerous auxiliary functions. It is required to preserve the cleanliness of the superconducting cavity, play the role of vacuum barrier between the cavity and the feeder waveguide (WG), allow some mechanical flexibility for alignment and thermal dilatation effects, permit variable coupling strength (external Q) and minimise static and dynamic thermal losses. In addition, the coupler must be equipped with the minimum of diagnostic elements to allow its safe operation. All of these constraints imply that careful design, from a mechanical, thermal and electromagnetic point of view, is mandatory for the success of any coupler project. An excellent review of coupler design can be found in reference 1. In this paper we will discuss the requirements and performances of relatively new coupler designs. Note that we will treat only linear accelerator projects, in progress or under study. Older accelerator

projects whose couplers have already been well documented (for example, TRISTAN, KEK-B, HERA, CESR, LEP etc.....) will not be covered in this review.

MANUFACTURE AND TESTING

As noted above, careful design is required to ensure coupler performance. Numerous commercial codes exist with which one can check the electromagnetic and thermal properties of any proposed coupler. Multipactor simulations are also used to guide the geometrical form of the coupler [2]. Once the design is complete the coupler may then be manufactured. This requires the application of numerous delicate technologies. In general, power couplers employ high-purity alumina (Al_2O_3) ceramic “windows” brazed onto the metallic guide (co-axial or WG) as a vacuum barrier. As the alumina has a high secondary electron emission (SEE) coefficient it is necessary to deposit a thin coating (~ 10 nm) of titanium-nitride on any ceramic surface exposed to vacuum in order to suppress multipactor. Thin (several skin-depths) copper coatings are used on stainless steel surfaces carrying RF in order to reduce Joule losses. This operation is particularly delicate on bellows, which are used to provide mechanical flexibility and permit variations in Q_{ext} . The construction of the different coupler parts also requires delicate welding and brazing operations which must yield smooth, defect free, RF surfaces. As parts of the coupler will share a common vacuum with the superconducting cavity the same care and attention which is given to cavity surface cleanliness must be accorded also to coupler parts, where possible.

Coupler conditioning

‘Conditioning’ or ‘processing’ is the procedure whereby the couplers are gradually exposed to higher peak and average powers up to and beyond their nominal operating values. This is necessary to validate the performance of the coupler before use in an accelerator and can be required to be repeated after some period of cryogenic operation. The conditioning must be performed in a safe and controlled manner through the use of interlocks associated to the coupler diagnostics (electron pick-ups, photo-multipliers, temperature sensors, vacuum levels, spark detectors) and the RF distribution (reflected and transmitted power). It is frequently convenient to test couplers in pairs as the RF windows isolate the up and downstream WG from the coupler vacuum (Fig. 1). When first exposed to RF power, dramatic increases in pressure are observed in the coupler vacuum, accompanied by the

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presence of electron signals. These vacuum bursts may appear at specific values of power which correspond to multipactor resonances. The impact of the multipacting electrons on the coupler surfaces results in a desorption of the adsorbed gases which in turn diminishes the multipactor intensity, presumably through a reduction in the SEE coefficient. This ‘processing’ of the surface must be continued until the vacuum bursts and electron signals no longer appear for any conceivable operating power of the coupler. The time required for this conditioning can be very different from one coupler to another. The reasons for these differences, and the search for faster conditioning procedures, remain a subject of great interest. In general, such tests are performed at ambient temperature for simplicity but the definitive test requires operation at cryogenic temperatures.

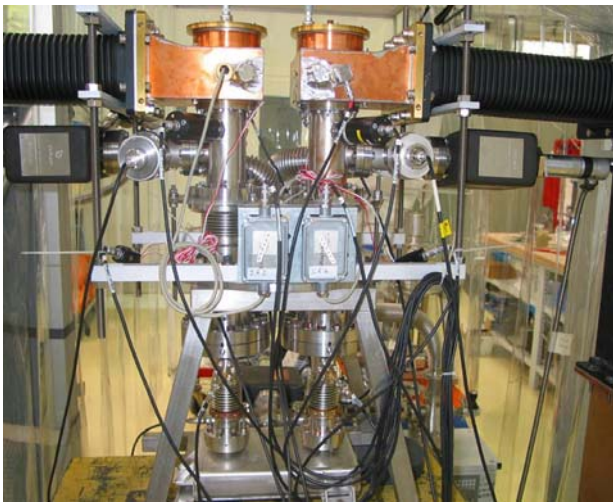


Figure 1. A pair of TTF-III couplers mounted on their test bench at LAL-Orsay.

PULSED POWER COUPLERS

There are two examples of such couplers, transmitting powers in the several 100 kW region, in operation to date. These projects are the Spallation Neutron Source, currently being commissioned in the USA and the TESLA Test Facility Linac (TTF) at DESY (Hamburg). One should note that KEK also have plans for a superconducting proton linac using cavities at 972 MHz. Couplers capable of transmitting 300 kW peak power for pulses of 3.0 ms / 25 Hz are being developed. Tests have shown that the couplers can handle this power. These couplers are based on the KEK-B design and have features common to the SNS design discussed below. Generally speaking, pulsed operation has the advantage that it leads to reduced average power requirements. However, pulsed operation brings other problems. The transient full power reflection on each pulse results in a standing wave, producing increased electric fields in the coupler. Each location in the coupler sees a continuously varying RF phase from the time at which one begins to fill the cavity until the “steady-state” amplitude has been reached. This can result in increased gas desorption from RF surfaces. Thermal and mechanical stresses can also be

induced by these transients and their long-term effects on the coupler performance are difficult to predict. The experience obtained with TTF will be of great importance for future pulsed SC accelerators such as the European X-ray FEL and the International Linear Collider (ILC).

The SNS Coupler

The Spallation Neutron Source (SNS), for condensed matter studies, will use a superconducting H⁻ accelerator currently being commissioned at Oak Ridge (Tennessee) by a collaboration of U.S. Department of Energy (DoE) laboratories [3]. The SNS has 81 cavities operating at 805 MHz and each powered by an individual 50 Ω co-axial coupler. The chosen coupler is a scaled version of the 508 MHz coupler successively used on KEK-B, modified to meet the constraints of the SNS cryomodule. The coupler specification is given in Table 1. A schematic of the coupler is shown in Fig. 2. The outer conductor on the vacuum side of the assembly is double-walled, copper plated, stainless steel, cooled by helium gas. The antenna is made from high purity copper. The outer co-ax of the air side is made from copper plated stainless steel, while the inner co-ax is made from high purity copper, cooled by water. The alumina ceramic disk window is TiN coated

Table 1. Power specification of the SNS coupler

Parameter	operation	processing
Impedance	50 Ω	50 Ω
Peak power	550 kW	2.4 MW
Pulse length	1.3 ms	1.3 ms
Repetition rate	60 Hz	60 Hz
Average power	53 kW max.	Klystron limit
D.C. bias	± 2.5 kV	± 2.5 kV

on the vacuum side. Matching to the WR-975 waveguide is achieved through a door-knob type transition. A 0.15 μm thick kapton layer insulates the outer and inner

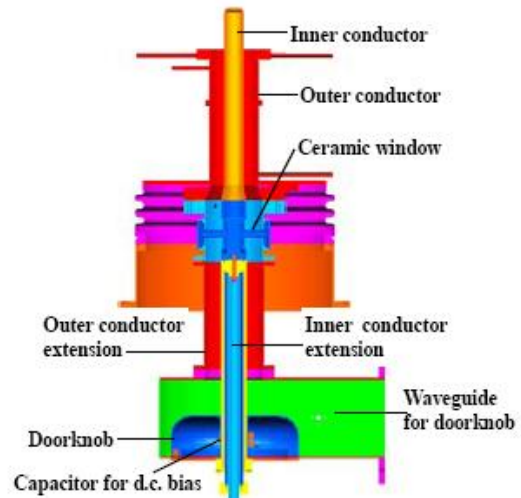


Figure 2. Schematic of the SNS Power Coupler.

co-axial parts to allow D.C. bias to be applied as an anti-multipactor measure [4]. The SNS power couplers have all been successfully tested to 1 MW peak power in travelling wave mode and 500 kW under full reflection.

The TTF Couplers

The TESLA Test Facility Linac was built as a prototype of the proposed TESLA collider. At the time of writing, there are three different coupler types used on TTF. These different couplers are the result of a continuous development programme. The power specifications of the TTF coupler, as well as the projects for which it is a prototype, are shown in table 2. For the case of the TTF and TESLA (500 GeV) couplers the heat loads at 2 K, 4 K and 70 K should not exceed 0.06 W, 0.5 W and 6 W respectively. An early design of TTF coupler came from the Fermi National Accelerator Laboratory [5]. It employs a ceramic WG window at room temperature to isolate the co-axial coupler from the feeder WG. A second, cold (70 K), window was formed from a conical ceramic mounted at the Brewster angle to the incident RF wave. The use of two windows on the TTF couplers was considered to be an important measure of security to reduce the accidental loss of vacuum in a module (or string of modules) should a single ceramic break.

Table 2. TTF / TESLA / X-FEL coupler specifications

Coupler	TTF	TESLA 500 GeV	TESLA 800 GeV	X-FEL
Beam power (kW)	208 kW	230 kW	925 kW	200 kW
Pulse length	1.33 ms	1.37 ms	1.33	1.33
Rep. rate	10 Hz	5 Hz	4 Hz	10 Hz
Q_{ext}	$10^6 - 10^7$	3×10^6	2.5×10^6	$10^6 - 10^7$

Variable coupling is possible through the use of bellows on the inner and outer co-axial lines which allow the antenna penetration into the beam pipe to be varied. Despite early problems with vacuum leaks on bellows and a lack of adhesion of copper plating on stainless steel, twelve of these couplers have operated routinely on TTF. An alternative coupler (TTF-II), designed at DESY, uses a warm WG window and cold cylindrical window, [6]. The latter has the advantage that it reduces the ceramic area exposed to the “line-of-sight” of the cavity beam pipe. Early experience with the CEBAF windows indicated that they could become electrically charged, and subsequently flash over, when exposed to the beam pipe. A more recent design (TTF-III) replaces the WG window with a cylindrical window in the transition [7]. This avoids having the transition under vacuum. The “warm” part of TTF-III is a 50 Ω, 62 mm external diameter co-ax, whereas the cold part is a 70 Ω line of 40 mm diameter to adapt to the TESLA cavity input flange. The antenna can be moved axially by adjusting a threaded screw at the

extremity of the air side of the coupler thus allowing variable Q_{ext} . As usual, the possibility of applying D.C. bias exists but little operational need for it has been found up till now. Presently, 19 couplers of type TTF-II and 11 couplers of type TTF-III have been used on the TTF linac and found to meet their specification. They have all passed 1 MW tests (1.3 ms, 2 Hz) on warm tests stands. Indeed the TTF-III coupler has been tested on a cavity with beam at a gradient of 35 MV/m (600 kW, 5 Hz). This last point being of particular interest for the future ILC project. Nevertheless, the couplers still exhibit rather long conditioning times (70 – 120 hours on a warm test stand). A schematic of the coupler is shown in Fig. 3.

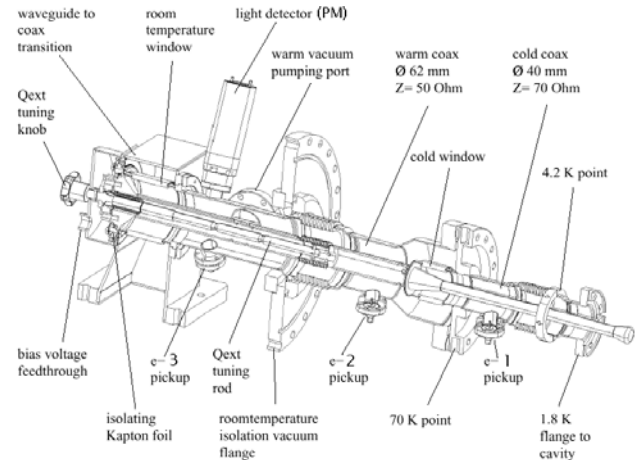


Figure 3. Schematic drawing of the TTF-III coupler.

The TTF-III coupler has been chosen for the European X-FEL. This ambition project will require almost 1,000 power couplers. As discussed above, many technologies are necessary for the production of these couplers and some effort is required to reduce the unit cost of these devices. Industrial studies of this coupler will be performed within the framework of a DESY / LAL-Orsay collaboration. A complete set of engineering drawings has been prepared, with support from the European Union CARE (Co-ordinated Accelerator Research in Europe) initiative, in order to prepare competitive tendering for the studies (Fig. 4).

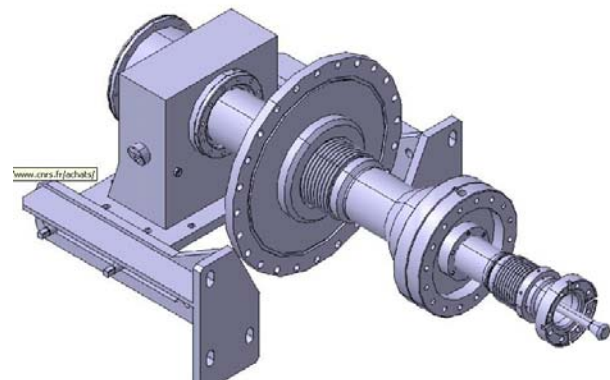


Figure 4. CAD image of the X-FEL Coupler.

CONTINUOUS WAVE COUPLERS

The success of the TESLA collaboration has led to proposals of other projects using TESLA technology. In particular, designs for Energy Recovery Linacs (ERL's) as drivers for ultra-high brightness X-ray sources using TESLA type cavities have emerged. The Cornell ERL injector plans to employ five two-cell cavities each delivering 100 kW (1 MV at 100 mA or 3 MV at 33 mA) of CW power to the electron beam [8]. Having chosen the TESLA cavity geometry it is then natural to consider using TTF-III couplers. However, this coupler, as noted above, was only designed for an average power of ~ 3 kW. The limited power-handling capability, due to excessive heating, was confirmed in tests, first at Rossendorf and then at BESSY, where this coupler is under consideration for the BESSY Free Electron Laser [9]. The Cornell group has made a number of revisions to the TTF-III coupler to reduce its thermal losses. Using extensive thermal (ANSYS) and electromagnetic (Microwave Studio) simulations they were able to determine the modifications necessary to reduce heating (forced air cooling of the warm window and warm inner conductor, additional heat sinks on the warm and cold bellows). They use a 62 mm external diameter coupler having an impedance of 46 Ω and 60 Ω for the warm and cold part respectively. Full details can be found in [10]. They have designed a twin co-axial coupler with each "twin" capable of transmitting 75 kW CW. The use of a twin coupler has the added advantage that the transverse fields on the beam axis are greatly reduced therefore reducing the transverse 'kick' given to the beam (Fig. 5). Such kicks can result in a dilution of the beam emittance, highly undesirable for an X-ray source.

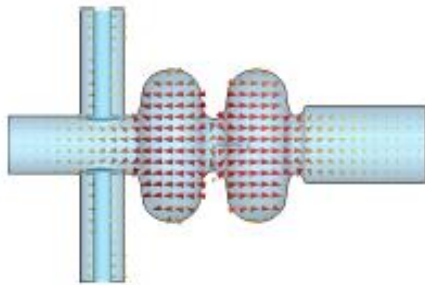


Figure 5. Schematic illustration of the twin coupler of the Cornell ERL injector cavity.

Spiral – II

Spiral-II is a radio-active ion beam project, recently approved by the French funding authorities, to be built at the GANIL laboratory [11]. This project will use superconducting, $\beta = 0.07$ and 0.12, Quarter Wave Resonators (QWR) operating at 88 MHz. Input couplers are required to transmit 20 kW power continuously to the ion beam with 1.4 MV resonator gap voltages. At the present time, two couplers are under study, using thermal and RF simulations, and both will be tested in the near future at the LPSC laboratory in Grenoble, France [12]. The couplers employ disk and cylindrical (Fig. 6)

windows respectively. Simulations indicate that both coupler designs are well matched (reflection less than -32 dB) and have acceptable field values



Figure 6. Proto-type of cylindrical window coupler for SPIRAL-II.

COUPLERS UNDER DEVELOPMENT

ILC Coupler Proposals

Although the TTF-III coupler appears to meet the power requirements of the International Linear Collider there are still questions to be raised concerning its unit cost and the time required to condition them. Consequently a number of alternative designs are under consideration for the ILC. In particular, disk-type window based couplers are being developed with larger (~ 60 mm) outer co-ax diameters than that of TTF-III with the aim of increasing the power handling capacity and pushing up the multipactor threshold levels. The company AMAC, supported by a DoE SBIR grant are developing such a coupler in collaboration with DESY and CPI (Fig. 7). Proto-types are currently being tested with some encouraging results [13].



Figure 7. The AMAC coupler developed for TESLA /ILC.

At Orsay, two couplers are being studied in the context of a DESY-LAL collaboration. The first (TW60) uses disk type windows (Fig. 8), while the second (TTF-V) uses cylindrical windows. The TW60 coupler uses a thin ceramic disk brazed into the co-axial line as a warm window. Global matching of the coupler to the WG is achieved by a reduced height WG part. The cold window is also a thin disk, matched this time by inductive sections in the co-axial line. The multipactor characteristics of such a "travelling wave" window have been analysed in [14]. The TTF-V coupler has essentially a TTF-III warm assembly, whereas the cold part is a 62 mm, 50 Ω co-axial

line, intended to allow higher power transmission than TTF-III and to push the multipactor levels to higher values. Such a coupler may be of interest should the ILC adopt a 'superstructure' cavity (2 x 9 cell).

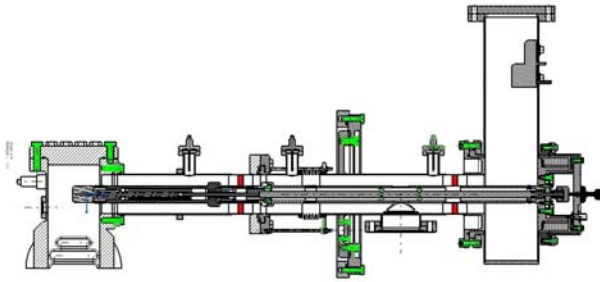


Figure 8. Schematic drawing of the TW60 Coupler.

SUMMARY

Despite the increasingly demanding requirements being placed on input couplers for superconducting cavities, new designs appear to be able to meet the challenges in terms of RF and thermal performance (e.g. the SNS and TTF power couplers). This is due to careful design work on both electromagnetic and thermo-mechanical aspects. Nevertheless, challenges remain if one wishes to reduce the construction costs of these devices and find new, faster, ways of conditioning them. Future projects (ILC, X-FEL, ERL's, Advanced Driver Systems) will need to meet these challenges.

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