POWER COUPLERS FOR THE ILC*

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Abstract

Fundamental Power Couplers are critically important components in all superconducting accelerators. Power couplers provide the vacuum and thermal interface between the superconducting cavity and the room temperature waveguide components and transmit microwaves generated by the high power microwave source. Power couplers must be extraordinarily clean and reliable to ensure that they meet the stringent requirements associated with superconducting accelerators. CPI power couplers are manufactured to our customer's specifications using processes which are standard to the vacuum electron device industry as well as processes which are specific to power couplers. To meet our customer's requirements, we have developed the capability of plating high residual resistivity ratio (RRR) copper on stainless steel. Plating is done in-house under carefully controlled conditions. Our high-RRR-copper plating has been qualified by CNRS-Orsay and Cornell. We have developed the capability of applying TiN coatings to ceramic windows. TiN coating is done in-house under carefully controlled conditions. Our TiN coating process has been qualified at DESY. Using these processes, CPI has manufactured over 50 power couplers of various designs. This year we will manufacture an additional 50 power couplers. This paper will focus on power couplers for the International Linear Collider (ILC). In particular, we will discuss some of the challenges to be faced during the manufacture of tens of thousands of power couplers for the ILC. These challenges were identified during our recent cost study for the ILC RF Unit [1].

POWER COUPLERS BUILT BY CPI

The Beverly Microwave Division of Communications & Power Industries, Inc. (CPI) has been fabricating power couplers for superconducting linear accelerators since 2000. Table 1 lists the power couplers built at CPI during that time frame. Typically, power couplers are designed by researchers at either a national laboratory, a university, or a small business. As the manufacturer, CPI provides engineering support to ensure that the design is manufacturable using our vacuum electron device fabrication processes. While prototypes may be built and tested as part of the production process, they are always delivered to the customer.

CPI started building power couplers in collaboration with AMAC International. The VWP1133, VWP1162, and VWP1136 power couplers were designed by AMAC in collaboration with CPI under SBIR and STTR programs, with CPI IR&D support. CPI then fabricated 32 TTF3 (VWP1137) power couplers for CNRS-Orsay. This production program involved very close collaboration between CPI, CNRS-Orsay, and DESY. We are currently manufacturing 42 additional TTF3 (VWP3049) power couplers for DESY and Fermilab as well as 10 power couplers for Cornell. Figure 1 shows the VWP1137 (TTF3) power couplers prior to final assembly. CPI has also fabricated power couplers designed by Fermilab and Advanced Energy Systems, Inc. (AES).

Table 1: CPI Power Couplers

CPI Model Number	**Accelerator Application**	**Freq. (MHz)**	**Peak and Average Power (kW)**	**Cooling**
VWP 1133	Spallation Neutron Source Prototype [2]	805	1000 and 60	water or air
VWP 1162	Rare Isotope Accelerator Prototype (MSU) [3]	805	1000 and 10	air
VWP 1137 (TTF3)	Tesla Test Facility (CNRS Orsay) [4]	1300	1100 and 7.2	air
VWP 1136	Tesla Test Facility (AMAC) [5]	1300	1100 and 7.2	air
VWP 3032	Energy Recovery Linac (Cornell) [6]	1300	75 and 75	air
VWP 1185/86	Free Electron Laser Injector (AES) [7]	748	350 and 350	water and helium
VWP 3038	Third Harmonic Accelerating Cavity (Fermi) [8]	3900	45 and 12.5	air
VWP 3049 (TTF3)	ILC Test Area (Fermi) and Tesla Test Facility (DESY)	1300	1100 and 7.2	air

INDUSTRIALIZATION OF POWER COUPLERS

CPI Beverly Microwave Division is an ISO9001:2000 and AS9100 certified organization that "designs and manufactures microwave devices and subsystems including solid state components, power supplies, and vacuum electron tubes." Our expertise in the design and manufacture of vacuum electron devices is directly

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applicable to the fabrication of power couplers. Vacuum electron devices, also known as microwave tubes, are very similar in technology and in manufacturing quantities to power couplers. Both involve ceramic to metal seals, joining of dissimilar metals at high temperatures, and require operation at ultrahigh vacuum levels and at very high microwave field levels. Vacuum electron device manufacturers are well suited to address the industrialization of power couplers.

From the manufacturer's perspective, there are several key aspects to industrialization of power couplers. The goal of industrialization is to take a preliminary design and refine it so that the power couplers can be manufactured at a minimum cost for the required quantity while retaining all key attributes. Key processes need to be developed and / or transferred to the manufacturer and validated. Manufacturing tolerances which are initially specified by the designer need to be challenged, relaxed where appropriate, and kept tight where necessary. Fixtures need to be designed, used, and refined. Knowledge must be transferred from the designer to the manufacturer. All of this requires that a reasonable quantity of power couplers be fabricated by the manufacturer.

Figure 1: VWP1137 (TTF3) power couplers prior to final assembly.

Industrial Manufacturing Capabilities Developed at CPI for Power Couplers

Several key manufacturing processes were developed at CPI during the fabrication of VWP1137 and VWP3049 (TTF3) couplers for CNRS-Orsay and DESY. We developed a high-RRR electroplating process for copper on stainless steel as well as a process to deposit an anti-multipactor TiN coating on surfaces. The high RRR copper plating process was qualified by CNRS-Orsay [9]· The TiN coating process was qualified by DESY.

The high RRR copper-plating process is an electroplating process. Details of this process are proprietary to CPI. Plating the TTF3 bellows was the most challenging, requiring significant process development. The design criteria for copper coating the TTF3 coupler bellows are:

- RRR ≥ 30 after baking at 400°C
- Thickness of 10 μm and 30 μm ±30% tolerance
- Sufficient adhesion with low hydrogen content
- Surface roughness Ra < 1.6 μm
- Nickel flash ≤ 1 μm

For the qualification process, copper-plated stainless steel strips were provided as samples to CNRS-Orsay. The RRR of as-received samples were in the range 20–46 with RRR values exceeding 100 after vacuum annealing at 400°C for 1 hour [9].

We chose to replicate the TiN coating process developed at DESY [10]. The TiN coating process involves the deposition of thin TiN films on alumina ceramics in a reactive ammonia atmosphere. TiN-coated copper test samples were provided to DESY. The multipacting behavior of these samples were measured in DESY's 500 MHz resonator, which was specifically built for multipacting tests on copper samples. Figure 2 shows the results of these tests. Sample 1 is an uncoated copper sample which exhibits 3000 s of multipacting time. An as-received TiN-coated sample, sample 2, reduces the multipacting duration to 800 s. The third measurement was done after the TiN-coated sample was cleaned in an ultrasonic bath, rinsed with isopropanol, dried with N_2 gas and baked at 200°C for 12 hours. These steps reduce the multipacting duration to 200 s. These measurements prove that the TiN coating composition and thickness are sufficient to suppress multipacting.

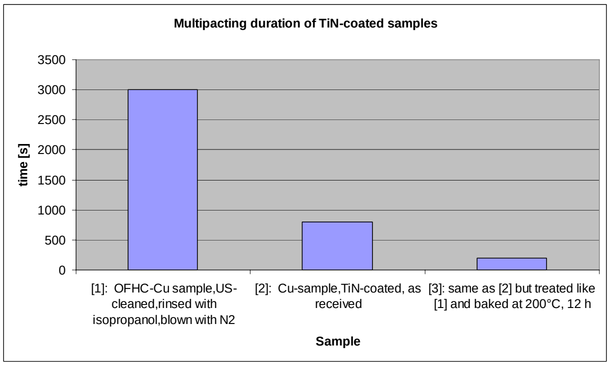

Figure 2: Results of DESY measurements on CPI samples showing multipacting duration of TiN-coated samples. Data provided by Arne Brinkmann of DESY.

Highlights of ILC Cost Study

CPI, AES and Meyer Tool and Mfg. Co. performed a cost study for Fermilab of 1, 250, and 750 RF Units for the ILC [1]. A single RF Unit is comprised of 3 cryomodules in series powered by a single RF power system. A single RF Unit contains 24 power couplers. CPI Beverly Microwave Division performed the power coupler cost study using the XFEL coupler, as specified in the Global Design Effort's Reference Design Report. While the cost data details are proprietary to CPI, several parameters can be summarized here. As part of this cost study, we provided an estimate for the fabrication, cleaning, assembly, and conditioning of 24, 6000 and 18,000 power couplers. Since at the outset of our cost study the most likely quantity to be manufactured by a single vendor was 6000 power couplers, we focus on that quantity here.

Fabrication cost estimates were based upon our experience building 32 TTF3 power couplers. At least two vendor quotes were obtained for all piece parts. Labor hours were estimated for each assembly step based on engineering estimates and history. Material costs constituted 45% of the total cost. Labor and overhead constituted 50% of the total cost. Fabrication equipment procurement costs made up the remaining 5% of the total cost of fabricating 6000 power couplers. Assembly labor made up 83% of the total labor to fabricate the power couplers.

We estimated the cost to clean and assemble and condition the fabricated power couplers based upon published data from CNRS-Orsay [11,12]. To date, industry has only fabricated power couplers with clean-room assembly and conditioning occurring entirely at national laboratories. In our cost study, a 90% learning curve was assumed as was 20 hours of average conditioning time. The overall cost to clean and assemble and condition 6000 power couplers was 26% of the total cost of power couplers. Our cost study included the cost of all capital equipment required to clean and assemble and condition the power couplers.

Challenges Building Couplers for the ILC

Several challenges were identified during our cost study. Fabricating, assembling, and conditioning 6000 power couplers over a 5 year period will require a significant effort. Fixtures will need to be designed and qualified to enable the fabrication of 5 power couplers per day. Additional fabrication equipment such as e-beam welders, TIG welders, vacuum furnaces, and copper-plating tanks will need to be procured and installed. RF conditioning stations, outgassing furnaces, a class-10 clean room, and wet process cleaning stations will be required for the cleaning, assembly, and conditioning of 6000 power couplers. Some significant facilities rearrangement will also be required to accommodate this additional capital equipment. Based on our cost model, approximately 44 skilled direct-labor employees will need to be hired and trained and employed for the duration of the program. Documentation tailored for large scale production will need to be carefully prepared and validated. Key process controls will need to be established and tested and refined to ensure that no manufacturing problems occur during the production program. Materials procurement strategies will need to be evaluated to minimize cost while keeping inventory to a manageable level. These challenges are not unique to the manufacture of power couplers. They are very similar to the challenges associated with many products CPI currently manufactures for military applications. Key elements to success include the fabrication of prototypes, low rate initial production (LRIP) runs and close cooperation between the manufacturer and the customer.

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