ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV017

PROCESSING AND TEST RESULT OF 650 MHz 50kW CW PROTOTYPE COUPLERS FOR PIP-II PROJECT

N. Solyak, B. M. Hanna, S. Kazakov, Fermilab, Batavia, Illinois, USA

Abstract

For PIP-II project Fermilab is developing 650 MHz couplers to deliver up to 50kW CW RF power to the superconducting low-beta (LB650) and high-beta (HB650) cavities. To meet project requirements two different designs of the couplers were proposed, one is conventional design with copper plated stainless steel walls. In second design (EM-shielded) a copper screen is used to shield stainless steel wall from electromagnetic field. For prototyping we built two couplers of each type and tested them at 50kW with full reflection at different reflection phases. In each test the assembly of two couplers were processed with DC bias up to +5kV, starting with short pulses and ramping power up to 100kW. Final run for 2 hours in CW mode at 50kW to reach equilibrium temperature regime and qualify couplers. One pair of couplers was also processed without DC bias. Finally, all four couplers demonstrated full requirements and were qualified. Based on test results the conventional coupler with some modification was chosen as a baseline design. Modified version of coupler is now ordered for prototype of HB650 cryomodule. In paper we will discuss details of coupler processing and results.

INTRODUCTION

The PIP-II/LBNF/DUNE project will be the first internationally conceived, constructed and operated mega-science project hosted by the Department of Energy of the United States [1]. The PIP-II project represents the upgrade plan of Fermilab accelerator complex. It will lead to the construction of world's highest energy and the highest power CW proton Linac reaching 800 MeV. Five types of cryomodules will be built to achieve this performance. For the highest energy part of this Linac, the LB650 and HB650 cryomodules equipped with 650 MHz Superconducting (SC) cavities are used. The same 650 MHz Power Coupler (PC) design will be used for both low-beta (LB650) and high-beta (HB650) cavities. PIP-II requires that coupler should work in 50kW CW regime with 20% power reflection. Before installation to the cavity each coupler should be tested and conditioned at the room temperature test stand. Power requirements for the test stand more stringent: 50kW with full reflection at any reflection phase to have more margin during long time coupler operation in cryomodules.

COUPLER PROTOTYPING

During project R&D phase two design modifications of the coupler were developed, built and tested [2,3]. First design called conventional is shown in Fig. 1. In second design stainless steel outer conductor in vacuum part is shielded from electro-magnetic (EM) fields by copper screens, as shown in Fig. 2. It allows minimize cryogenic heat loads at 5K and 50K and eliminate copper plating on vacuum surfaces in vicinity of SC cavity (no flakes, no contaminations). All rf losses will be in copper. The only difference between two designs is a vacuum (cold) part with ceramic window and antenna.

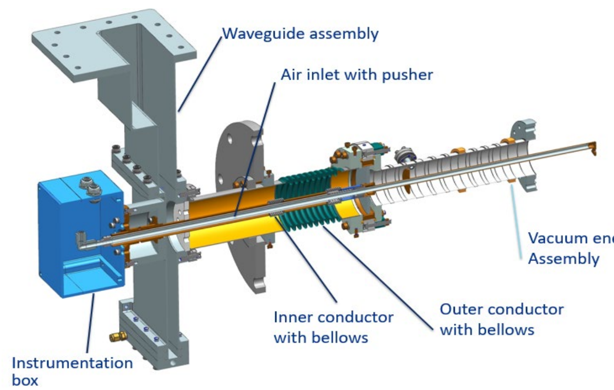

Figure 1: Cut view of the 650 MHz prototype coupler with convectional design.

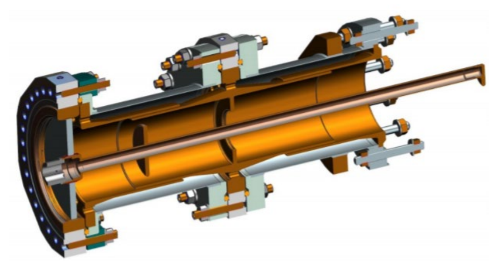

Figure 2: Cut-view of the vacuum part of the EM-shielded coupler. Middle copper shield is connected to 50K thermal strap.

Coupler consists of two parts: cold vacuum part with flat ceramic window brazed to antenna and air part with bellows in inner and outer conductors and transition to narrow WR1150 waveguide. All stainless steel tubes and bellows in air part are copper plated, antenna is made of solid copper, polished to reduce thermal radiation. In conventional design outer conductor of vacuum part also copper plated. Ceramic window is always kept at room temperature above freezing point even without heating from RF power, for that heater on the window flange are installed

Antenna and air part of the coupler are cooled by dry air with flow rate up to 5 g/s, propagation through coaxial tube in inner conductor. After returning back air will cool antenna and will go to the air part through the holes in inner conductor, cooling window and air part of coupler.

Kapton 5-layer foil isolates inner conductor and allows apply DC bias up to 5kV to damp multipactoring activity in the coupler vacuum part. Instrumentation box is used for air and high voltage connections.

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Two temperature intercepts 5K and 50K on outer conductor in vacuum part are connected to corresponding helium lines in the cryomodule by thermal straps with mounted on it temperature sensors. Window flange also connected by thermal straps to cryomodule flange, located at room temperature. Length of the antenna is fixed, but orientation of the flag at the end of antenna provides possibility to change coupling with cavity by rotating the cold part of the coupler during coupler-to-cavity installation in the clean room. Angle of rotation is defined by pattern of the holes on the coupler flange.

TESTING OF COUPLER PROTOTYPE

Two 650 MHz couplers of each design were fabricated and tested [4]. Most critical vacuum parts were fabricated at CPI, qualified vendor for coupler (Fig. 3). Two warm parts were fabricated separately and installed on the test stand.

Figure 3: Vacuum cold parts of the conventional coupler (on the left) and EM-shielded coupler (right).

Preparation for RF Power Test

Cold vacuum coupler parts were inspected, cleaned in ultrasonic bath and after drying assembled in clean room. Two vacuum coupler were assembled together through the chamber-coupling cavity (Fig. 5). Antennas of both couplers were connected by using bridge made of solid copper. (Fig. 4). Bridge has enough flexibility to accommodate elongation of antenna due to RF heating. After completing assembly cold parts with chamber and leak checking, full assembly were baked in oven with 120°C for 48 hours with pumping of vacuum all time. After baking vacuum assemble were connected to air coupler parts on the support table

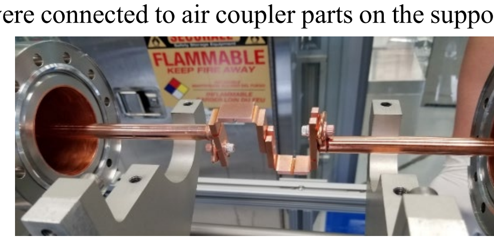

Figure 4: Antenna connection with copper bridge.

RF Power and Tuning of Reflection Phase

Power source available for the coupler test is IOT with maximum CW power 30kW. Available RF power for qualification test is 100kW, using resonance scheme to multiply power. We provided resonance conditions between movable reflector and movable short and typically measured amplification in power between x5 and x7. Test stand schematic of the RF circuit is shown in Fig. 5. In such configuration couplers always see standing wave regime, for changing reflection phase we use waveguide insertions of different length installed between coupler and short. For each phase we adjust resonance frequency by moving reflector, installed on the entrance of test stand.

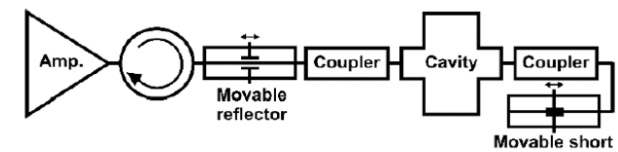

Figure 5: Schematic of test stand RF power.

COUPLER TEST STAND DIAGNOSTICS

Coupler Test Stand installed in the cave is shown in Fig. 6. Power from IOT is delivered to couplers through WR1150 waveguide. Coupler assembly shall be tested in full reflection configuration. The goal of test is to rise power up to maximum (50 kW) in CW mode and keep coupler in this point long enough time to reach thermal equilibrium (~ 2 hours). This procedure is repeated 4 times for 4 different phases of reflecting power shifted 90 degrees: (0°; 90°; 180°; 270°). Each phase point is defined by length of WR1150 waveguide insertion (0; $\lambda/8$, $\lambda/4$; $3\lambda/8$), where λ is wavelength in waveguide line.

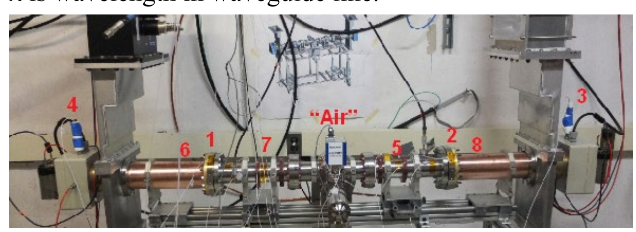

Figure 6: Two couplers installed on the test stand.

Diagnostics

We measured RF forward/reflected power from IOT and power in the couplers by using directional WG couplers. Air flow was measured by flow sensors and we also measured air inlet temperature. For temperature control 8 sensors were installed around couplers: 1&2-ceramic window flange; 3&4 –air outlet temperature, 5&7 -50K intercepts in vacuum part, 6&8 – temperature on air outer conductor.

We also measured DC bias voltage and current and controlled vacuum in the coupling cavity.

Testing Protocol for Coupler with DC Bias

Based on preliminary test we formulated testing protocol for coupler qualification. We start with short pulses and maximum power 100kW. It allows to excite all multipactipacting zones, average power small in this regime. Then we increased pulse length and finally switched to CW regime. Duration on each step is defined by vacuum activity

- Pulse 10ms, power ramped up to 100kW, average power ≤1 kW, ~15min

20th Int. Conf. on RF Superconductivity SRF2021, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-233-2 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2021-TUPTEV017

- Pulse 100ms, power ramped up to 100kW, average power ≤10 kW, ~15min
- Pulse 650ms, power ramped up to 80kW, average power ≤50 kW, limited by vacuum.
- CW mode, ramping up to 50kW, Time: ~2 hrs or longer if vacuum exceeds 1.E-6 Torr.

This procedure was repeated 4 times for each phase points. HV bias was applied from very beginning, +4 kV. For each working point bias voltage is adjusted (up to +5kV maximum) to suppress multipacting.

Air flow should not be below 10 SCFM-standard cubic feet per minute (minimum), typical value 23 SCFM.

Processing is completed for each reflection phase, if vacuum level is better than 5.e-7 Torr at 50kW CW.

Test History

Conventional design:

- HP processing with bias up to +5kV.
- Waveguide heating test

EM shielded design:

- HP processing with DC bias (nominal regime)
- DC bias polarity test
- HP processing without bias
- Test with nominal warm parts (bellows and SS inner/outer conductor copper plated)
- Memory test (fill couplers with dry nitrogen and pump again, then re-test)

TEST RESULTS

Conventional coupler was tested with DC bias +4.5kV. Bias voltage was set to suppress multipactoring at the highest RF power 100kW. Power and vacuum plots for 4 reflection phases are presented in Fig. 7. RF processing and qualification was done pretty quickly, totally in less than 20 hours, including ~8 hours of staying at nominal 50 kW CW regime by protocol. Most difficult processing was found at 270 degrees of reflection phase. Easier processing required for 180°. For reflection phases 0° and 90° almost no processing required to reach qualification requirements.

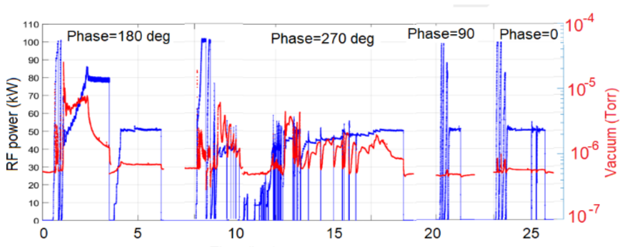

Figure 7: HP processing for conventional coupler. RF power – blue, vacuum – red.

Temperature in different locations is shown in Fig. 8. One can see than air outlet temperature rise (+20ºC) is higher than that measured on window flange (+10ºC). Temperature depends on reflection phase.

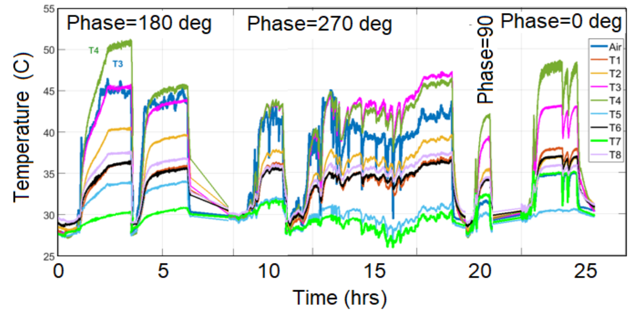

Figure 8: Coupler temperature: 1,2 window; 3,4 outlet air.

WG Heating Test

Waveguide was heated during coupler tests. For comparison with simulation we tested temperature of waveguide for different levels of power in CW regime 10kW, 20kW, 30kW and 40kW. Reflection phase was 0 degrees in this test. For test all fans were switched off to provide pure convective cooling regime, short plate of the narrow waveguide was water cooled as designed. Four temperature sensors from the coupler were re-installed to waveguides for temperature measurements, position and names of the temperature sensors are shown in Fig. 9, measured temperature data are presented in Fig. 10. Fig. 11 presents measured data and calculated temperature at 50kWpower. Calculations done for all reflection phases, two lines in plot corresponds minimum and maximum temperature. Measurements are in a good agreement with simulations.

Simulations predict that maximum power dissipation in waveguide ~427W and maximum temperature exceed 68°C with water cooling (short) and 137°C without water cooling. In pre-production design instead of narrow waveguide we will use standard WR1150 which allow significantly reduce dissipated power and temperature even without water cooling.

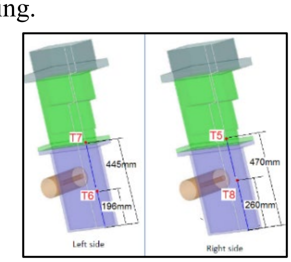

Figure 9: Position of temperature sensors on waveguide.

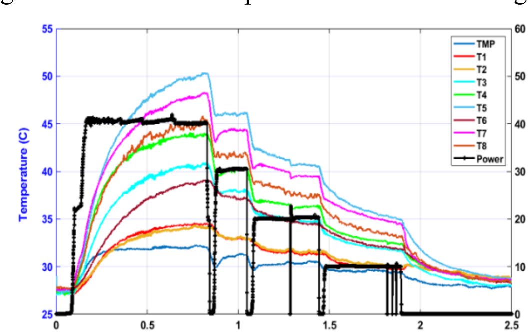

Figure 10: Temperature profile for different RF power.

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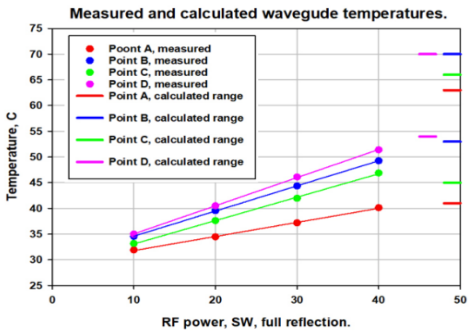

Figure 11: Measured and calculated temperature rise vs. rf power in coupler.

Testing of EM-shielded Couplers

EM shielded couplers were cleaned, assembled and baked the same way as conventional ones. Test results for first test with DC bias is presented on Fig. 12, where green color is RF power and red color is vacuum pressure. For each reflection phase we run at 50kW CW mode for 2 hours to reach equilibrium temperature. One can see that with bias processing is very smooth with mild multipactoring activity. The maximum temperature of outlet air not exceed 50ºC

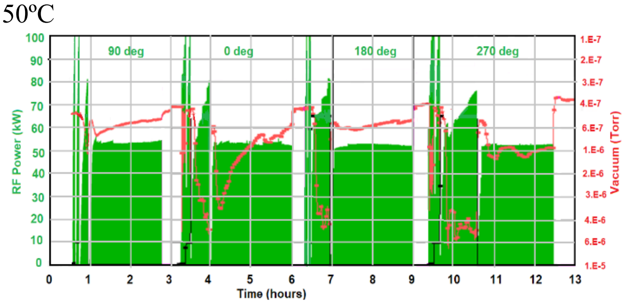

Figure 12: Processing history of EM-shielded couplers with DC bias +5kV. Power-green, vacuum pressure-red.

Effect of HV Bias Polarity

To understand effect of bias polarity on coupler performance we changed polarity from positive to negative and repeat processing using same protocol for the last configuration point with reflection phase 270 degrees. For negative bias we use another HV power supply, limited by -3.0 kV. Positive and negative bias was applied for short pulses (10ms) to compare the multipactor threshold at 3 kV bias. For negative polarity the MP activity starts at about 18 kW, while for the positive bias the threshold was moved to 50 kW power level. Without bias MP starts at ~6kW. For negative polarity -3kV couplers were conditioned for about 4 hours at short 10ms pulses ramping power up to 100 kW power. The vacuum was ~ 4.E-6 Torr or worse and signal was noisy ('hairy'), which indicates that multipactor was not suppressed completely. After that bias was re-connect to positive power supply and voltage set to +3.2 kV. Coupler was processed another 4 hours by following usual protocol: 10ms, 100ms, 650ms and CW up to 50 kW average power. For the positive polarity in 10ms pulses 100kW power level was reached in a few minutes with very minor vacuum drop. For 650ms pulses, 80kW power and in CW regime we do not detect any unusual vacuum activity, there was no sign of multipactoring for this polarity.

At next step we increase negative bias voltage up to -5kV (the polarity of original HV supply was changed by minor modification inside HV block). Coupler was processed again with this bias according to usual protocol, it took 2.5 hours, including last hour at 50kW in cw regime, when vacuum already reached 4.e-7 Torr as equilibrium level. But vacuum plot still has some 'hairy' noise. From that we concluded that MP was not suppressed completely. From bias polarity test we can conclude that positive bias is much more effective for the current configuration than negative polarity bias.

Power Processing without Bias

For each reflection phase configuration the RF processing without DC bias starts in the pulse mode with 1Hz repetition rate and ramping RF power from 2 kW up to the maximum 100kW for very short pulses <0.1ms and up to 50kW for longer pulses. The first power scan was done at 10µs pulses with ramping power up to 100kW. In this regime available energy is <1 Joule/pulse which is safe for coupler. It allows identify multipacting (MP) zones and do processing. Final step of processing is CW mode with ramping power up to nominal 50kW.

Power ramping rate starts from ~1dB/step and decreases to 0.5dB/step for the RF power above 20kW. After vacuum soft trips (interlock 1.e-6 Torr) the RF power reduces -2dB and processing continue.

Processing time and exact number of pulse length steps depends of reflection phase as clear from Fig. 13. For example in pulse regime outgassing rate for 270 degrees of reflection phase was ~3.e-6Torr and it took ~10 hours of processing. For 90 degrees of reflection phase vacuum activity during pulse processing was very low (vacuum < 4.e-7Torr) and it took 3 hours to complete processing.

The basic processing protocol for testing without DC bias is the following:

- Short pulses: 10;20;50;100,200,500 µs, Power ramp 0 => 100 kW, (average power < 50 W)
- Long pulses: 1;2;5;10;20;50;100;200; 500 ms. Power ramp 0=>50 kW, (avrg power < 25 kW)
- CW, Power ramp 0 => 50 kW, after that stay 2 hours at 50kW

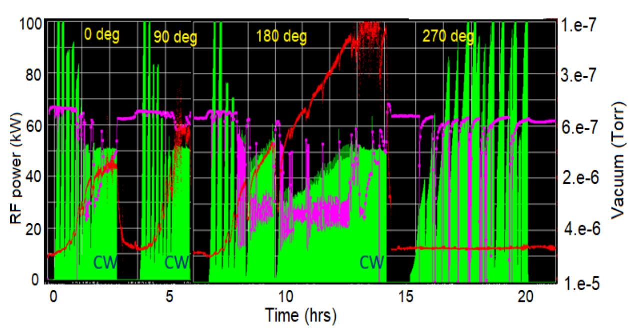

Figure 13: Example of coupler RF processing without DC bias (green-rf power, magenta-vacuum pressure). Reflection phase:0º; 90º; 180º, 270. Scales: power 0-100kW; vacuum pressure 1.e-5 to 1.e-7 Torr.

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Processing without HV bias requires more pulse duration steps and takes more time than processing with bias. We hope it can be improved by longer baking, better pumping on test stand and optimizing processing protocol. In pre-production couplers we are planning to use TiN coating of ceramic to supress MP in this area.

DESIGN MODIFICATION OF PRE-PRODUCTION COUPLERS

Both designs of prototype 650 MHz coupler successfully pass through processing and demonstrated all required performance and used for testing 650 MHz cavities in STC at Fermilab and HTS in India. Conventional design was chosen as baseline for PIP-II cavities. This choice was done based on coupler complexity and weight and effort needed for assembly of parts.

Based on lessons learnt from testing of prototypes we made several modification of the conventional couplers to improve performance and simplify manufacturing and assembly (Fig. 14). Most significant changes are the following:

- Narrow waveguide replaced with standard WR1150 waveguide, which improve pass-band and reduce heating
- Thicker ceramic window, copper sleeve modified for better brazing
- Use standard CF flanges for window connection. It provides compactness, smaller weight, easier handling.

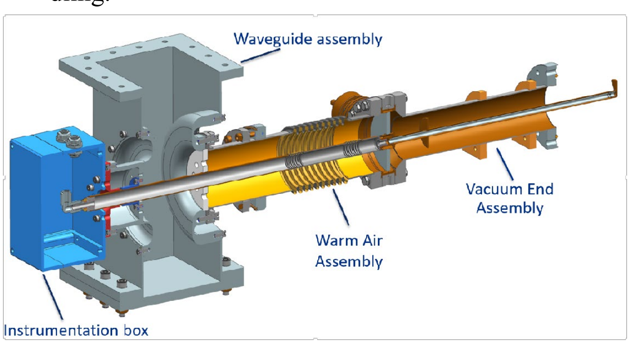

Figure 14: Cut-view of the baseline pre-production 650 MHz coupler

In coupler test stand we replaced coupling cavity by chamber, which provides capacitive coupling between two antennas through copper insertion. It reduce risk of damaging ceramic during assembly. We also improving vacuum system of test stand to achieve better pumping capability. Chamber with two couplers is shown in Fig. 15.

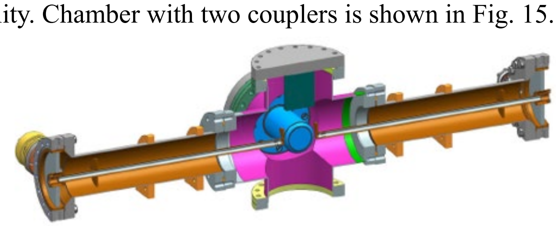

Figure 15: Cut view of the coupling chamber with two couplers

CONCLUSION

Two prototypes of 650MHz couplers for PIP-II project were designed, built and tested. One is conventional design, second is EM-shielded design, where copper screens shield SS outer conductor from EM-field. Both designs passed successfully through qualification test and demonstrated excellent performance with DC bias applied. Some of them already tested with cavity in horizontal cryostat. One pair of couplers were successfully processed without bias. Processing w/o bias is more time consuming, but better clean coupler vacuum surfaces by multipacting.

Based on assembly, testing experience and lessons learnt, we chose conventional design as a baseline for PIP-II. Design was modified for pre-production series to improve handling and performance.

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