ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB096

TESTING OF PIP-II PRE-PRODUCTION 650 MHz COUPLERS IN WARM TEST STAND AND CRYOMODULE

N. Solyak†, S. K. Chandrasekaran, B. Hanna, J. Helsper, J. Holzbauer, S. Kazakov, A. Sukhanov
Fermiilab, Batavia, USA

Abstract

650 MHz fundamental power couplers were developed for PIP-II project to deliver RF power for low-beta and high-beta elliptical cavities [1]. Few prototypes were built and tested and after some modification we built 8 pre-production couplers (with three spares for vacuum side) for ppHB650 cryomodule. All couplers were successfully tested in pulse mode (up to 100 kW) and in CW mode (up to 50 kW) in test stand at full reflection at 8 phases. In baseline configuration with DC bias we do not see any multipactoring activity after short processing. We also tested power processing without bias for uncoated and TiN coated ceramic window. Results of these studies presented in this paper. One of the coupler was assembled on LB650 cavity and tested at cryogenic environment in STC cryostat at ~30 kW power with full reflection at different reflection phase. We also demonstrated good result from power processing without bias for warm and cold cavity. Six couplers were assembled on HB650 cavities in pre-production cryomodule. Test results from cryomodule qualification is discussing in this paper.

INTRODUCTION

In PIP-II project both LB650 and HB650 cavities will use same design for 650 MHz fundamental power coupler. Mechanical model of pre-production coupler design is shown in Fig. 1 [2]. Coupler consist of few sub-assemblies: vacuum side, air side, wave-guide assembly and instrumentation box. Ceramic window is part of vacuum assembly and separate vacuum from the air. Antenna and all air side components are cooled by dry air.

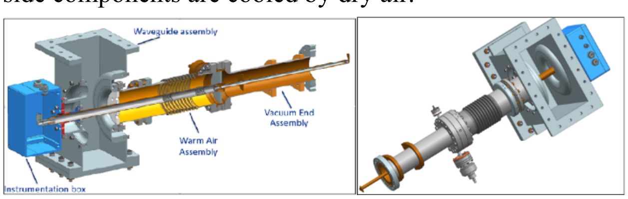

Figure 1: Mechanical design of the 650 MHz pre-production coupler. Cut-view on the left picture. Vacuum gauge and pickup antenna are located near the ceramic window.

Current design of the coupler is based on experience learnt from building and testing two coupler prototypes: one is conventional design and another is RF shielded design, details and test result was reported in paper [3, 4]. Two vacuum parts of each design were built by CPI, both designs demonstrated good performances [3, 4]. For production we choose convention design which looks simpler in manufacturing and lighter which is beneficial to eliminate potential transportation problem. Several modifications were introduced in the pre-production design to compare with prototype [2]. Major modifications in pre-production couplers are the following:

- Thicker ceramic window: 7 mm vs. 6 mm.
- Conflat flanges for warm to cold connection and for connection antenna assembly to vacuum outer conductor to replace aluminum diamond seal flanges.
- Standard WR1150 waveguide (instead of narrow two steps waveguide) matched to coaxial coupler.
- Vacuum gauges located in vicinity of window.
- Pickup antenna is longer and moved closer to ceramic
- Modification of air cooling channel design
- Modification of instrumentation box.

As a result waveguide heating reduced, passband increased, added vacuum diagnostics, stresses on ceramic window decreased and assembly process improved.

For HB650 prototype cryomodule project built 8 preproduction couplers and extra 3 cold-end assemblies at Canon/Japan. All couplers were accepted and qualified in coupler test stand. We tested coupler pairs 1&2; 3&4; 5&6; 8&9 and 10&11 with DC bias at 50kW CW full reflection. Pair 10&11 was also tested without DC bias for coupler #11. Two couplers after tests received TiN coating of vacuum side of ceramic at CPI (#7 and #11) and currently assembled for testing performance with and without DC bias.

Additional to that coupler #7 was used for fatigue test and couplers #7 and #11 for the pressure tests.

Power Specification

Most strict power requirements for 650 MHz coupler comes from high-beta HB650 cavities. Maximum forward power in operation with 2 mA beam is ~43 kW with 20% reflection, but most of time linac will work in regime without beam at ~30 kW forward power. Total power (forward + reflection) in both cases more or less the same < 60 kW (Figure 2). Test stand power requirements for the coupler is higher: 50 kW CW at full reflection at arbitrary reflection phase. Power overhead allows cover cavity operation at higher gradient with high detuning from microphonics and tolerate higher coupling errors.

* Work supported, in part, by the U.S.Department of Energy, Office of Science, Office of High Energy Physics, Under U.S. DOE CONTRACT NO. DE-AC02-07CH11359.
†solyak@fnal.gov.

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB096

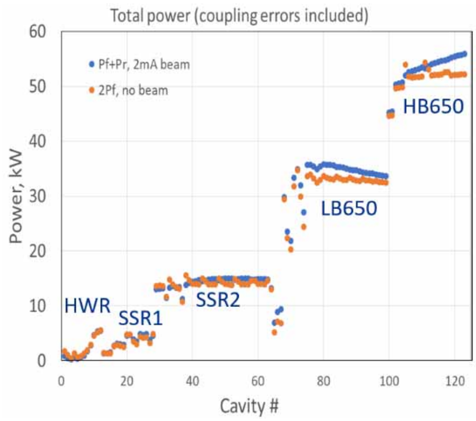

Figure 2: Total power propagating through couplers in different PIP-II systems for operation with 2 mA beam and without beam, microphonics and coupling errors included.

RF TEST STAND

RF power for coupler test stand is provided by 30 kW IOT which is not enough for coupler test. Proposed schematic for resonance excitation of the fields in two couplers (Figure 3). Resonance between short and movable reflector allows increase power, achievable gain in our case x(4-6) which provides >100 kW CW for coupler test. This is standing wave (SW) regime. To change reflection phase we need move short by adding waveguide insertion and adjust position of reflector to keep system in resonance.

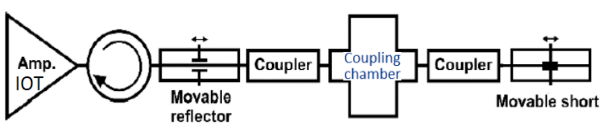

Figure 3: Schematic of RF system in coupler test stand. With resonance conditions between movable reflector and short.

Coupler Preparation and Installation for Test

Two coupler vacuum ends are assembled on coupling chamber (Figure 4) in clean room, then pumped out, leak checked and baked under vacuum at 120 °C for 48 hours in oven.

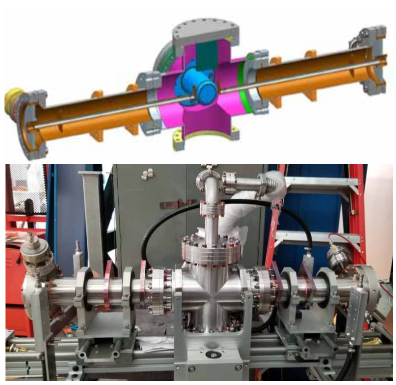
Figure 4: Two vacuum sides of coupler assembled on the coupling chamber. Antennas are coupled through the copper electrode (blue). Gap between each antenna and electrode ~1 mm.

In testing area couplers are assembled with air parts and connected to power waveguide and movable reflector (Figure 5). Air cooling lines and DC bias connected to each instrumentation box. Four copper straps for each coupler provide thermal connection between ceramic window flange and water cooled sinks, installed on the frame. Vacuum system is connected and leak checked and both vacuum gauges activated. Schematic of temperature diagnostics and locations of thermos-sensors are shown in Fig. 6.

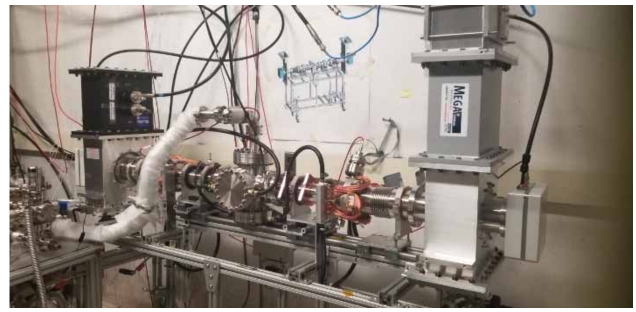
Figure 5: Warm RF test stand for qualification of two 650 MHz couplers in SW regime.

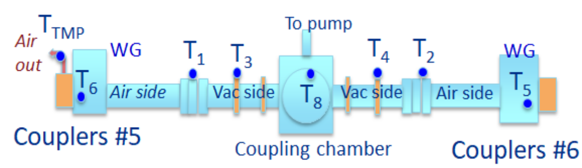

Figure 6: Location of the temperature sensors.

RF Testing Protocol

All couplers are tested at full reflection (Standing Wave regime) for 8 reflection phases. For each phase position of short and reflector adjusted to keep system in resonance. For each reflection phase configuration we start from short pulses with power ramped up from 0 to 100 kW and then go to CW up to 50 kW. At maximum CW power we stay at least ~ 1 hour to reach equilibrium temperature.

RF qualification protocol:

- Pulse mode with DC bias: 10, 20, 50, 100, 200, 500 ms: ramping RF power up to 100 kW.
- Pulse mode w/o DC bias: 10, 30, 100, 300 µs; 1, 3, 10, 30, 100, 300 ms;
- CW mode: ramping RF power up to 50 kW. Stay 1 hour to reach equilibrium temperature and final vacuum <2.e-7 Torr at 50 kW.

Testing Conditions and interlocks:

- DC bias 4.5 kV on inner conductor (each coupler) - interlock
- Air flow rate 13 SCFM (7.4 g/s) for each antenna - interlock
- Colling water flow rate - interlock
- Temperature interlocks: T<60° on ceramic window flange
- Vacuum gauges - interlock 2.E-6 Torr

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB096

TEST RESULTS

Figure 7 summarizes result for testing coupler pairs 3&4 ; 5&6 ; 7&8 and 10&11. (pair 1&2 is not shown here). Upper plot shows typical RF power profile for pulse mode following by CW mode 50 kW ~1 hour (flat plateau for) eight reflection phases. Other four plots below present coupler vacuum, measured by vacuum gauges near ceramic window. In these tests DC bias 4.5 kV was applied to all couplers. One can see that MP activity mostly excited at power level above 50 kW in pulse mode. For some 'good' reflection phases : 180°, 225°, 270° there is no MP for all power levels, while for 'bad' phases : 0° and 90° we always see MP activity in pulse mode. Pair of couplers 8&9 shows MP for two reflection phases only. At 50 kW CW mode MP is completely suppressed by bias.

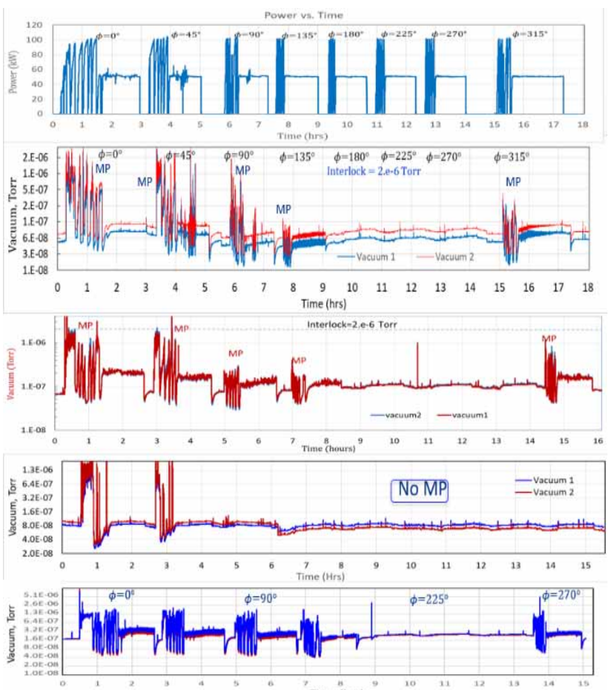

Figure 7: Summary of MP activity in the couplers for 8 reflection phases. Upper plot shows RF power profile for couplers 3&4. Next 4 plots show vacuum reading for couplers 3&4, 5&6, 8&9, 10&11.

History of window flanges and coupling chamber is shown in Fig. 8. Equilibrium temperature vs. reflection phase is plotted in Fig. 9. The maximum temperature in window flange was ~50 °C, below 60 °C requirements.

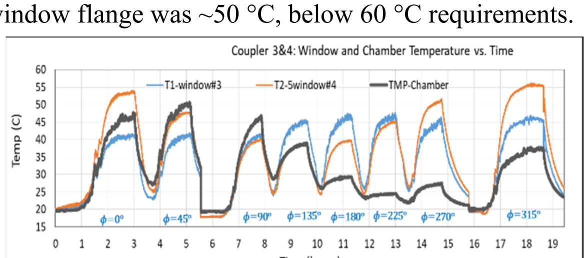

Figure 8: Couplers 8&9: Temperatures plot for coupling chamber and both window flanges, shown for 8 reflection phase configuration.

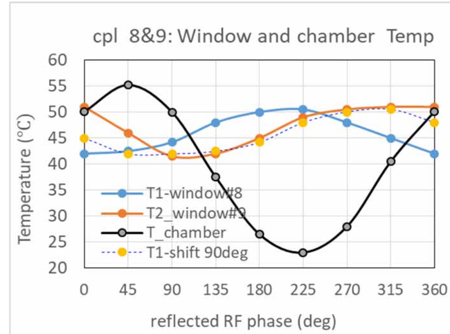

Figure 9: Couplers 8&9: Equilibrium temperature for 50 kW CW for coupling chamber and both window flanges vs. reflection phase.

In last tested pair 10&11 one coupler #11 was tested without DC bias. We spent significant amount of time to clean coupler by MP. For "good" phases MP was successfully processed out, but for two "bad" phases we still see residual MP activity in CW mode below 50 kW.

Inspection After Test

Inspection after testing first couplers pair 1&2 discovers oxidation of air bellow as shown in Fig. 10. Our explanation that it could happened during test with reduced air flow rate studies done for this coupler. Oxidation was clean out, no any other damages observed after tests.

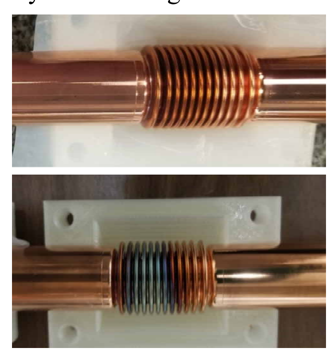

Figure 10: Air side inner conductor bellow before and after coupler (#1) test. It happened when low air flow regime was tested at high average power.

After testing of coupler#11 without DC bias when we see significant MP activity we found that vacuum side of ceramic changed color from white to yellowish (Figure 11). Material analysis shows traces of silicon only, no carbon or other unusual species.

Figure 11: Picture of vacuum (left) and air (right) side of ceramic window (#11) after power processing without DC bias.

ISBN: 978-3-95450-234-9 ISSN: 2673-5504 doi:10.18429/JACoW-SRF2023-WEPWB096

Coupler Testing in Spoke Test Cryostat (STC)

One coupler (#8) was assembled on LB650 cavity and tested at STC in cold and warm condition at 28 kW available power. Test result can be summarized as the following:

- With 4.5 kV DC bias: no MP activity up to 28 kW CW, full reflection (cavity ON/OFF resonance)
- Without DC bias:
  - cavity at room temperature; no MP w/o bias
  - Cold cavity OFF resonance: pulses 10 Hz (0.01…500 ms) and CW-mode up to 28 kW; No MP activity after minor processing
  - Cold cavity ON resonance: Pulses 10 Hz (0.01…19 ms) up to 28 kW. No MP
  - Cold cavity detuned (phase +/- 45°); Pulses (0.01…5 ms), 28 kW. No MP

Coupler Performance in ppHB650 Cryomodule

After qualification tests six power couplers were assembled on cavities and installed in ppHB650 cryomodule for testing at cryogenic temperature [5]. To keep temperature of the window always above freezing point a few heaters were mounted on the window flange and 4 copper straps are installed between flange and cryostat vessel. Without RF power in coupler the heater power was set to ~15 Watts when cooling air flowing, and ~20 Watts when no cooling air.

All couplers were tested with 4.5 kV DC bias at maximum available power 37 kW CW at full reflection (cavity OFF resonance). Air flow kept at ~4 scfm when no RF and ~8.5 scfm when RF. In tests we never saw any MP activity on the cold cathode gauges, no e-probe signals.

CONCLUSION

For ppHB650 cryomodule Fermilab built 8 full 650 MHz couplers and 3 antenna assemblies. All Couplers were successfully qualified at warm test stand with DC bias. No MP seen below 50 kW cw after short power processing in pulse mode up to 100 kW. Pulse processing above 50 kW helps to clean surface.

In qualification tests the temperature of ceramic flange never exceeds 60 ºC (stress limit for ~0.1 Mcycles) for 50 kW CW. For coupler operation in cryomodule with power <30 kW and air flow rate 5 g/s the expected flange temperature < 45 ºC.

One coupler (#11, no TiN coating) was also tested without DC bias for power processing studies. After more than week processing time the residual MP activity still exists for some "bad" reflection phase configuration.

After RF qualification test coupler #8 was assembled on LB650 cavity and tested in STC cryomodule in warm and cryogenic environment with and without DC bias at the maximum available power 28 kW CW. Test was done for different reflection phases when the cavity was ON and OFF resonance and for detuned cavity (+/- 45º). In all cases there is no MP activity was detected in coupler, it works well up to ~30 kW available power.

Six couplers were assembled on ppHB650 cryomodule and tested in cold environment at PIP2IT cryomodule test stand at a maximum available power ~37 kW. All test were done with 4.5 kV DC bias. All couplers performed as expected, no vacuum activity or window overheating detected. Analysis and other coupler tests are coming.

Two couplers (#7and #11) after qualification tests received TiN coating on vacuum side of ceramic window. Next step is testing power processing for coated couplers.

ACKNOWLEDGEMENTS

The work completed would be impossible without Fermilab's dedicated technicians R. Kirschbaum, T. Fermanich, D. Plant, and their supervisor D. Bice.

REFERENCES

[1] A. L. Klebaner, C. Boffo, S. K. Chandrasekaran, D. Passarelli, and G. Wu, "Proton Improvement Plan II: Overview of Progress in the Construction", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 182–189. doi:10.18429/ JACoW-SRF2021-MOOFAV05

[2] J. Helsper *et al.*, "Design, Manufacturing, Assembly, Testing, and Lessons Learned of the Prototype 650 MHz Couplers", in *Proc. LINAC'22*, Liverpool, UK, Aug.-Sep. 2022, pp. 462-465. doi:10.18429/JACoW-LINAC2022-TUPOPA25

[3] S. Kazakov, B. M. Hanna, O. V. Pronitchev, and N. Solyak, "Latest Progress in Designs and Testings of PIP-II Power Couplers",in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 263-266. doi:10.18429/JACoW-SRF2019-MOP080

[4] S. Kazakov, "RF Couplers for PIP-II", presented at Worldwide Workshop in Fundamental Power Couplers, CERN, Jun. 2017. https://indico.cern.ch/event/642503/contributions/

[5] V. Roger *et al.*, "Design of the 650 MHz High Beta Prototype Cryomodule for PIP-II at Fermilab", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 671–676. doi:10.18429/JACoW-SRF2021-WEPTEV015