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INITIAL CONDITIONING OF THE 1.5 GHz PROTOTYPE COUPLERS FOR VSR DEMO*

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Abstract

Two prototype 1.5 GHz fundamental power couplers for the VSR (Variable pulse length Storage Ring) DEMO project at Helmholtz Zentrum Berlin (HZB) were produced by Research Instruments (RI) and Thales, with the aim of reaching 16 kW continuous wave (CW). To allow for conditioning of the couplers, a dedicated coupler test stand was designed, installed, and commissioned. The couplers were delivered March 2023 after substantial reworking; however, due to a vacuum leak during mounting, further reworking was required and were installed on the test stand June 2024. Such levels of rework dictated a more cautious testing plan. After a 120 C baking, an initial short conditioning run was performed in August 2024, followed by a longer run from April to May 2025. Here, we present the first conditioning results.

INTRODUCTION

VSR DEMO is a feasibility study of a 3rd harmonic (1.5 GHz) SRF system for 500 MHz high current storage rings. Several 1.5 GHz components have been designed and manufactured and are now being tested at HZB including HOM damped multicell 1.5 GHz SRF cavities [1, 2]. These cavities require fundamental power couplers to provide 16 kW CW RF power. The 1.5 GHz VSR couplers are a scaled version of the Cornell ERL couplers [3, 4] with modifications to meet the VSR DEMO requirements.

The initial design and subsequent development is found in [5–8]. Prototype production by Research Instruments (RI) and Thales began in 2021; however, manufacturing challenges prompted design changes, including a significant change to the RF and vacuum seal between the warm part of the coupler and the waveguide. (Full details [9].) These modifications during production led to significant reworking, which, along with insufficient protection during welding and brazing, led to concerns about prototype quality and the implementation of a more cautious testing plan.

CONDITIONING SET-UP

Couplers must be conditioned to process away contaminants and minimize the conditions for multipacting, ensuring reliability and good performance. To condition the couplers a dedicated RF testing set-up was designed and built (cf. Fig. 1), comprising of a base RF testbox designed specifically for these couplers, with 1.5 GHz cut off frequency and a separation between the couplers that ensures good transmission. The couplers are mounted onto the RF testbox and suspended in a vacuum cryostat up to the 300 K flange, to prevent icing and condensation when cooled. The system is cooled using gaseous helium at ≈90 K, with direct cooling on the base RF testbox and thermal strips on the coupler cold bellows, creating an environment that mimics module conditions. Additional cooling is provided with air and water cooling circuits. The couplers are equipped with a DC bias to combat possible multipacting, allowing for a voltage to be applied to the warm inner conductors.

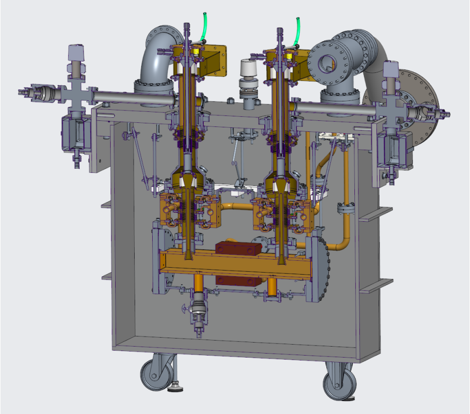

Figure 1: A cut through of the testing setup showing base RF testbox and couplers suspended in the vacuum of a cryostat.

Diagnostics and Monitoring

For diagnostics and monitoring, the testing setup is split into three parts shown in Fig. 2. The upstream coupler, is defined as the warm part of the coupler connected to the RF input. The cold part, is the largest area and encompasses the cold parts of both couplers and the base RF testbox. Finally, the downstream coupler is defined as the warm part of the coupler connected to the RF output (a load). Each part is carefully monitored using the following sensors;

- Two arc detectors, one per coupler.
- Four vacuum gauges and getter pump readouts, one per region and one for the cryostat vacuum.

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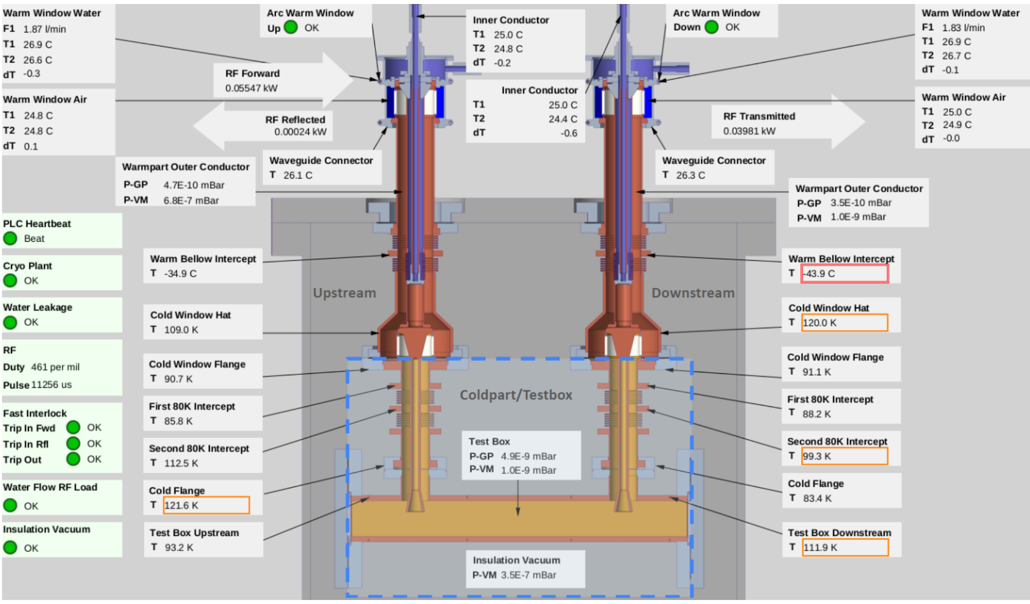

Warm Window Water
F1 1.87 l/min
T1 26.9 C
T2 26.6 C
dT -0.3

Warm Window Air
T1 24.8 C
T2 24.8 C
dT 0.1

Arc Warm Window
Up ● OK

RF Forward
0.05547 kW

RF Reflected
0.00024 kW

Inner Conductor
T1 25.0 C
T2 24.8 C
dT -0.2

Inner Conductor
T1 25.0 C
T2 24.4 C
dT -0.6

Warmpart Outer Conductor
P-GP 4.7E-10 mBar
P-VM 6.8E-7 mBar

Waveguide Connector
T 26.1 C

PLC Heartbeat
● Beat

Cryo Plant
● OK

Water Leakage
● OK

RF
Duty 461 per mil
Pulse 11256 us

Fast Interlock
Trip In Fwd ● OK
Trip In Rfl ● OK
Trip Out ● OK

Water Flow RF Load
● OK

Insulation Vacuum
● OK

Warm Bellow Intercept
T -34.9 C

Cold Window Hat
T 109.0 K

Cold Window Flange
T 90.7 K

First 80K Intercept
T 85.8 K

Second 80K Intercept
T 112.5 K

Cold Flange
T 121.6 K

Test Box Upstream
T 93.2 K

Test Box
P-GP 4.9E-9 mBar
P-VM 1.0E-9 mBar

Insulation Vacuum
P-VM 3.5E-7 mBar

Arc Warm Window
Down ● OK

RF Transmitted
0.03981 kW

Waveguide Connector
T 26.3 C

Warm Window Water
F1 1.83 l/min
T1 26.9 C
T2 26.7 C
dT -0.1

Warm Window Air
T1 25.0 C
T2 24.9 C
dT -0.0

Warmpart Outer Conductor
P-GP 3.5E-10 mBar
P-VM 1.0E-9 mBar

Warm Bellow Intercept
T -43.9 C

Cold Window Hat
T 120.0 K

Cold Window Flange
T 91.1 K

First 80K Intercept
T 88.2 K

Second 80K Intercept
T 99.3 K

Cold Flange
T 83.4 K

Test Box Downstream
T 111.9 K

Figure 2: The diagnostics panel used to monitor the coupler during conditioning shown after 12+ hrs of no testing. Values highlighted in red are outside the desired range (in this case too cold) and orange are outside the ideal range but not the interlocked range.

- 18 PT100 temperature sensors, four on the upstream coupler, four on the downstream coupler and 10 on the testbox and cold parts.
- Four electron pick ups (not in use due to readout issues).
- Two water flow sensors for the cooling water circuits
- Additional temperature sensors on the inputs and outputs of the cooling circuits to give ΔT.
- Two temperature sensors on the output load

These readouts feed into the interlock, conditioning software and the EPICS control system for monitoring and archiving during conditioning (cf. Fig. 2. The process is interlocked by vacuum level, sudden increase of reflected power or temperature and occurrence of arcs. The vacuum was initially interlocked at 1×10^{-6} mbar for the upstream couplers, and 1×10^{-7} mbar for the cold part and downstream coupler but this was increased to 5×10^{-6} mbar for all parts during conditioning.

Assembly and Testing Prep

The assembly and testing prep of the coupler test stand is long and complex, Fig. 3 shows the different assembly steps from the cleanroom to ready for testing, and full details are as follows.

All parts are inspected on delivery, then the cold parts moved into the cleanroom, blown with dry nitrogen and a particle count performed. The cold parts are mounted onto the base RF testbox (cf. Fig. 3A), pumped down, leak tested and then moved from cleanroom to clean assembly area.

In the clean assembly area the warm outer conductors are mounted to the cryostat lid, and the warm inner conductors are mounted to the warm outer conductors. Then the cold parts are mounted to the warm parts and the cryostat lid, and the internal cooling systems are connected (cf. Fig. 3B). To improve performance a 120 °C bakeout is performed. (cf. Fig. 3C). After baking diagnostics are mounted, and the parts moved into the cryostat covered with multilayer insulations and the lid closed. The sealed cryostat is then pumped and leak tested.

Finally the testing set-up is moved into the radiation bunker and the diagnostics and supplies are connect (cf. Fig. 3D). The S-parameters are checked using a vector network analyser. Then the RF waveguides are connected, and the amplifier is used check power balance and perform low power tests. There is a final check of the diagnostics and supply systems and then conditioning starts at 40 Hz and 1‰ duty cycle with a slow ramp to 5 kW to warm up the amplifier.

Conditioning Plan

Conditioning followed the XFEL plan [10], with a stepwise power increase for short pulses up to max power (14 kW). Then the pulse length increased by way of the duty cycle and the ramp repeated for increasing pulse lengths up to CW. This is combined with the ramping down scheme used to condition the bERLinPro couplers at HZB [11, 12]. There is a pulse width factor (PWF) to further shorten the pulses if needed.

Automated software monitors the vacuum signal and uses set thresholds to change the power accordingly, allowing processing to occur rather than triggering the interlock. If the vacuum raises above the first threshold the power increase pauses. If the vacuum reduces below the threshold the sweep resumes, if it increases further beyond a second threshold the power drops. If at the lower power the vacuum reduces

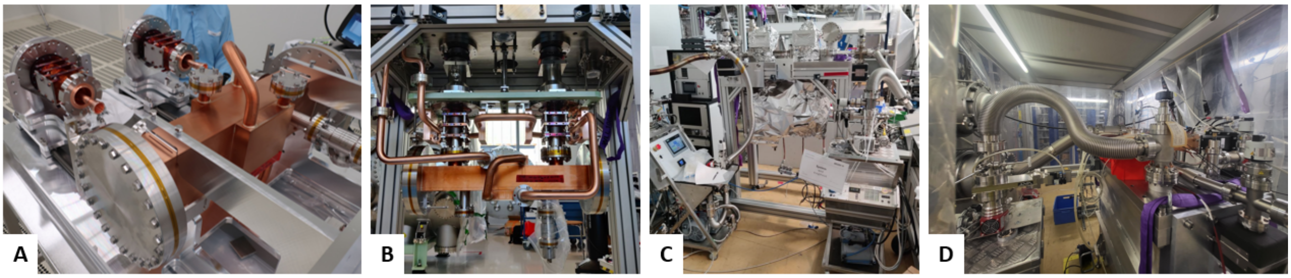

Figure 3: The assembly steps for mounting and installing the coupler test stand A) Cleanroom mounting of the cold parts to the base RF testbox. B) Mounting of the cold parts to the warm parts and the cryostat lid. C) The 120°C bake. D) Testing set-up in place with all supplies and diagnostics connected.

then the sweep will resume from that level, if it continues to rise to the interlock threshold the power shuts off. Once an interlock event has occurred, the vacuum must reduce to below 5×10^{-9} mbar in all regions before a restart.

CONDITIONING RESULTS

The prototype couplers underwent three distinct conditioning runs, an initial run in August 2024 to verify the concept, a longer comprehensive run in April 2025 and a short final run in May 2025 to confirm the conclusions.

Conditioning August 2024

A short conditioning run was performed after coupler installation to check the system and iron out any bugs. The power meters and solid state amplifier were configured to support pulsed mode operation and an attempt was made to integrate readouts for the e-pick ups. Once this was completed two days of conditioning were possible. Figure 4 shows the results of the last day of conditioning, low power runs were performed first at 100‰ then 200‰ and finally 400‰ pushing up to 8 kW, at which point strong vacuum trips were observed in the downstream coupler. The first of which reached 2×10^{-6} mbar after which the base level only dropped to 2.3×10^{-9} mbar. After this, the duty cycle was dropped to 120‰ in an attempt to push through. Once back at 400‰ at around 7.2 kW a conditioning regime is entered with repeated vacuum activity in the cold part. Simultaneously the temperature in the waveguide to coax transition of both couplers rose. The 400‰ ramp is retried many times but processing through a barrier at 5 kW was not possible. It is possible to push through the barrier when dropping to 200‰, however returning to 400‰ restarts the vacuum events in the upstream coupler, and an arc is observed.

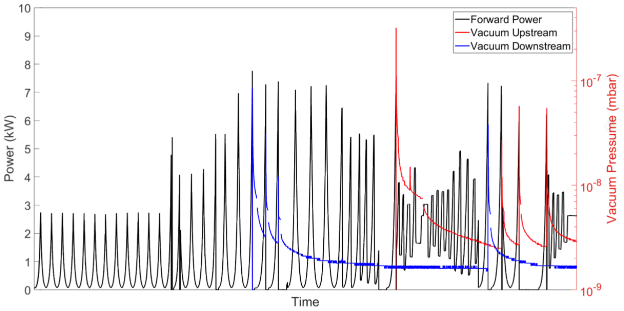

Figure 4: The ramps from August 2024, showing peak power reached of 8 kW and downstream vacuum activity.

The conditioning run was ended due to planned machine shutdown and conditioning was paused until 2025 due to staff availability. This run started to identify a multipacting barrier observed in the 2025 runs that was ultimately overcome by the implementation of the DC bias. The 400‰ run also hints at the issues with vacuum events in the cold part.

Conditioning April 2025

The main bulk of the conditioning occurred in April 2025, with a duration of 14 days, it was concluded due to vacuum activity observed in the cold part. In the initial few days conditioning at low duty cycles, two problems were identified, firstly a faulty vacuum gauge on the upstream coupler (cf. Fig. 2 warmpart outer conductor readout) this was solved by swapping all vacuum monitoring to the getter pump readouts.

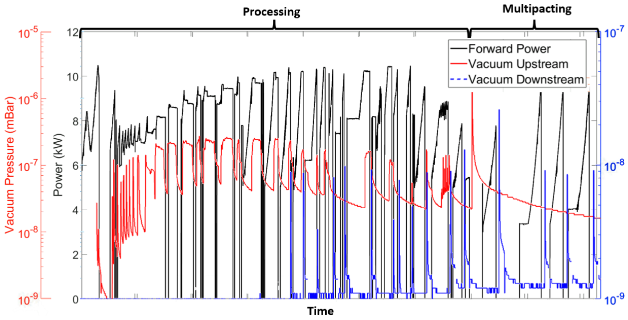

Figure 5: A plot showing low duty cycle conditioning, and then multipacting.

The second issue was multipacting, seen in Fig. 5 as an exponentially sharp rise in the vacuum which stops and returns to the base level as soon as the power is off. Two multipacting barriers were observed, the first at 7 kW could be processed through by dropping the pulse length and repeating power sweeps. The second at 10 kW could not. Figure 5 shows low duty cycle conditioning (note the power increase being paused, and occasionally dropped but no interlock events), and then the multipacting barrier at 10 kW where the vacuum response swiftly tripped the interlock.

To tackle multipacting the couplers have a built-in DC bias on the inner conductors, this was applied on the downstream coupler and it was possible to condition through the 10 kW barrier. When further multipacting was observed on the upstream coupler the same DC bias was applied there. With 3 kV DC bias applied to both couplers, vacuum activity in both the upstream and downstream parts reduced significantly.

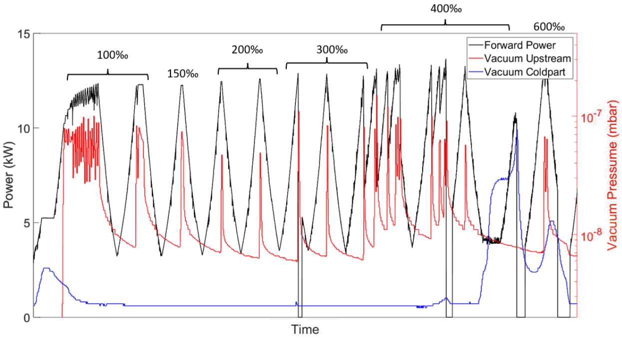

Figure 6: Plot showing progress after installation of DC bias. Where the limiting factor is pulse length and not the power.

With the DC bias installed the max amplifier power (13 kW rising towards 14 kW as pulse lengths increased) was reached successfully on the first ramp for duty cycles up to 400‰ (pulse length 9.756 ms). Above this pulse length vacuum activity in the cold part tripped the interlock (cf. Fig. 6). Through dropping the power and pulse length and repeated processing a duty cycle of 600‰ was reached. Anything above 600‰ (pulse length 14.635 ms) caused significant vacuum response in the cold part and subsequent lower duty cycle runs were not possible without a substantial pause (1+ hrs power off), to allow the vacuum to drop below 5×10^{-9} mbar.

Two steps were taken to overcome this. The first was to increase the penetration depth of the couplers by 2 mm (range ±4 mm). Peak fields in simulations were found at the coupler tip close to the testbox port, a potential source of heating, thus pushing the tip further into the testbox would reduce this. This allowed 700‰ at peak power to be achieved for a short period of time. The next step was to use the PWF to create even shorter pulses and attempt to process through the barrier. Starting at 100‰ and PWF=0.25, the power was ramped up and down and then the PWF increased, this was done for PWF 0.25, 0.35, 0.55, 0.75 and 1. Then the duty cycle would be increased and the PWF dropped to 0.25 and the process repeated. Using this scheme it was possible to reach 990‰ with PWF=1 at 13 kW for 500 ms and then successfully ramp down, attempts to hold at peak power for longer than 500 ms failed due to vacuum activity in the cold part.

CW ramps were attempted and a swift ramp up in power to 10 kW and back down was achieved however any attempt to hold at that power caused vacuum interlock events in the cold part. Switching back to pulse operation anything with a pulse length of over 17 ms caused vacuum events in the cold part with long recovery time and often subsequent lower duty cycle runs were not possible. The possible cause of this is discussed in ”limiting factors”.

Conditioning May 2025

A further conditioning run of 3 days was performed in May 2025 to confirm our findings and see if a warm up and cool down of the set up had any effect. In light of previous conditioning runs a slightly modified scheme was used. After amplifier warm up, the PWF was set to 0.5, the duty cycle increased from 400‰ to 990‰, then with PWF=0.75 the duty cycle was stepped up again. Finally with PWF=1 the duty cycle was ramped again and then if successful slow CW sweeps would be performed. Table 1, shows the pulse length for each duty cycle and PWF. The aim of the run was to hold at peak power for 5 minutes without vacuum spikes and then step down. Full conditioning was not successful. The highest duty cycle reached with PWF=1 was 600‰, all runs at higher duty cycles failed on the 5 min hold.

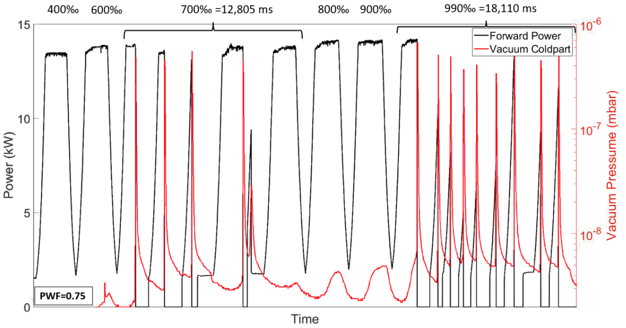

Figure 7: The power ramps for PWF=0.75 at the different duty cycles and the vacuum response in the cold part. Showing processing around 700‰ and then failure at 990‰.

From this round of conditioning, it was possible to identify the point at which the cold part vacuum response dominates and conditioning cannot progress further. As pulse length increases to around 10 ms there is a noticeable up-tick in vacuum activity, predominately in the downstream coupler, (cf. Fig. 6). Through repeated runs, dropping the pulse length and repeatedly pushing to peak power then returning to the longer pulse length it is possible to condition through this boundary. However, when the pulse length reaches 16-18 ms the vacuum response is dominated by the cold part, cf. Fig.6 and Fig. 7, here significant vacuum spikes are observed and there is little chance of recovery. Despite repeated attempts at shorter pulse lengths it was not possible to condition through this barrier.

Limiting Factors

After these conditioning runs it became clear that the significant vacuum activity in the cold part would halt further

Table 1: Pulse Length for Given PWF and Duty Cycles, and the Power at Which the Run Succeeded. A * Denotes that a Successful Ramp Was Only Possible After Processing

PWF	Duty cycle	Pulse length (ms)	Power at hold (kW)
0.5	400‰	4.878	12.5
0.5	600‰	7.317	13.2
0.5	700‰	8.537	13.2
0.5	800‰	9.756	13.6
0.5	900‰	10.976	13.6 *
0.5	990‰	12.073	14*
0.75	400‰	7.317	13.4
0.75	600‰	10.976	13.8
0.75	700‰	12.805	14*
0.75	800‰	14.634	14
0.75	900‰	16.463	14
0.75	990‰	18.11	FAIL
1	100‰	2.439	12.3
1	200‰	4.878	12.5
1	400‰	9.756	13.5
1	600‰	14.635	13.8
1	700‰	17.073	FAIL

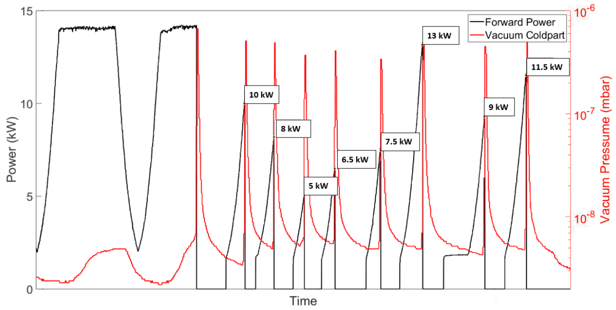

Figure 8: The 900‰ and 990‰ ramps at PWF=0.75, showing the powers at which vacuum spikes occur.

testing. The source of this vacuum activity remains unclear, initially this was thought to be multipacting, as the vacuum raises swiftly to very high values. However, these spikes do not corresponded to any specific power level (cf. Fig. 8). Localised heating of the testbox, leading to outgassing could be a potential source, however no temperature rise was observed at any sensor on the cold part or in the cooling media. The base vacuum level in the cold part also took a significant amount of time to recover after a spike, and often a ramp could not be restarted unless the power was switched off for over 30 minutes.

RF simulations do not show fields in the cold part that would result in heating which would cause such significant out gassing, thus the theory is that surface contaminants are causing the response. These could be the result of poor cleaning or surface issues caused by the significant reworking. A thorough cleanroom inspection of the cold parts is planned after disassembly with the aim to identify the source of the vacuum activity.

THE SERIES COUPLERS

The first series pair was completed May 2025, and after inspection at RI shipped to HZB July 2025. During inspection it was clear that significant improvements had been made to the manufacturing and assembly steps of the series couplers. In particular the protection during e-beam welding and the brazing relating to the ceramic windows. In the prototypes metalisation was observed on the warm ceramics as a result of inadequate protection, this was not observed for the series. In the prototypes copper deposition was observed on the flanges near the cold ceramics windows, resulting in copper flakes on the surface, this was not observed for the series. The first series pair passed inspection with two notes. Two very small dark specs on the cold ceramics which are easily removed and a UC de-greasing mark on the 2 K flange, (a region of low field) that was accepted as would have no effect on the leak-tightness. The first series pair will be mounted this year with the intention of conditioning in 2026.

NEXT STEPS

With the inspection and delivery of the first series pair, the priority will be to condition them before reconditioning the prototypes. The current plan is as follows:

Prior to prototype disassembly: Double check calibration used to ensure measurement accuracy.

During disassembly: Inspect all parts to identify areas that indicate local heating or field emission.

When installing and conditioning the series: Check cleanliness of parts (compare to prototype particle count) and potentially re-clean. Bake out the couplers twice, once just the cold part and base RF testbox and then the full set-up. Consider installing an additional diagnostic on the base RF testbox. Use PWF conditioning scheme.

When re-conditioning the prototypes: Bake out the couplers twice, as with the series. Swap upstream and downstream couplers. Use the PWF conditioning scheme.

CONCLUSIONS

This conditioning made it clear that the inclusion of a DC bias was critical, though conditioning was not fully successful, it would have ended much sooner without the inclusion of the DC bias. This conditioning run also informed the procedure for future runs, and helped to form a more defined conditioning scheme using the PWF to facilitate shorter pulses for better processing. The prototype couplers will be carefully inspected after disassembly which should provide clarity on the cause of the activity in the cold part that limited the conditioning. The aim is to install the series couplers this year and begin conditioning in 2026. Currently it is unclear whether the prototype couplers will be reconditioned or whether the second series pair will be prioritized.

ACKNOWLEDGMENTS

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