PRODUCTION OF THE 1.5 GHZ FUNDAMENTAL POWER COUPLERS FOR VSR DEMO

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Abstract

Research Instruments (RI) and Thales have been producing the first two prototype 1.5 GHz fundamental power couplers for the VSR (Variable pulse length Storage Ring) DEMO since early 2021 and delivered these prototypes in late March 2023. These couplers are designed to provide up to 16 kW CW power to two 1.5 GHz superconducting cavities of the VSR DEMO module and provide variable coupling with a Q_{ext} range from $6{\times}10^6$ to $6{\times}10^7$. The paper describes the challenges in fabricating a scaled coupler and provides details on the modifications to the design as a result of these challenges. The impact of the late stage design modification is discussed along with how this affects future conditioning plans.

INTRODUCTION

Initially conceptualised as an upgrade to BESSY II at the Helmholtz-Zentrum Berlin (HZB), VSR DEMO is an SRF technology research and development project. VSR DEMO aims to validate SRF technology to achieve high current (300 mA) - high gradient (20 MV/m) – continuous wave (CW) operation enabling future storage ring projects to manipulate the longitudinal bunch phase space. To do this an SRF module [1] equipped with two 1.5 GHz SRF cavities and two fundamental power couplers (FPCs) along with ancillary components will be commissioned at high power. The couplers must provide 16 kW CW power and variable coupling with Q_{ext} from $6{\times}10^6$ to $6{\times}10^7$.

The design started by scaling the 1.3 GHz Cornell coupler design [2, 3] for operation at 1.5 GHz. This initial scaled design can be seen in [4], however as the design progressed it became clear that the complex nature of VSR [5, 6] significantly affected the design. Thus modifications such as fixing the cold coax dimensions to reduce HOM propagation and modifying the tip design were made to meet VSR requirements, see [7–9] for details of these modifications.

MANUFACTURING CHALLENGES

The couplers are being manufactured by Research Instruments (RI) in partnership with the sub-vendor Thales. Figure. 1, shows the final FPC design at the start of coupler manufacture in early 2021. However, several small changes were made as a result of discoveries during fabrication along with the larger change to the waveguide to coax transition of the coupler, where the RF feeds into the coupler, this is detailed below. In addition to this certain components required more qualification than expected most notably the ceramics, which is detailed in [9] and the copper coating which is detailed in the section below.

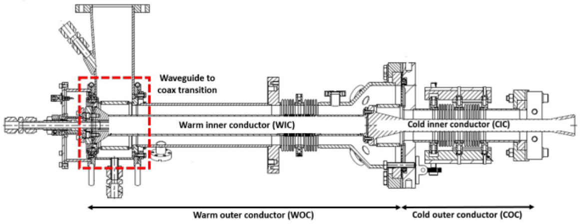

Figure 1: A technical drawing of the full coupler, with the 4 key coaxial parts labelled and the waveguide to coax transition highlighted by the red box.

Copper Coating Qualification

Since couplers for SRF applications must deal with cryogenic temperatures at the cavity side and room temperature at the RF waveguide side, each coupler spans 5-300 K. This means the coupler must be as thermally insulated as possible, to avoid heating the cavity and causing a quench. Thus a high quality copper coating is critical to provide good RF transmission while remaining thin enough to maintain thermal insulation.

Copper coating was required for the following coupler parts: the warm inner conductor (WIC), the warm outer conductor (WOC), and the cold outer conductor (COC), all shown in Fig. 1, and all including at least one bellow. The following tolerances were initially specified; 20μm ± 5μm for tubes and flanges including those at <5K and 20μm ± 10μm -0 μm for bellows. After discussion with Thales, the tolerances were relaxed to 25μm ± 30% for all parts (max 32.5μm and min 17.5 μm), as this better reflected what Thales had been able to achieve in previous coupler projects [10]. This was further relaxed to a maximum of 35 μm with a minimum of 17 μm for the warm parts, and a minimum of 15μm for the cold parts, after the bellow sub-supplier and design were fixed.

The coating qualification of each part was an iterative process. First a simple sample was used for initial coating tests, and then once the process was perfected, a one-to-one sample was used for the final coating test. Coating qualification started in April 2021, the WIC was approved in early July 2021, closely followed by the WOC in late July

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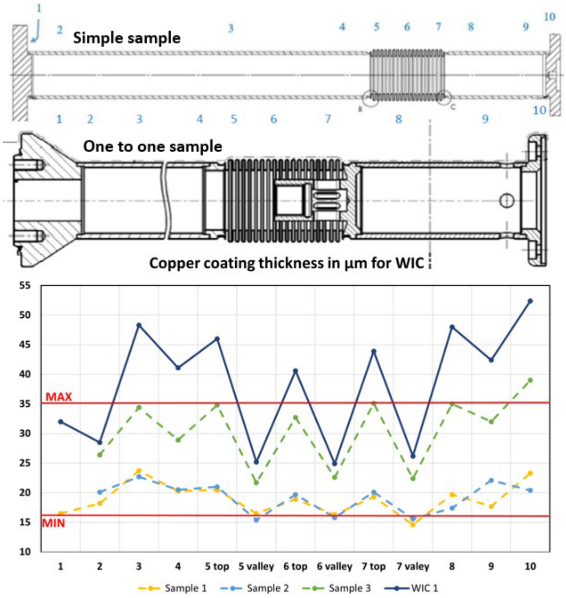

Figure 2: An illustration of the iterative copper coating qualification process for the WIC. The simple sample and the one to one sample (WIC 1) are shown including measurement locations and corresponding results.

2021 and finally the COC in September 2021, meaning the whole qualification process took 5 months.

Figure. 2 shows this process for the WIC, with the measurements points labelled for both the simple and one to one samples. The red lines in the results graph of Fig. 2 indicate the minimum and maximum specified values, anything outside of these lines is out of tolerance. Though the final one to one sample WIC 3 was out of tolerance, Thales identified the issue (poor masking too long in bath) and showed with sample 3 that tolerances could be met. As expected the bellows were the critical parts, with areas out of tolerances localised to the extremes of the bellows as seen in Fig. 3. This was more of an issue for the external parts as the bellows here were only 6 convolutions (rather than the 18 convolutions in the WIC) and coating was dependent on how much they could be expanded during the process.

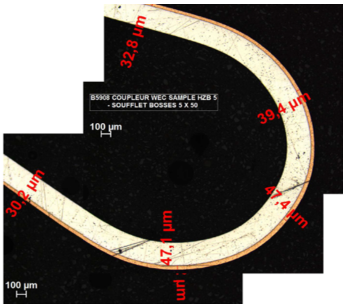

Figure 3: The copper coating of the peak of the bellow of the WOC, showing over tolerances on the extremes.

After discussion with colleagues from XFEL [10], it was found that these over tolerances on the bellows were common and could be accepted. Overall the quality of the coating was high and so far no issues with inclusions or bald spots have been identified.

Waveguide Coax Transition Redesign

During the later stages of fabrication, it became clear that a significant redesign was required to the waveguide to coax transition of the coupler, where RF feeds into the coupler, see red box in fig 1. This is where the WIC connects to the WOC and it is critical to have both a vacuum seal, to preserve the isolation vacuum of the coupler, and an RF seal, in the form of an RF spring, to avoid RF leakage. For the 1.3 GHz Cornell coupler shown in Fig. 4 it can be seen that both the RF spring and the CF vacuum connection sit on the back face of the conical part of the inner conductor.

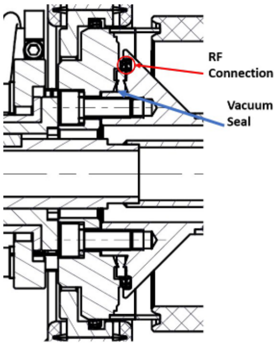

Figure 4: The waveguide to coax transition area for the 1.3 GHz Cornell coupler.

However, when scaling to 1.5 GHz and optimising for best RF transmission [4], the dimensions of the inner conductor were reduced. This meant the available space was significantly reduced, and both the RF and vacuum seal could not be placed behind the cone part of the warm inner conductor. The CF vacuum connection remained behind the cone but the RF spring connection was moved to sit on top of the cone, as seen in the left-hand side of Fig. 5 (original design). This eventually led to two significant problems: firstly, the placement of the RF spring was not simple and required specific tooling. Secondly, because the RF spring requires good contact between inner and the outer conductor, the top face of the inner conductor cone sat very close to the outer conductor. This resulted in a very tight fit, which made disassembly after heat treatment impossible without damaging the coupler.

Due to these two factors and the resultant damage to the coupler, it was critical that the waveguide to coax transition be redesigned. In the redesign both the RF and vacuum seals are positioned behind the cone part of the inner conductor, as in the Cornell design. This was possible due to the increase in warm inner conductor dimension made to improve cooling. Though the warm inner conductor dimension was modified before manufacture started [8], the waveguide to coax transition was not modified then as the issues detailed above were not know. In addition to the moving of both seals, more space was created where the inner conductor and outer

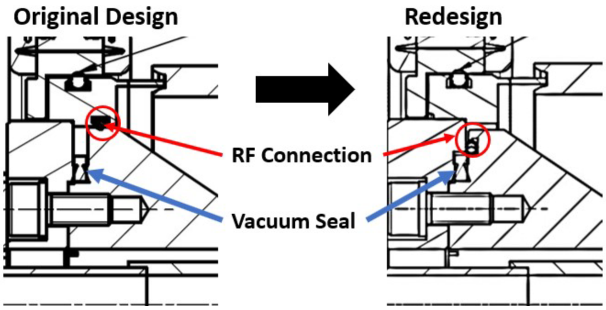

Figure 5: A comparison of the original (left) and the redesigned (right) waveguide to coax transition.

conductor sit parallel to one another to avoid the issue of tight fitting. These changes can be seen in the right-hand part of Fig. 5 (redesign).

CURRENT STATUS

The parameters for the e-beam welding changed with the redesign so required re-optimisation to ensure successful welds. This process has taken approximately 3 months and resulted in two unsuccessful welds, one which required the removal and eventual disposal of a warm ceramic due to significant copper depositions on the inner surface and the other which required a repair, see Fig. 6.

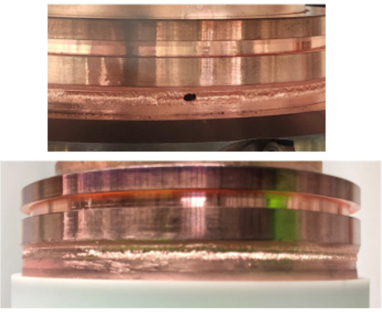

Figure 6: The second failed e-beam weld (above) and the successful repair (below).

This repair entailed creating a small plug of high-quality copper to patch the hole seen in Fig. 6. This plug was welded into place by laser welding and then smoothed with a low-power e-beam weld. After the first e-beam pass the repair appeared successful however the leak test of the part failed and on closer inspection, there was not full penetration of the weld. A second low-power smoothing pass was performed and the second leak test passed. This was then inspected one final time, using a borescope to check the inner surface and small amounts of copper deposition were found on the edge of the ceramic on the inner surface.

The source of the copper depositions likely comes from being unable to correctly place the protection for the ceramic during welding as a direct result of the required redesign. Due to the damage to the parts as a result of the close fit the ceramic was cut away from the conflat unit on one side and then re-welded to the redesigned part. For these welds positioning the weld protection required sliding it the full length of the WIC (roughly 500 mm) and then securing it, rather than placing the protection around the ceramic and then positioning the remaining parts of the WOC ready for welding.

Though this copper deposition is far from ideal, further rework would be time consuming and may not lead to a better result. Therefore, a final leak test of the warm parts was performed and they were assembled into the prototype couplers for heat treatment and residual gas analysis (RGA). These parts underwent a final factory acceptance test (FAT) in March 2023 and were then shipped to HZB, for assembly and conditioning.

In light of the copper deposition on the inner surface of the prototype coupler ceramics, a new conditioning plan must be formed to analyse just how much power these couplers can handle. The initial goal will be to reach low power (< 1 kW) CW operation, for 6 hrs at thermal equilibrium. This will be done with extra monitoring of the warm window using an IR sensor or camera pointed down the RF waveguide. If 1 kW CW is achieved then further conditioning in which the power is increased by small increments will be performed, with continued close monitoring until the couplers either reach 16 kW or fail.

CONCLUSION

After a long manufacturing process the prototype couplers are now on site at HZB and being prepared for conditioning. Assembly ready for testing has begun with the initial clean room assembly of the cold parts and final leak test. This will then be moved to a designated assembly area where the warm parts will be mounted and the whole system baked out before finally assembly into the cryostat. Conditioning is planned to start late summer 2023.

The manufacturing process highlighted some issues with scaling a design to a higher frequency, which will only become more extreme at higher frequencies. These design challenges have impacted the manufacture, potential performance and conditioning plan of the 1.5 GHz prototype couplers. However, learning from this should facilitate successful production of the series couplers, though the e-beam welding of the warm windows must be closely monitored as a critical production step, and if necessary, the tooling to protect the ceramic will be modified to ensure there are no deposition issues for the series coupler. The conditioning plan for these couplers has evolved with their manufacture and now includes a low power CW stage which can be omitted if the production issues are eliminated for the series.

ACKNOWLEDGEMENTS

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REFERENCES

[1] F. Glöckner *et al.*, "The VSR Demo Module Design – A Spaceframe-Based Module for Cavities with Warm Waveguide HOM Absorbers", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 233. `doi:10.18429/JACoW-SRF2021-MOPTEV013`

[2] V. Veshcherevich, S. Belomestnykh, P. Quigley, J. Reilly, and J. Sears, "High power tests of input couplers for Cornell ERL injector", in *Proc. SRF'07*, Beijing, China, Oct. 2007, paper WEP26.

[3] V. Veshcherevich *et al.*, "Design of High Power Input Coupler for Cornell ERL Injector Cavities", in *Proc. SRF'05*, Ithaca, NY, USA, Jul. 2005, paper THP54, pp. 590–592.

[4] E. Sharples, M. Dirsat, J. Knobloch, and A. V. Velez, "Design of the High Power 1.5 GHz Input Couplers for BESSY VSR", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 978–981. `doi:10.18429/JACoW-IPAC2017-MOPVA051`

[5] H.-W. Glock *et al.*, "Progress of the BESSY VSR Cold String Development and Testing", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 1434–1436. `doi:10.18429/JACoW-IPAC2019-TUPGW019`

[6] A. V. Velez *et al.*, "The SRF Module Developments for BESSY VSR", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 986–989. `doi:10.18429/JACoW-IPAC2017-MOPVA053`

[7] E. Sharples, M. Dirsat, J. Knobloch, Z. Muza, and A. V. Vélez, "Design Development for the 1.5 GHz Couplers for BESSY VSR", in *Proc. SRF'19*, Dresden, Germany, Jun.-Jul. 2019, pp. 795–799. `doi:10.18429/JACoW-SRF2019-WETEB9`

[8] E. Sharples-Milne, V. Dürr, P. Echevarria, J. Knobloch, A. Neumann, and A. V. Vélez, "Final Design Studies for the VSR DEMO 1.5 GHz Coupler", in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 2300–2303. `doi:10.18429/JACoW-IPAC2021-TUPAB343`

[9] E. Sharples-Milne, V. Duerr, S. Schendler, N. Wunderer, A. Velez, and J. Knobloch, "The 1.5 GHz Coupler for VSR DEMO: Final Design Studies, Fabrication Status and Initial Testing Plans", in *Proc. SRF'21*, East Lansing, MI, USA, Jun.-Jul. 2021, pp. 652. `doi:10.18429/JACoW-SRF2021-WEPTEV009`

[10] S. Sierra *et al.*, "Status and Lesson Learned from Manufacturing of FPC Couplers for the XFEL Program", in *Proc. LINAC'16*, East Lansing, MI, USA, Sep. 2016, pp. 572–574. `doi:10.18429/JACoW-LINAC2016-TUPLR048`