DEVELOPMENT OF QUALITY CONTROL PROCEDURES FOR THE PROCESSING OF REA3 COPPER PLATED FUNDAMENTAL POWER COUPLER

R. Oweiss[#], J. Crisp, A. Facco[+], M. Leitner, D. Morris, J. Popielarski, L. Popielarski, J.Wenstrom
Facility for Rare Isotope Beams (FRIB), Michigan State University, East Lansing, MI 48824, USA
[+]INFN - Laboratori Nazionali di Legnaro, Padova, Italy

Abstract

The processing of copper plated fundamental power couplers (FPCs) has posed major risks to the successful performance of superconducting cavities. This paper discusses the lessons learnt throughout the development of quality control procedures for the ReA3 copper plated FPCs. Michigan State University (MSU) Re-Accelerator project (ReA3) utilizes eight copper plated coaxial FPCs to power the 80.5 MHz β=0.085 quarter-wave resonators (QWRs) for which baseline quality control procedures are established. The effectiveness of visual inspection process using the microscope & borescope to qualify FPC components is evaluated. The adaptive use of quality control diagnostic devices as the liquid particle counter, surface particle detector & desiccator for the clean processing & assembly is assessed. A summary of the collaborative work to refine & optimize FPC design & processing in correlation to cavity performance & experimental results is presented.

INTRODUCTION

The ReA3 project at Michigan State University utilizes a cryomodule consisting of 8, β=0.085 QWRs all of which have been tested at 4.2 K & 2K showing results largely above specifications [1]. The ReA3 cryomodule design incorporates 8 coaxial copper plated FPCs to enable operation in CW mode, transmitting up to 2kW of RF power to all 8, β=0.085 QWRs & beam.

In order to maintain the good performance & high gradient of the ReA3 β=0.085 QWRs, their auxiliary FPCs were subject to stringent inspection, processing & assembly procedures.

Quality control (QC) processing procedures were developed, implemented & refined as the FPC was subject to a series of RF testing using a good performing ReA3 β=0.085 QWR. As a result, the FPC design had to undergo several iterations for optimization to ensure the integrity & performance stability of the FPC & the powered β=0.085 QWR.

DESIGN EVOLUTION

The ReA3 FPC design (Fig. 1) consists of an outer conductor copper plated stainless steel formed bellows with 22.2 mm inner diameter, a center conductor copper tube with 9.5 mm outer diameter & 7-16 DIN ceramic feed-through. To balance RF loss with thermal conduction the desired plating thickness is 15µm (2 skin depths at 80.5MHz).

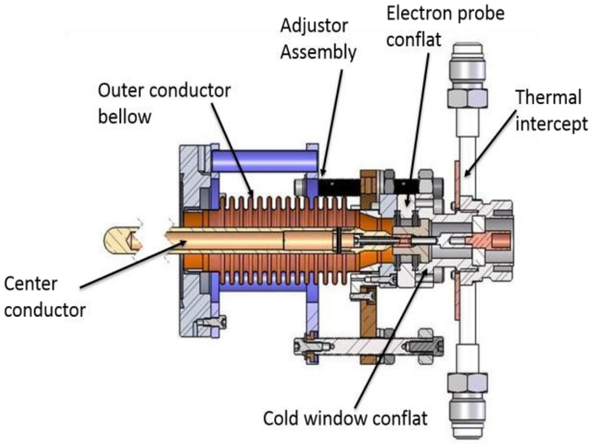


Figure 1: ReA3 FPC initial design.

FPC Design I

The FPC design (Fig. 1) was tested using a β=0.085 QWR. RF results showed field emission levels at 3.2 MV/m. cleanroom assembly was quite difficult as it involved many small fasteners & components. Vacuum grease (Apiezon®) was applied to stainless steel fasteners to avoid galling to the stainless steel adjustors & cold window mini conflat, posing a risk of contamination to the clean assembly. In this design (Fig. 1) the center conductor base was screwed to the cold window & then threaded onto its long tip. Post a cold test; the center conductor & cold window assembly came loose.

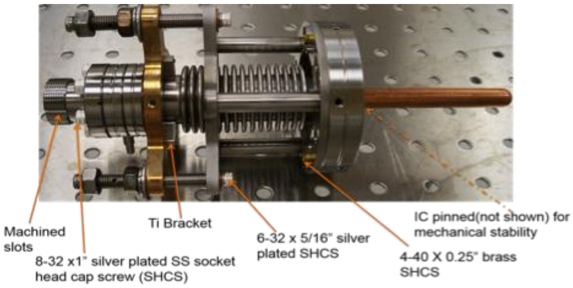


Figure 2: FPC design I.

---

* This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE SC0000661.

[#] oweiss@frib.msu.edu

The design (Fig. 2) was modified to eliminate the use of vacuum grease. The material of a few components was changed to entail a clean assembly with minimal risk of contamination. The center conductor was also redesigned (Fig. 3) to include a small pin to secure the center conductor tip to its base & ensure mechanical stability.

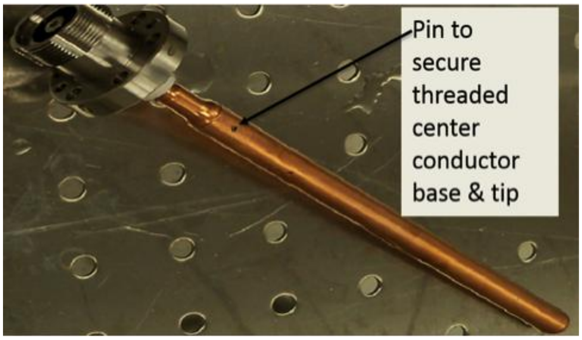


Figure 3: FPC center conductor with pin.

Center Conductor Final Design

The FPC design I was tested on a β=0.085 QWR & RF results showed field emission onset at 3.2 MV/m. Post RF test inspection a few copper shavings were found inside the center conductor assembly. Further tests were performed on several center conductor assemblies (Fig. 3): we discovered that upon the repetition of the assembly, the inner threads on the center conductor tip & base start to wear out, not only to produce copper shavings but to misalign its pin holes. To resolve the misalignment & add the pin the result was an unstable center conductor assembly.

The center conductor was redesigned to eliminate the pin & a copper beryllium stud was added to fasten the center conductor tip to its long base (see center conductor design in Fig. 4).

As the final center conductor was under fabrication, a good FPC with a stable pinned center conductor was tested in a QWR & found field emission free (Fig. 5- 6th with FPC). The RF test was repeated for 15 hours showing no field emission (Fig. 5- 7th with FPC). However, the FPC cable still had overheating problems.

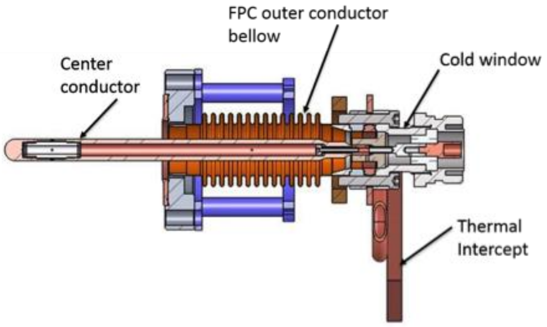


Figure 4: ReA3 FPC final design.

The final inner conductor design was assembled to an FPC bellows with acceptable plating & tested in a QWR, showing field emission onset at 6 MV/m (Fig. 5).

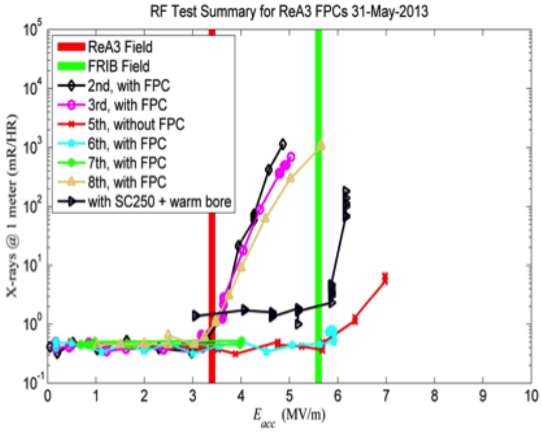


Figure 5: Field emission onset versus accelerating gradient E_{acc} for ReA3 β=0.085 QWRs with FPC.

ReA3 FPC Final Design

A high static heat load (5 KW) was also recorded on an RF test (Fig. 5- 8th with FPC). As a result, the thermal intercept at the FPC bellows flange was redesigned with the cold end bolted to an LN2 cooled copper plate & the electron probe was eliminated to void the excessive heat load. In addition, to overcome the FPC cable overheating problem, a 1.27 cm solid jacketed air dielectric cable was chosen (RFS HCA12-50JPL) & thermal intercepts were developed to remove power & maintain acceptable temperatures. Sapphire thermal links were installed between the cable inner & outer conductors, & the outer conductor was cooled with liquid nitrogen.

The final ReA3 FPC bellows were fabricated with improved plating quality. FPC bellows were inspected for QA [2]. FPC bellows with excellent plating quality was identified for processing & assembly to a β=0.085 QWR. RF results with the new FPC design (Fig. 4) showed no field emission & no signs of cable overheating with the direct cooling provided to the FPC mini flange via the new thermal intercept; the cavity static heat load was minimal (0.5 W).

QUALITY ASSURANCE INSPECTION & PROCESSING

To qualify the integrity of the copper plating on the ReA3 FPC bellows (Fig. 1), the following quality assurance (QA) tests were performed: visual inspection of knife edges, leak check, thermal cycle in liquid nitrogen at 77 K, borescope inspection, leak check.

The Borescope & ReA3 FPC Copper Plating Problems

The borescope, a nondestructive video probe system was used to inspect the interior bellows surface.

Borescope inspection revealed plating discoloration, dark spots -a common feature seen on most of the bellows- as well as plating deposit or splatter (Fig. 6-left). As a result, a couple of bellows were sent back to the vendor for re-plating.

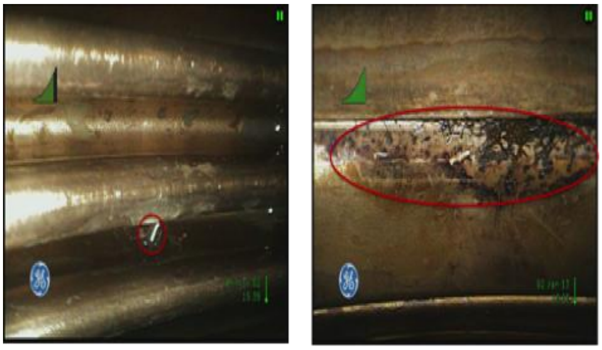


Figure 6: Borescope pictures for plating discoloration & splatter on FPC bellows #6 (left) & poor plating quality on a re-plated FPC bellows #2(right).

Upon receipt of re-plated bellows, borescope inspection clearly indicated poor plating quality on one bellows (Fig. 6– right).

To further investigate the copper plating quality issue, a 1200 psi high-pressure rinse test was performed on a perforated bellow. The rinse took place for a few minutes using an 8-jet nozzle with 0.5mm orifice diameter & some plating peeled off [2].

With arguments on the validity of a destructive high-pressure rinse test on the perforated bellow; an intriguing observation on the plating of a few processed FPC bellows was reported. Five FPC bellows (Fig. 7) were inspected, processed & assembled in ISO 5 cleanroom. After a few weeks of storage in the cleanroom, the copper plating on the cuff weld area & the mini conflat on 2 bellows appeared questionable. The QA department performed a simple Scotch® tape test at the suspected area & the plating peeled off immediately. All bellows were sent back to the vendor for re-plating. The FPC plating quality, acceptance criteria listing were highlighted for further research for improvements [2].

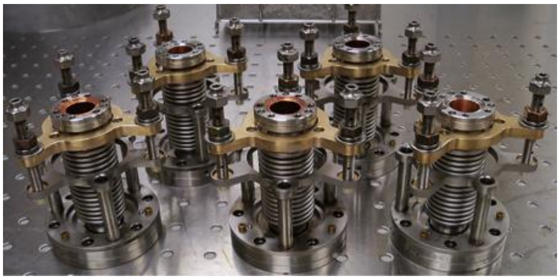


Figure 7: Processed FPC assemblies in ISO 5 cleanroom.

Final Processing & Cleanroom QC Procedures

With the goal to study & validate the FPC design & processing procedures with performance, it was decided to identify, process & test the good plated FPC bellows. The borescope inspection showed a few dark spots, with an overall acceptable plating quality on FPC bellows #1 (Fig. 8) & re-plated bellows #6.

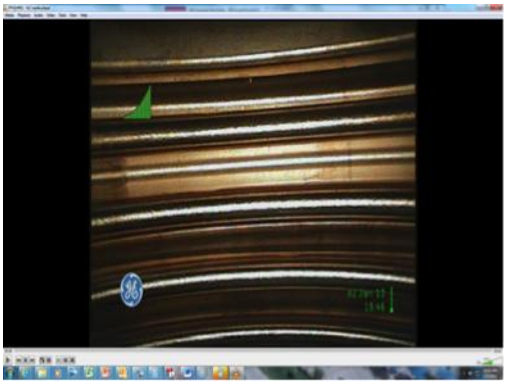


Figure 8: Borescope movie for copper plating inspection on FPC #1.

Preparatory & cleaning procedure on identified FPC bellows & assembly components were followed. Residual magnetic field checks were performed on all stainless steel components & the FPC bellows. ReA3 procedures to demagnetize components were followed if their residual magnetic field was greater than 50 mG. Dimensional checks were performed on the center conductor. The center conductor was also polished using Scotch-brite®. The copper plated FPC bellows & copper center conductor were wiped with acetone, 1% solution of Surface cleanse in deionized (DI) water, DI water rinse followed by ethanol rinse. All other components & fasteners were cleaned using the same procedures with exception of using Micro-90® instead of Surface cleanse®. The FPC bellows & copper inner conductor parts –separated from fasteners- were ultrasonic cleaned together using 1% solution of surface cleanse® & ultrapure water (UPW) at 38°C for 20 minute, followed by a medium pressure rinse. Using the same detergent in the ultrasonic cleaner; fasteners & the rest of the assembly components were ultrasonic cleaned at 38°C for 30 minutes followed by medium pressure rinse. Then, a rinse cycle in only UPW takes place to ultrasonic clean the FPC bellows & center conductor at 38°C for 30 minutes followed by a medium pressured rinse. Next, another rinse cycle in UPW to ultrasonic clean the fasteners & components at 60°C for 40 minutes. Finally, all ultrasonic cleaned components were set to dry in ISO 5 cleanroom for the clean assembly on the next day. As the first FPC was assembled & tested in a QWR, field emission onset levels were detected at 3.2 MV/m (Fig. 5).

The Liquid Particle Counter was primarily used to qualify the FPC assembly prior to its assembly to a QWR cavity. The FPC assembly was medium pressure rinsed & rinse sample were collected to check the 0.3 µm cumulative liquid particle counts (Fig. 9). The rinse step was repeated until liquid counts were within the

UPW baseline of around 300 particles/ml (for the 0.3, 0.5, 1 & 5 µm particles).

Figure 9: FPC assembly rinse (left) & liquid particle counter (right) in the cleanroom.

When the next FPC was assembled to its cavity for testing, RF results showed field emission onset at 3.2 MV/m (Fig. 5). As a result, this step was refined to qualify & rinse the FPC bellows & the inner conductor assembly separately.

The Cleanroom Desiccator (Fig. 10) was used to dry the medium pressure rinsed bellows & center conductor assembly. The desiccator is designed to provide dry nitrogen flow into its stainless steel cabin until a relative humidity (RH) set point of 6% is reached. The QC step was added to refine the procedure & fully dry any residual water inside the bellows due to the convulsions geometry or poor cuff weld trapping contaminants & causing field emission [2]. It was also recommended to ensure complete drying of the center conductor as some oxidation marks (Fig. 11 -left) were visible on its surface post an RF test. The oxidation marks disappeared when wiped with 1% solution of Citranox® & DI water (Fig. 11 -right).

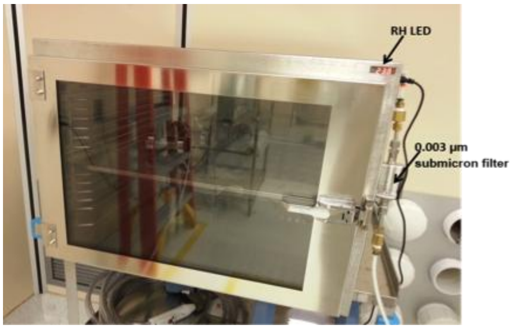


Figure 10: FPC bellows drying in the cleanroom desiccator.

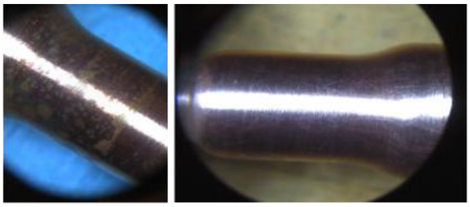


Figure 11: Microscopic inspection for the center conductor assembly post an RF test before (left) & after Citranox® cleaning (right).

Air & Surface Particle Detectors were used for QC. Air particle counts were performed prior to any critical assembly to detect the 0.5 µm particle size counts. The QC threshold of less than 1333 particles/m^3 must be attained for the FPC assembly to take place. Surface counts were performed on the dry bellows (Fig. 12) as well as inner conductor to qualify the clean assembly. A threshold of 0.05 particles/cm^2 must be reached to pursue the assembly.

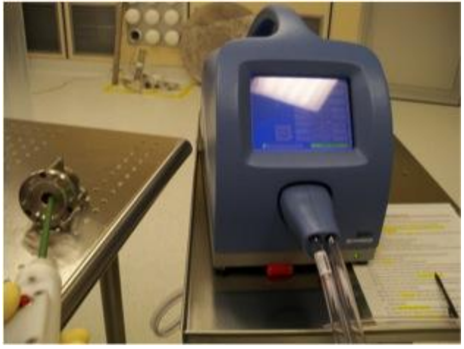


Figure 12: Surface particle detector probe scans the inner surface of the FPC bellows.

ReA3 FPC Bake Manifold (Fig. 13) was designed & built to accommodate up to 9 FPC assemblies for pump down, leak check & 200°C bake in the cleanroom. FPC assembly was completed on a bake manifold. The manifold was purged with dry filtered nitrogen to create a positive pressure & ensure a clean assembly. Surface particle counts were taken on the manifold nipple where the FPC was assembled.

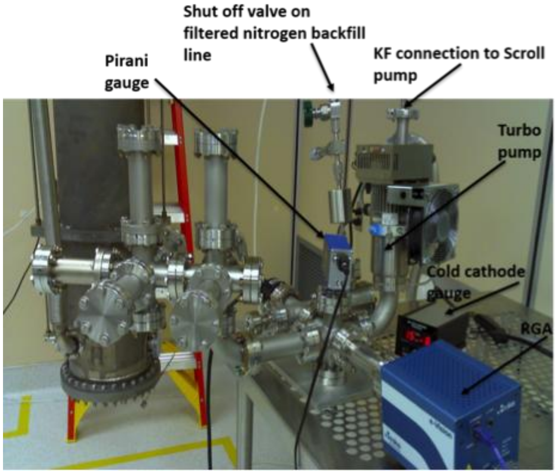
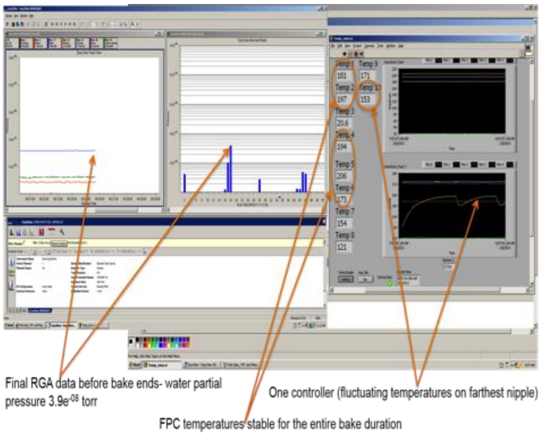


Figure 13: ReA3 FPC bake manifold in ISO7 cleanroom.

The FPC was pumped down & leak checked & finally baked at 200°C using heat tape. The manifold pressure was monitored via residual gauge analyzer (RGA) & bake temperatures were also monitored by lab view program (Fig. 14). At the end of the bake, the manifold was purged with filtered dry nitrogen & FPC assembly was removed from the manifold & assembled to its β=0.085 QWR for RF testing.



Final RGA data before bake ends- water partial pressure 3.9e-08 torr

One controller (fluctuating temperatures on farthest nipple)

FPC temperatures stable for the entire bake duration

Figure 14: ReA3 FPC#6 UHV bake data.

CONCLUSIONS

Diagnostic devices were powerful & effective tools for making informative decisions on improving the quality of copper plating for the ReA3 FPC bellows & the refining processing procedures & the coupler design. The FPC copper plating specification to improve the plating quality & acceptance criteria listing was further investigated. We were able to confirm our matrix for plating acceptance & the cleanroom QC thresholds; despite the discoloration on FPC bellows, RF test results exceeded the FRIB field (5.6 MV/m). ReA3 FPC final design developed & tested successfully for reliable operation with the mitigation of the cable overheating & excessive heat load issues.

ACKNOWLEDGMENTS

The authors would like to thank all the members of the NSCL & FRIB for their significant contribution to work in this paper, in particular Byambatsogt Enkhbat, Steve Bricker, Kenji Saito & Michael Goodrich. We also would like to acknowledge & thank Bob Laxdal, Michael Kelly & Peter Kneisel for their weekly contribution to our SRF teleconference.

REFERENCES

[1] A. Facco et al., “Faced Issues in ReA3 Quarter-wave Resonators and their Successful Resolution”, SRF 2013: Paris, France, 2013, THIOD02.

[2] L. Popielarski et al., “Testing of Copper Plating Quality on ReA3 Coupler Bellows and Approach to Improved Plating for FRIB Production”, SRF 2013: Paris, France, 2013, THP067.