RF-LOSS MEASUREMENTS IN AN OPEN COAXIAL RESONATOR FOR CHARACTERIZATION OF COPPER PLATING *

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Abstract

An experiment has been conducted to measure differences in cavity Q caused by various cavity surface treatments. A requirement of the experiment was that it show little sensitivity to the reassembly of the apparatus with various test pieces. We chose a coaxial half-wave resonator, with an outer conductor extending significantly beyond the length of the inner conductor. At 700 MHz the outer conductor acts as a cut-off tube, eliminating the need for electric termination and thus any RF-contacts that can influence the accuracy of the Q-measurements. The experiment is aimed at qualifying the performance of cyanide-copper plated GlidCop Al-15 LO-OX in comparison with that of a machined GlidCop Al-15 LO-OX surface. To maximize the sensitivity of the measurement we use a fixed outer conductor made of Oxygen Free Electronic (OFE) copper and only replaced the inner conductor, which is mounted on a low-loss Teflon pedestal located in the low electric field region of the half-wave TEM mode. The Q-values of machined GlidCop Al-15 and cyanide-copper plated GlidCop Al-15 inner conductors are measured against the reference Q of the annealed OFE co-axial cavity. This extremely simple configuration allows a statistically significant number of repetitions of measurements and should provide accurate comparative measurements. The results will be useful for the community in deciding the surface treatments for high-Q copper accelerators. While outside of the scope of the qualification of the cyanide copper plating, two UBAC plated OFE copper pieces have been added to the comparison.

EXPERIMENTAL SETUP

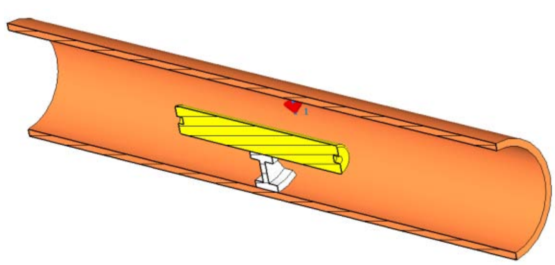

Figure 1: Coaxial resonator geometry without rf-joints.

Based on an idea proposed by James Potter in the 1980s [1] a coaxial cavity was built that did not have any rf-joints (Figure 1). The outer conductor with a cut-off frequency > 700 MHz was picked to extend beyond each end of the inner conductor to a length, where the fields attenuate down to –60 dB, thus no terminating walls are needed. The length of the inner conductor sets the frequency of the resonator. In this configuration there is free access to the cavity volume to place and exchange the inner conductors. As no rf-joints need to be opened, the Q-values for properly placed inner conductors should be very repeatable and the Q-value itself will not be changed by the quality of the rf-joint. The inner conductors were placed on a low-loss Teflon (ε_r=2.1, tan δ=0.00015) saddle that could be freely moved in and out of the outer tube. The position of the Teflon holder was selected in the low electric field region to minimize its rf-loss contribution.

Validation of the Setup

Before starting the evaluation of the various copper pieces the setup has been validated for measurement accuracy. The following checks have been done:

- *Repeatability of the Q-measurements:* One inner conductor was placed inside the tube, and the loaded Q was measured. The inner conductor was removed again and the procedure was repeated several times. The loaded Q measurements were all within ± 0.5%.
- *Insensitivity against the position of the inner conductor in the outer tube:* One inner conductor was moved axially in the outer tube and the Q was re-measured for deviations from the center point of the tube up to 1 inch. The change in loaded Q was less than 1 %. As we could place the inner conductor with an accuracy of < 1/8", we could do much better than this largest deviation. This result also shows that the length of the outer tube has been picked long enough to provide a cavity boundary by attenuation.
- *Change of the Q measurement due to the rf-losses in the Teflon saddle:* We had 2 Teflon saddles available that could be placed side by side at the same axial location (spanning an angle of 120 degrees). The difference in measurement between the loaded Q with one and with 2 saddles can be used to deduct the losses due to one Teflon piece. Again the influence on the loaded Q was < 0.5%, which was within the range of measurement errors.
- *Influence from the rf-probes (drive and pick-up):* The only rf-contacts that could not be avoided were the contacts of the rf-probes. Measurements were repeated with the probes screwed in by different amounts. After correction for the changed coupling,

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the unloaded Q values were within the measurement accuracy.

- *Human influence:* For every change of the setup we recalibrated the network analyzer. This involved quite a few steps including the setup for Q measurement (from transmission) and loading by the probes (in reflection). To minimize errors we always performed those steps and the measurements themselves with 2 people present.

After confirming that the outer tube was long enough under rf-considerations we capped both ends for the measurements with a cardboard cap to avoid air moving through the cavity (breathing warm air into the cavity immediately changed the frequency of the resonator).

MEASUREMENT SERIES

A number of measurement series have been performed that were accompanied by polishing and heat treatment.

The first series measured the Q-values of the original inner conductor pieces, two machined OFE pieces, two machined GlidCop Al-15 LO-OX pieces and two cyanide-copper plated GlidCop Al-15 LO-OX pieces. The Q-values of all these pieces were much lower (10 – 22 %) than the expected theoretical Q-values from simulations with Superfish [2], MWS [3] and MAFIA [4].

In a first processing step one of each type of inner conductor was polished. From the un-plated pieces, 3 mils of material were removed using Scotch-Brite and 500 grit sandpaper, both made from aluminum oxide. From the plated piece only 2 mils of material were removed with aluminum oxide sandpaper to make sure that the GlidCop was not exposed. The second series of measurements still showed very low Q-values in all specimens, even though the polished pieces showed a performance improvement by 1.5 – 2.5 %.

As none of the parts have been annealed after machining, in a next step all pieces including the OFE outer conductor were heat treated at 800^{o} C in a nitrogen atmosphere. While the Q-values improved significantly, they still were too low compared to the theoretical value. The largest improvement was achieved in the cyanide copper plated inner conductors that improved by more than 10%. The polished OFE inner conductor Q-value still only achieved 95% of the theoretical value. All other conductors performed lower.

As numerical Q-value predictions for OFE copper resonators are accurate within better than a percent, the results to this point indicated that the surfaces were still off optimal conditions. The surface condition of the outer conductor was identified as one source of Q-reduction, as it was rough (the surface roughness before polishing was estimated at 64 micro-inches rms) due to machining with a pointed tool without any polishing. Polishing the outer conductor improved the surface roughness to an estimated 32 micro-inches rms. Also, the previously polished inner conductors were polished further. Their surface roughness was estimated at 16 micro-inches rms. Not surprising, the performance of all pieces dropped after the polishing due to the amount of work done to the surfaces. In a final processing step all pieces were annealed again. This heat treatment step mimicked the blistering test that usually is done for plated surfaces. The parts were heated to 1750^{o} F in a hydrogen atmosphere.

The measurements of the pieces in the best possible surface conditions finally provided confidence in the results. For the OFE inner conductors the theoretical value was achieved. So the performance of the GlidCop and cyanide copper plated pieces can be put in perspective with the ideal copper performance.

COPPER SURFACE COMPARISON

To compare the performance of the various surfaces it has to be considered that the measured Q-values represent the combined value for the inner and outer conductor system. To separate out the inner conductor Q-values for comparison the outer conductor Q needs to be known. There is no combination of measurements that provides a sufficient number of known quantities to algebraically separate out this number. The only method to get this number is through the simulation results. In the simulations of the ideal properties the split of the rf-losses between inner and outer conductor is known. Thus the theoretical value of the outer conductor Q-value is known. This value does not change when the inner conductors are changed. Thus, as the experiment with only OFE surfaces achieves the theoretical value, it can be assumed that the outer conductor Q-value is also identical to the theoretical value. Now the inner conductor Q-values can be calculated as

$$1/Q_{inner} = 1/Q_{all} - 1/Q_{outer} \ . \qquad (1)$$

The overall Q-value has been obtained from the measured loaded Q by correction for the coupling loops.

Comparison

From the simulations the ratio of rf-losses between inner and outer conductor is 3.44. Using the theoretical Q-value for the all-OFE configuration of 10094, Q_{outer} = 44777. Table 1 shows the comparison of the GlidCop surface and the cyanide copper plated surface with respect to the OFE copper performance.

Table 1: Q-values of the various copper surfaces

Material	Q	Δ to Reference
OFE #2	13017	Reference
OFE #1	12708	-2.37 %
GlidCop #2	12248	-5.90 %
GlidCop #1	12029	-7.59 %
Cyanide #2	11828	-9.13 %
Cyanide #1	11599	-10.89 %

For each material the piece #1 was not polished, piece #2 was polished according to the description above. The table shows that polishing and annealing the surfaces gives the best results. Machining without polishing reduces the performance by approximately 2%. Both GlidCop and cyanide copper plated surfaces were low compared to the OFE surfaces, GlidCop being a better choice if rf-losses are limiting an application.

Addition of UBAC Plating to the Comparison

Originally we limited our investigation to the previously reported materials. Another plating that is frequently used is UDYLITE Bright Acid Copper (UBAC) plating. We had not considered this, as we were interested in surfaces where we were familiar with brazing procedures, which was not the case for UBAC. To complete the comparison we added UBAC plated inner conductors. These conductors have been measured before and after a 1750^{o} F heat treatment. As shown in Table 2 in both cases their performance was superior to GlidCop and cyanide copper plating. After annealing the performance was almost identical to that of the ideal OFE surface.

Table 2: Q-values of UBAC surfaces compared to OFE copper, with and without heat treatment (HT)

Material	**Q**	**Δ to Reference**
OFE #2	13017	Reference
UBAC #1 (no HT)	12657	-2.77 %
UBAC #2 (no HT)	12715	-2.32 %
UBAC #1 (HT)	12942	-0.58 %
UBAC #2 (HT)	12934	-0.64 %

SUMMARY

OFE copper, despite its superior rf-properties in many cases is not the best material for rf-resonators. GlidCop, due to its better mechanical properties is often chosen as a replacement. To improve the rf-performance of GlidCop resonators, plating can be applied to the surfaces. For a better understanding of the performance degradation by using GlidCop or cyanide copper plating on GlidCop an experiment has been devised and highly accurate measurements of Q-values of these materials have been compared. Previous experiments at LANL were done at much higher frequency (22 GHz) and were of limited accuracy [5]. The data show that GlidCop and cyanide copper plating increase the rf-losses by 6 – 9%. Polishing of the surfaces is important; otherwise for our machining procedure the losses increase by another 2%. The experiment showed that cyanide copper plating has higher rf-losses than the clean GlidCop surface. A better plating that shows a performance similar to OFE copper is UBAC plated copper. We gave this material a lower priority in our experiment, as we are lacking experience in brazing UBAC plated surfaces.

ACKNOWLEDGEMENTS

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REFERENCES

[1] James Potter, JP Accelerator Works, private communication
[2] Superfish, electromagnetic simulation software from the Los Alamos Accelerator Code Group (LAACG), http://laacg.lanl.gov/laacg/services/
[3] Microwave Studio (MWS), electromagnetic simulation software from CST, Germany, http://www.cst.com/
[4] MAFIA, electromagnetic simulation software from CST, Germany, http://www.cst.com/
[5] Jian Fei Liu et al., ‘’RF-Surface Resistance of Copper-on-Beryllium at Cryogenic Temperatures measured by a 22-GHz Demountable Cavity’’, Proceedings of PAC 2003, Portland, OR, USA

