APPARATUS AND TECHNIQUE FOR MEASURING LOW RF RESISTIVITY OF TUBE COATINGS AT CRYOGENIC TEMPERATURES*

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Abstract

An *in-situ* technique for coating stainless steel vacuum tubes with Cu was developed to mitigate the problems of wall resistivity that leads to unacceptable ohmic heating of the cold bore of superconducting magnets and generation of electron clouds in RHIC that can limit future machine luminosity enhancement. Room temperature RF resistivity measurements indicated that 10 μm Cu coated stainless steel RHIC beam tube has a conductivity close to copper tubing. Before coating the RHIC beam pipe with copper, it is imperative to test the Cu coating's conductivity at cryogenic temperatures to ensure coating effectiveness in lowering resistivity. A folded quarter wave resonator structure has been designed and built to be inserted inside a cryogenic system to measure the RF resistivity of copper coated RHIC tubing at liquid helium temperatures. The design is based on making the resonator structure out of a superconducting material such that the copper coating is the most lossy material. RHIC tubing samples prepared with different magnetron sputtering deposition modes are to be measured by the apparatus. Cu coating is to be optimized by iterative processes. Additionally, this device can also be used for the development of better, cheaper superconducting radio frequency (SRF) cavities and electron guns. The apparatus and its design details will be presented.

INTRODUCTION

Electron clouds, which have been observed in many accelerators, including the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory [1-3], can act to limit machine performance through dynamical beam instabilities and/or associated vacuum pressure degradation. Formation of electron clouds is a result of electrons bouncing back and forth between surfaces, with acceleration through the beam, which can cause emission of secondary electrons resulting in electron multipacting.

One method to mitigate these effects is to provide a low secondary electron yield surface within the accelerator vacuum chamber. At the same time, high wall resistivity in accelerators can result in unacceptable levels of ohmic heating or to resistive wall induced beam instabilities [4]. This is a concern for the RHIC machine, as its vacuum chamber in the cold arcs is made from relatively high resistivity 316LN stainless steel. This effect can be greatly reduced by coating the accelerator vacuum chamber with oxygen-free high conductivity copper (OFHC), which has conductivity that is three orders [5,6] of magnitude larger than 316LN stainless steel at 4 K. Originally there were plans to explore coating walls with titanium nitride (TiN) or amorphous carbon (a-C) that have shown to have a small secondary electron yields (SEY) [7]. But, later results [8] strongly suggest that a-C has lower SEY than TiN in coated accelerator tubing. Nevertheless, new experimental SEY measurement indicated that there was no need to pursue a-C coating either, since well-scrubbed bare copper can have its SEY reduced to 1 [9] (SEY < 1.3 is needed to eliminate electron cloud problems).

Consequently, any of the new machines with RHIC-like intensity and bunch spacing are being built with internal coatings, the large hadron collider (LHC) with its copper cage [10] being but one example. Applying such coatings to an already constructed machine like RHIC without dismantling it is rather challenging. In the case of RHIC this is due to the small diameter bore of the vacuum chamber and the limited number access points, which are about 500 meters apart.

A deposition technique based on a magnetron mole was developed and successfully coated long narrow stainless steel RHIC sample tubing with 2 μm, 5 μm, and 10 μm, thick OFHC [11-14]. RF resistivity measurements at room temperature on 32 cm long RHIC stainless steel tubes coated with 2 μm, 5 μm, and 10 μm, thick OFHC indicated that for the later 2 coatings conductivity was about 84% of pure copper. Since joints and connectors reduce the experimentally measured Q, the conductivity value of coatings may be even closer to pure solid copper. Computations [15] indicate that 10 μm of copper should be acceptable for even the most extreme future scenarios. Nevertheless, since resistivity at cryogenic temperature might be different, it must be measure in a system that's being developed.

A device for measuring RF resistivity of copper coated stainless steel tubes at cryogenic temperatures is being developed. The technique is based on Q measurements, from which the RF resistivity is to be determined, since for a fixed geometry the quality factor of a resonant cavity is proportional to the inverse of the real part of the surface resistivity. Although variations on that technique can have multiple applications, the focus of this effort is to develop a device and technique for measuring and optimizing conductivity at cryogenic temperatures of RHIC tubing coated with OFHC. With this device, Cu coating of RHIC tubes is to be optimized by iterative processes.

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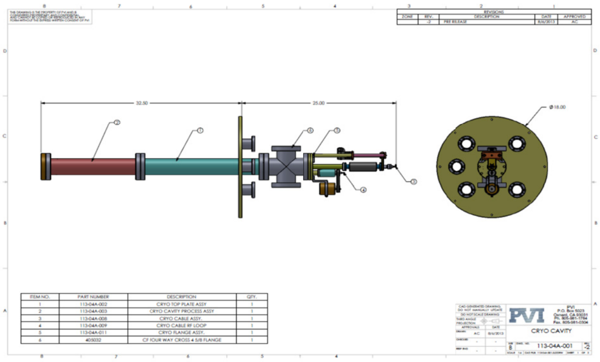
DESIGNED GOALS

As stated earlier a major concern for the RHIC machine, whose vacuum chamber is made from relatively high resistivity 316 L stainless steel, is high wall resistivity that can result in unacceptably high ohmic heating for superconducting magnets, which can limit future machine luminosity enhancement. The high resistivity can be addressed with a copper coating. Copper coated RHIC tube samples, whose room temperature RF resistivities were measured, have yielded very encouraging results. However, before proceeding to coat the entire RHIC cold bore with copper, it is critical to measure and to optimize RF conductivity of the coatings at cryogenic temperatures, since the resistivity can vary strongly due to crystallographic effects, which are unknown for the copper coated layers at cryogenic temperatures. Resistivity usually increases as defect prevalence increases, especially at cryogenic temperatures. Hence it is imperative to develop an apparatus that can facilitate these measurements. Folded quarter wave resonator structures are to be built inside a cryogenic system to measure the resistivity of coatings. The goal is to obtain coatings with a residual resistivity ratio of at least 100. The resistivity of samples are to be deduced from the Q value of resonant modes between 180 and 2000 MHz. Copper coated RHIC tubing samples are to be prepared with different magnetron deposition modes and their resistivity measured by the proposed apparatus. RF conductivity of copper coated tubing is to be optimized by iterative deposition processes as well as optimized thickness.

THE RESONANT CAVITY

Since measurements need to be performed at liquid helium temperatures, it is prudent to fabricate all internal resonator components (except for test samples) out of superconducting materials. Consequently, when the resonator is cooled to liquid helium temperature, the bulk of the losses will be due to the copper coating and a calculation will give the copper coating resistivity at cryogenic temperature. Design of the folded quarter wave resonator structure mounted flange, which includes drives for adjustment of signal launch and pickup to facilitate measurement of multiple frequencies, is shown in Figs. 1-4.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	113-04A-002	CRYO TOP PLATE ASSY	1
2	113-04A-003	CRYO CAVITY PROCESS ASSY	1
3	113-04A-008	CRYO CABLE ASSY.	1
4	113-04A-009	CRYO CABLE RF LOOP	1
5	113-04A-011	CRYO FLANGE ASSY.	1
6	405032	CF FOUR WAY CROSS 4 5/8 FLANGE	1

Figure 1: Cavity assembly on flange to be mounted on a BNL cryostat.

To stay within the allotted budget – the liquid helium cost for a small company without a helium liquefier can be prohibitive – an important design consideration is low helium consumption. Consequently the designed device features adjustable in-situ, at cryogenic temperatures, signal input and output couplers for enabling multiple frequency measurements in each cool-down. The input coupler is small and adjustable to provide weak coupling even at the top frequencies; both input coupler and output coupler are adjustable, motor driven. Superconducting components will be fabricated from high RRR niobium for better thermal conductivity. The first prototype resonator, including all fabricated mechanical components, is to be sent to BNL for debugging the RF measurement technique.

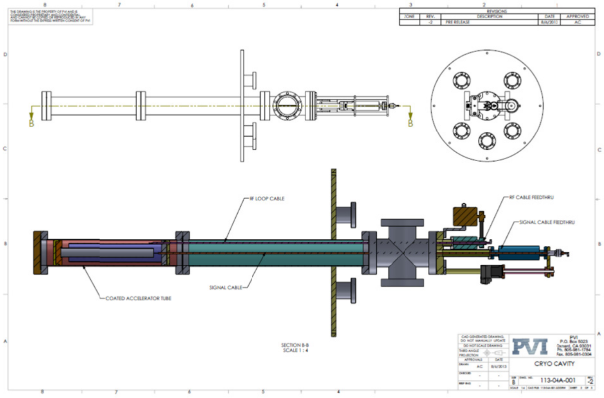


Figure 2: Internal structure of cavity assembly.

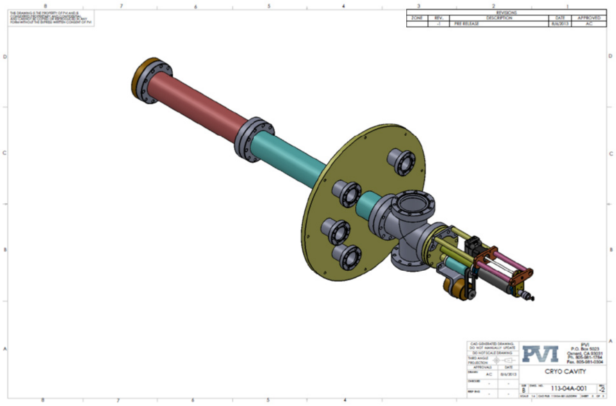


Figure 3: Isometric representation of cavity assembly.

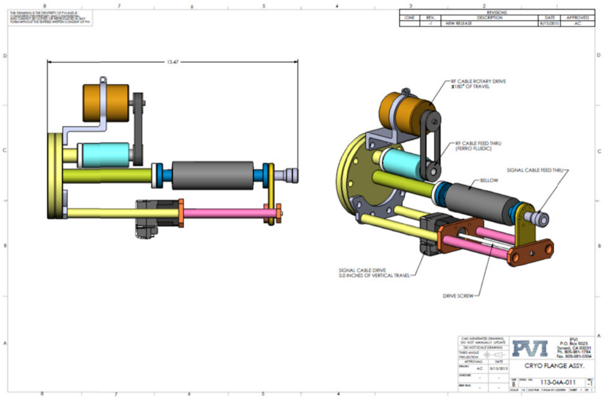


Figure 4: Flange mounted drives for adjustment of signal launch and pickup.

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Two cryostats are to be employed for resistivity measurements: one at BNL, the other at PVI. In figures 1-4 the resonant cavity is on a mounting flange for insertion into a BNL Dewar. Additionally a market ready device is to be setup at PVI on a modified purchased cryostat. Other than the mounting, the resonant cavity is identical to what is shown in Figs. 1-4.

Both RF signal launch and signal pick-up couplers are motor driven adjustable to facilitate multiple frequency measurements during each cool-down. The RF input loop is to be in-situ rotated by a rotary ferrofluidic drive, which has ±180^0 rotation capability, while the output signal coupler has 4-inch linear motion facilitated by bellows. Motion of the input and output couplers are to be under computer control. A network analyzer is to be used to inject RF energy into the cavity through a signal cable and a small RF loop; the output coupler will receive the signal and send it back to be analyzed. The network analyzer will sweep a range of frequencies to detect resonant points. By adjusting the rotation of the RF loop and the position of the signal cable, the signal levels can be fine-tuned for maximum resolution inside the analyzer. Based on these measurements, the RF resistance or impedance of the film can be determined. A PC attached to the network analyzer will control the testing process, log all data collected and interface to the vacuum and motion control systems. The inside of the resonant cavity will be pumped down to a vacuum before being cooled to cryogenic temperatures to remove gases that will condense and freeze and possibly interfere with the motion of the signal cable and RF loop. A vacuum gauge will monitor the internal cavity pressure. One or more cryogenic temperature sensors will be used to determine when the cavity has reached the proper test temperatures. Network Analyzer measurements are to be compared with MicroWave Studio calculations.

STATUS

As shown in Fig. 5, most of the components for the first resonant cavity have been fabricated and are about to be shipped for mounting on the BNL cryostat.

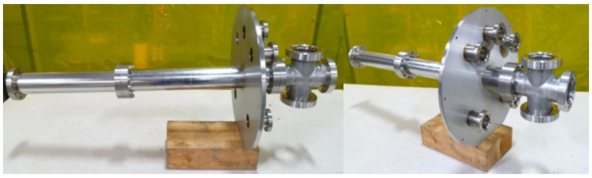

Figure 5: cavity photos for mounting on the BNL cryostat.

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