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NOVEL DEVICE FOR *IN-SITU* THICK COATINGS OF LONG, SMALL DIAMETER ACCELERATOR VACUUM TUBES*

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Abstract

To alleviate the problems of unacceptable ohmic heating and of electron clouds, a magnetron mole with a 50 cm long cathode was designed fabricated and successfully operated to copper coat a whole assembly containing a full-size, stainless steel, cold bore, RHIC magnet tubing connected to two types of RHIC bellows, to which two additional pipes made of RHIC tubing were connected. To increase cathode lifetime, a movable magnet package was developed, and the thickest possible cathode was made, with a rather challenging target to substrate distance of less than 1.5 cm. The magnetron is mounted on a carriage with spring loaded wheels that successfully crossed bellows and adjusted for variations in vacuum tube diameter, while keeping the magnetron centered. Electrical power and cooling water were fed through a cable bundle. The umbilical cabling system, which is enclosed in a flexible braided metal sleeve, is driven by a motorized spool. A process to ensure excellent adhesion was developed. Coating adhesion of 10 µm Cu passed all industrial tests and even exceeded maximum capability of a 12 kg pull test fixture. Details of experimental setup for coating two types of bellows and a full-scale magnet tube sandwiched between them will be presented. Previous SEY Cu coating results indicated that there was no need to pursue amorphous carbon coating, since well-scrubbed copper can have its SEY reduced to 1. Room temperature RF resistivity measurements indicated that 10 µm Cu coated stainless steel RHIC tube has a conductivity close to copper tubing. Work is in progress to repeat the RF resistivity measurement at cryogenic temperatures.

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 vacuum pressure degredation. 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 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. Both effects can be greatly reduced by coating the accelerator vacuum chamber with oxygen-free high conductivity copper (OFHC), which has a conductivity three orders of magnitude larger than 316LN stainless steel at 4 K [5,6]. Originally there were plans to explore coating walls with titanium nitride (TiN) or amorphous carbon (a-C) that have small secondary electron yields (SEYs) [7,8]. But, later results [9] 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 [10] (SEY < 1.3 is needed to eliminate electron cloud problems).

Applying such coatings to an already constructed machine like RHIC without dismantling it is rather challenging due to the small diameter bore with access points that are about 500 meters apart. Essentially, a device and technique for *in-situ* coating of the RHIC cold bore vacuum tubes has been developed. But before embarking on the large task of coating RHIC, a couple of studies are needed to ensure that the expected benefits of coating the RHIC cold bore vacuum tubes with 10 µm of copper are realized.

DEPOSITION PROCESSES AND OPTIONS

Exploration of coating techniques was done before selecting an approach to RHIC coating. Coating methods can be divided into two major categories: chemical vapor deposition (CVD) and physical vapor deposition (PVD). Unless otherwise noted, information contained in the next two sections is referenced in [11], which contains a comprehensive description of CVD and PVD.

Due to the nature of the RHIC configuration, only PVD is viable for in-situ coating of the RHIC vacuum pipes. First, the temperature under which coating can be made cannot be high (400^{o}C is required for some conventional CVD), since the RHIC vacuum tubes are in contact with superconducting magnets, which would be damaged at these temperatures. A second very severe constraint is the long distance between access points. Vapor injected from access points, which are 500 meters apart into tubes with

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7.1 centimeters ID, would likely not propagate far and result in extremely non-uniform coating.

But these constraints also severely restrict PVD options. Obviously evaporation techniques (ovens, e-beams) cannot be used in 7.1 centimeters ID, 500-meter long tubes, as well as a wide variety of vapor generation techniques ranging from high temperature evaporation to sputter bombardment by electron beams, ion beams and plasma, which are precluded by the geometry. Therefore, evaporation must be accomplished locally.

MAGNETRON DEPOSITION STATE-OF-THE-ART

Of the plasma deposition devices like magnetrons, diodes, triodes, cathodic arcs, etc., magnetrons are the most commonly used plasma deposition devices. Major advantages of magnetron sputtering sources are that they are versatile, long-lived, high-rate, large-area, low-temperature vaporization sources that operate at relatively low gas pressure and offer reasonably high sputtering rates as compared to most other sputtering sources. Because of these superior characteristics magnetron sputtering is the most widely used PVD coating technique. Although arc discharges operate with higher intensity, they require the use of special filters [12] to eliminate macroparticles that reduce the net deposition rate to those of magnetrons.

Typical coating rates by magnetrons (with argon gas) are 5 Å/sec for a power of 10 W/cm^2 on the magnetron cathode, though with intense cooling cathode power of 20 W/cm^2 is achievable.

THE DEPOSITION TECHNIQUE

Originally the objective was to develop a plasma deposition device for *in-situ* coating of long, small diameter tubes with about 5 - 10 µm of Cu following by a coating of about 0.1 µm of a-C. But recent results [12] indicated that clean, conditioned copper coating had sufficiently low SEY, i.e., no a-C coating is needed. The magnetron design underwent a number of iterations. First a mobile magnetron with a 15 cm long cathode was designed, fabricated, and tested to coat various samples of RHIC cold bore tubes with up to 10 µm with OFHC at an average coating rate of 30 Å/sec. Internal ring permanent magnets form the magnetic field. Magnetron assembly was mounted on a carriage (***mole***) pulled by a cable assembly driven by an external motor. The cable bundle, which is enclosed in 6 mm diameter stranded SS (or braided copper), contains electric power and water cooling feeds, as well as some instrumentation wires. Umbilical spool chamber and the cable assembly are under vacuum. Other aspects including the dragline have been described elsewhere [13, 14, 15].

Next a magnetron with a 50 cm long copper cathode was designed fabricated (cooling and weight limits the length), and successfully operated to coat an assembly containing a tube of a full-size, stainless steel, cold bore, Relativistic Heavy Ion Collider (RHIC) magnet tubing connected to two types of RHIC bellows, to which two additional pipes made of RHIC tubing were connected. To increase cathode lifetime, movable magnet package is used, and thickest possible cathode was made, with a target to substrate distance of less than 1.5 cm. It was rather challenging, when compared to commercial coating equipment, where the target to substrate distance is 10's cm; 6.3 cm is the lowest experimental target to substrate distance found in the literature. Additionally, the magnetron developed during this project provides unique omni-directional uniform coating.

The magnetron has a 50 cm long copper cathode, which is shown in figure 1. The magnetron is mounted on a carriage with spring loaded wheels that successfully crossed bellows and adjusted for variations in vacuum tube diameter, while keeping the magnetron centered. The carriage can also be seen in figure 1. Some deposition experiments were performed with spring loaded wheels on both sides of the magnetron, such that a set of wheels rolls over coated areas. No indentation in or damage to coating was observed, i.e. the train like assembly option is viable.

Figure 1: Photo of the magnetron assembly: 50-cm long cathode magnetron and spring loaded guide wheels. Leading edge guide wheels are inserted in a full-size RHIC tubing section.

To increase cathode lifetime, the thickest possible cathode is used, which reduces the target to substrate distance to less than 1.5 cm. Strong internal ring permanent magnets, and movable magnet packages are used. Two types of mechanisms, shown in figure 2, for moving the magnet package were tried in order to maximize copper utilization (having stationary magnets resulted in deep groves, due to fast erosion at maximum magnetic field, which require frequent cathode replacements).

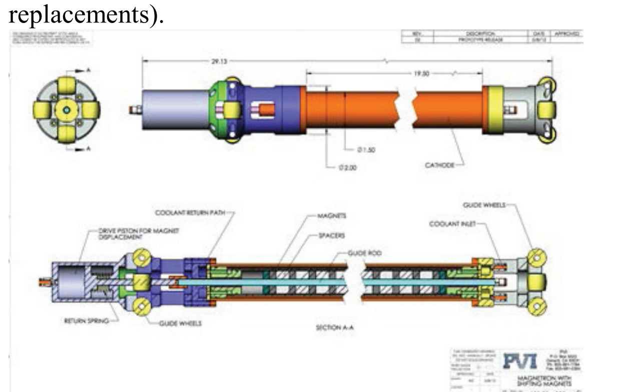

Figure 2: Drawings showing two types of mechanisms for moving the 50-cm long cathode magnetron magnet package hydraulic (top) and guide wheel motion (bottom).

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One mechanism is based on hydraulics, utilizing the magnetron cooling water. Another option tried used guide wheel motion to move the magnet package (both are proprietary). Figure 3 shows that guide wheel motion results in more uniform erosion, and hence, better copper utilization.

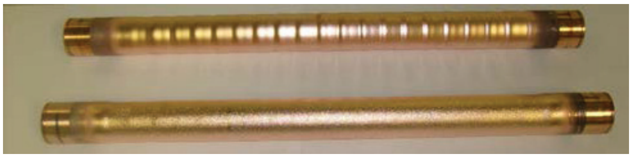

Figure 3: 50-cm copper cathode erosions: hydraulic drive mechanism (top) and guide-wheel driven motion (bottom).

COATINGS RF RESISTIVITY & SEY

Room and cryogenic temperature SEY measurements were performed at CERN on 2 µm, 5 µm, & 10 µm thick OFHC coated stainless steel samples. Obtained results coupled with those reported in the literature [15,16] indicate that baked & scrubbed Cu coating can achieve SEY of 1.

RF resistivity measurements 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 experimentally measured Q, conductivity value of coatings may be even closer to pure solid copper. Computations indicate that 10 µm of copper should be acceptable for even the most extreme future scenarios [17].

COATING ADHESION STRENGTH

Consistent coatings with good adhesion are achieved routinely with discharge cleaning. Although discharge cleaning for surface preparation has been known for a while [18], ours was optimized with a first (proprietary) step that may not be needed in RHIC. Next a positive voltage (of about 1 kV) is applied to the magnetron or a separate cleaning anode; the discharge is then moved down the tube at a pressure of over 2 Torr. The optimized results yielded adhesion strength of over 12 kg [16]. This fact bodes well for magnetic quench survival.

DISCUSSION

Basically, the only remaining issue to resolve is determination and optimization of RF conductivity at cryogenic temperatures and performing magnet quench tests on copper coated RHIC cold bore tubing. Otherwise Lowering RHIC cold bore resistivity and SEY with in-situ copper coating seems feasible. Since resistivity at cryogenic temperature might be different, it must be measure in a system that's being developed.

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