ENHANCING RHIC LUMINOSITY CAPABILITIES WITH IN-SITU BEAM PIPE COATING*

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Abstract

Electron clouds have been observed in many accelerators, including the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL). They can limit the machine performance through pressure degradation, beam instabilities or incoherent emittance growth. The formation of electron clouds can be suppressed with beam pipe surfaces that have low secondary electron yield. At the same time, high wall resistivity in accelerators can result in levels of ohmic heating unacceptably high for superconducting magnets. This is a concern for the RHIC machine, as its vacuum chamber in the superconducting dipoles is made from relatively high resistivity 316LN stainless steel. The high resistivity can be addressed with a copper (Cu) coating; a reduction in the secondary electron yield can be achieved with a titanium nitride (TiN) or amorphous carbon (a-C) coating. Applying such coatings in an already constructed machine is rather challenging. We started developing a robotic plasma deposition technique for in-situ coating of long, small diameter tubes. The technique entails fabricating a device comprised of staged magnetrons and/or cathodic arcs mounted on a mobile mole for deposition of about 5 μm (a few skin depths) of Cu followed by about 0.1 μm of TiN (or a-C).

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 degredation. Formation of electron clouds is a result of electrons bouncing back and forth between surfaces, which can cause emission of secondary electrons resulting in electron multipacting effect. One method to mitigate these effects would be 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 that in turn can lead 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 high conductivity copper (OFHC), which has conductivity that is three orders [5,6] of magnitude larger than 316LN stainless steel at 4 K. And, walls coated with titanium nitride (TiN) or amorphous carbon (a-C) have shown to have minimal secondary electron yields[7,8]. This coating also protects the underlying OFHC coating from oxidation, which would reduce its performance.

Consequently, any of the new machines with RHIC-like intensity and bunch spacing are being built with internal coatings, the large hadron collider (LHC) design [9] being but one example. Applying such coatings to an already constructed machine like RHIC without dismantling it is rather challenging due to the small diameter bore and the access points, which are about 500 meters apart.

DEPOSITION PROCESSES AND OPTIONS

Coating methods (at least with relevance to OFHC and TiN coating) can be divided into two major categories: chemical vapor deposition (CVD) and physical vapor deposition (PVD). Reference [10] contains a comprehensive description of the various deposition processes; unless otherwise noted, information contained the next two sections is referenced to reference [10].

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 one conventional CVD TiN deposition), 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. Introduction of vapor from access points that are 500 meters apart into tubes with 7.1 centimeters ID would necessarily be very non-uniform, which would make resultant coating properties very non-uniform.

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 for the same reasons. Therefore, evaporation must be accomplished locally. One option is a plasma device on a mole that generates and deposits the vapor locally.

Presently, there are a variety of PVD methods used to deposit coatings on various substrates[10]. By definition, physical vapor deposition entails purely physical processes of evaporating materials. The vapor then condenses on the desired substrate. There is a wide variety of vapor generation techniques ranging from high temperature evaporation to sputter bombardment by electron beams, ion beams and plasma. The latter involves a discharge like RF, glow, or an arc. The long distance between access points and the need to have a mole like deposition device precludes the use of RF plasmas.

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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. In "conventional" magnetrons, magnetic fields are utilized to confine electrons that generate high density plasma (usually argon or xenon) near the surface of the material that is being sputtered. 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 [11] to eliminate macroparticles that reduce the net deposition rate to those of magnetrons.

Typical coating rates by magnetrons (w/argon gas) are 5 Å/sec for a power of 50 W/inch^2 on the magnetron cathode, though with intense cooling cathode power of 100 W/inch^2 is achievable. In the above discussion,

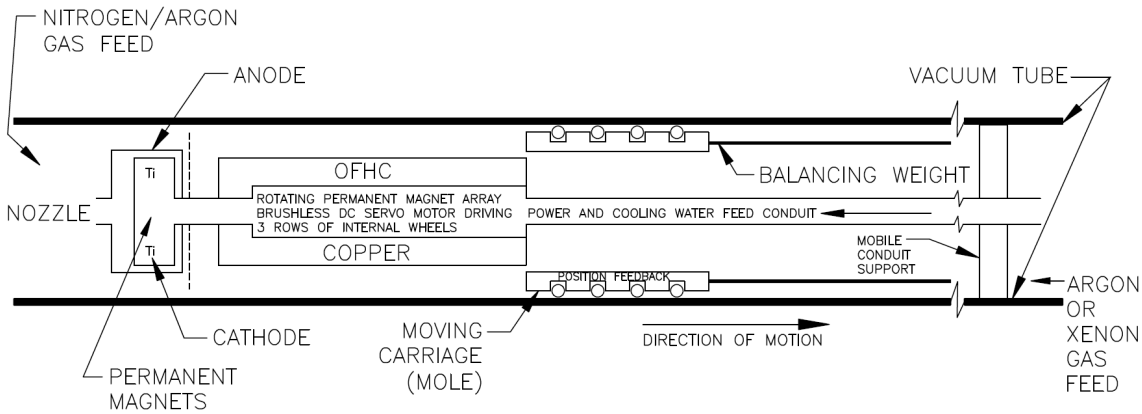

Figure 1 diagram of the deposition device.

(conventional) magnetron implies "balanced" magnetron. "Balanced" means that the bulk of the plasma (especially energetic electrons) is concentrated near the magnetron cathode by magnetic confinement.

Although not yet adopted by industry, a substantial advance in magnetron deposition technology has occurred. Unbalanced magnetron devices, developed by Window and Savvides [12], have proven to have higher deposition rates and deposition at high flux (> 1 mA/cm^2) resulting in lower intrinsic film stresses [13]. Unbalanced magnetrons can operate routinely over a large pressure range from 1.5x10^{-4} Torr [14] to 4.5x10^{-2} Torr [15], with discharge characteristics that vary over a wide range 100 – 500 Volts, and 100's mA – a few Amps. Unlike "balanced" magnetrons, where the bulk of the plasma is concentrated near the magnetron cathode, in unbalanced magnetrons, some of the plasma extends to the substrate. It is accomplished by a magnetic field configuration with some field lines reaching the substrate.

Very relevant for this case is the fact that there is plasma in the vicinity of the substrate, unlike in typical commercial magnetron sputtering deposition systems, with large cathode to substrate distances. Development of the unbalanced magnetron makes a mole mounted sputtering magnetron system, for a configuration with small radial dimensions and short cathode to substrate distance, feasible. The concept for the deposition method described in this paper is supported by conclusive data from an unbalanced magnetron with a long cylindrical copper cathode [16,17], and for a planar magnetron with a titanium cathode operating in N_2/Ar mixture depositing TiN on Cu [14]. Additionally, there is even data showing effective deposition of amorphous carbon on copper [18] with an unbalanced magnetron.

PLANNED DEPOSITION TECHNIQUE

The ultimate objective is to develop a plasma deposition device for *in-situ* coating long, small diameter tubes with 5 μm of copper following by a coating of 0.1 μm of titanium nitride. Figure 1 is a scheme of a plasma deposition technique based on staged magnetrons. A brushless DC servo-motor driving 3 rows of internal wheels moves the carriage, which has position feedback, as well as an external motor that moves, conduit, cables, and assists carriage motion. The first stage is a cylindrical magnetron consisting of a long cylindrical OFHC cathode with the vacuum tube serving as the anode for copper coating the vacuum tube. Permanent magnets coated with epoxy form the magnetic field. Water is used to both cool the cathode and, if needed, spin the magnet array to ensure uniform sputtering (though at this point magnet or cathode rotation does not seem necessary [19]). Argon or xenon can be fed through long, small diameter tubes. Though xenon is much more expensive, it yields higher deposition rates, which may result in lower total cost. The second stage is a conventional titanium cathode planar magnetron with permanent magnets coated with epoxy

forming the magnetic field. Titanium ions in N_2 form titanium nitride upon deposition on copper coated surface.

The nozzle is to optimize the Ti flow for the best TiN coating (too close to the cathode a coating too rich in Ti can be formed [19]). The operating gas can be a N_2/Ar mixture [14,20] with a gas flow ratio of about 1/10. Basically, argon forms the bulk of the sputtering plasma in both magnetrons, which can operate at the same pressure (though a membrane with no contact to wall could be used to separate stages).

Electrical power and cooling water for both stages are fed through semi-rigid conduits with mobile supports that include water pumps and voltage converters to enhance water flow and to reduce ohmic loss.

Since the needed Cu coating is thicker than the TiN coating by a factor of 50, the coating rate is determined by the rate of copper deposition. Assuming a copper coating rate of 5 Å/sec ("conventional" magnetron deposition rate), it would take 2.78 hours to deposit 5 μm of copper. Therefore, it would take close to 3 hours to move one cathode length. Since magnetrons with 2.1 meter long cylindrical cathodes exist in commercial systems [21], a 2 meter long cathode is possible for this system, in which case it would take 695 hours (or 29 days) to coat 500 meters, which is a fraction of a typical RHIC shutdown period. The coating time scales linearly with cathode length, i.e. shorter cathodes are viable options. But, the higher power density levels can compensate for the shorter cathodes. Based on improved performance of unbalanced magnetrons (by a factor of 3-5) [16,17], lower power and/or higher coating rates could be achieved (also due to close proximity of substrate; unlike commercial systems where coating material is lost due to effusion and open geometry). The copper volume needed to coat 500 m. is 557.6 cm^3. A 2 m long, 4 cm OD cathode, would require ablating a 2.2 mm thickness of Cu, i.e., coating a 500 m section with one cathode is feasible.

DISCUSSION

Although the coating technique seems conceptually feasible, a number of rather challenging hurdles are anticipated such as finding the optimal magnetron operating parameters. Among engineering issues to be resolved are cabling and bellow crossing (with mechanical expanding collet inchworm technology). Though these hurdles are non-trivial, but none of the obstacles appear insurmountable.

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