INSERTION DEVICE VACUUM CHAMBER FOR THE LINAC COHERENT LIGHT SOURCE*

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Abstract

The vacuum requirement for the undulator line of the Linac Coherent Light Source is extremely challenging: a low resistive wall impedance 3.42-m-long chamber that fits within a 6.3 mm undulator gap that has ultralow outgassing and a surface finish, less than 100 nm Ra. A prototype chamber will be fabricated from electropolished semiconductor-processing-grade stainless-steel seamless tubing. Since stainless-steel tubing has a high electric resistivity, which can increase the resistive wall wake, a thin layer of copper will be deposited to minimize this effect. A thin nickel plating will be deposited in advance for better adhesion. This process will be followed by electropolishing of the copper surface. The first approach for Cu coating of the vacuum chamber has been investigated. Roughness measurements and preliminary coating results with a one-meter-long tube will be presented.

1 INTRODUCTION

The Linac Coherent Light Source (LCLS) is a high-brightness x-ray free-electron laser (FEL) project that will be constructed at the Stanford Linear Accelerator Center (SLAC). In the LCLS project, the electron beam is accelerated through the 2 mile SLAC linac and will pass through a 121 meter array of 33 separate undulator segments. One of the most important contributions to performance in the LCLS is the control of the wakefield effects inside the undulator. The wakefield effects can be reduced by proper design of the vacuum chamber.

In the LCLS, the 6.3 mm undulator gap necessitates a narrow OD vacuum tube with inside radius of just 2.5 mm. The electron beam interaction with the narrow undulator vacuum tube can generate an energy gradient across the bunch that can potentially reduce the FEL gain. These wakefields are influenced by both beam pipe surface roughness and conductivity. The former are called the surface roughness wakefields, and the latter are called the resistive-wall wakefields. The resistive-wall wakefields can be reduced to a desired level by Cu coating on the interior of the stainless steel tubing or by using copper tubing [1-3]. In addition, wakefields due to surface roughness of the interior of tubing may interact with the beam in the vacuum chamber, which causes degradation of beam emittance.

In this report, techniques for minimizing the wakefield effects in the LCLS vacuum chamber design will be discussed. Specifically, technical issues such as the vacuum chamber material, surface roughness measurements, and Cu-coating process are addressed.

2 TECHNICAL ISSUES

The LCLS conceptual design report (CDR) recommends stainless steel (SS) 316L as the vacuum tube material [3]. In general, the vacuum properties of stainless steel (SS) are excellent, but it has a high electrical resistivity. The design requires minimizing the electric resistivity on the inside of the vacuum chamber surface, which the beam might closely approach, and minimizing the contribution of the resistive-wall wakefield to orbit distortion and emittance growth. To do that, the CDR recommends an application of a thin layer of oxygen-free electronic (OFE) copper (~10 μm thickness to cover the skin depth of 58 nm) followed by electropolishing of the copper-coated surface. A thin nickel substrate may be required as the undercoat before copper coating for better adhesion of the copper to the SS tube.

However, there are many technical challenges with respect to the Ni & Cu plating/coating process of a 3.42 m-long and 6 mm-narrow tube. In addition, the surface roughness of the chamber required by CDR must be less than 100 nm (4 μ inch Ra) after coating. To achieve this extremely smooth surface, the CDR recommends the coated surface of tubing to be electropolished. However, some special considerations must be taken, especially in soft metals like copper. Electropolishing can generally improve the surface roughness of a product by about 50%, based on the input surface Ra. For example, to achieve a surface finish of 4 μinch Ra, we might be able to finish the surface to at least an 8 μinch Ra by a mechanical method before electro-polishing. Also, the surface cannot be smeared in the mechanical polishing process, or the electropolishing may cause the surface finish to be made worse instead of better. Another option for the vacuum chamber is to use OFE annealed copper tube. In the CDR, OFE copper was considered as a vacuum chamber material as well. However, it mentions that this OFE copper material is marginal for repeated beam exposures at the same location and is not suitable for the scenario of continuous beam exposure. Herein, however, copper is still considered as one of materials for the LCLS vacuum chamber.

In this study, aluminum or ceramic materials may be some other possible options. Including all possible options, a comparison of vacuum chamber materials has been summarized in Table 1. There exist some technical challenges to complete the vacuum chamber design, such as Ni & Cu coatings and electropolishing of a long, narrow tube, etc.

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Table 1: Comparison of possible approaches for the LCLS vacuum chambers.

Chamber	Advantages	Disadvantages
SS316L tube + Ni, Cu Coat + Electropolish	Low roughness, Vacuum quality	Coating, Electropolish, Mechanical tolerance
OFE Cu tubing + Electropolish	Conductivity, No coating, Cost reduction	Low melt temperature, Electropolish, Flange attachment
SS316L plate + Machining + Coating + Welding	Plating, Electropolish, Flexible design	Machining, Twists, Post-weld annealing Mechanical strength
Al Extrusion 6063-T5	No Coating, Cost reduction	Low melt temperature, Electropolishing

3 ANALYSIS OF VACUUM TUBE MATERIALS

To compare the surface roughness of chamber materials, sample specimens were prepared from SS and copper tubes. Surface roughness data were collected by using a KLA-Tencor alpha-step 500 profilometer and an atomic force microscope (AFM).

1″ long samples were cut from ¼″ OD x 0.036″ thickness SS 316L tubing and from 0.236″ OD x 0.020″ thickness OFE copper tubing by using a wire EDM process. The part was flushed with DI water during cutting. The EDM wire is made of brass and tungsten alloy. The finished samples were subsequently cleaned with Citrinox.

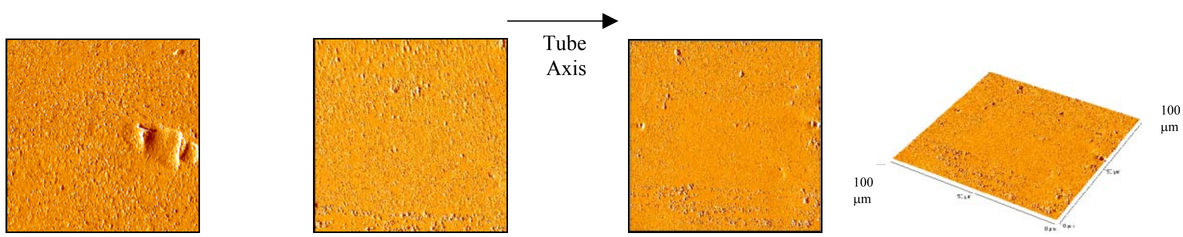
For the AFM measurements, we obtained the surface plots in noncontact mode and used the cantilever tips of a Veeco Metrology group (Model # 1650 for SS 316L and # 1895 for Cu). These tips have resonant frequencies of 260 and 280 kHz, respectively. The images were taken at scan rates between 50 ~ 100 µm/sec to accurately track the sample surface, and all images were flattened to reduce the effects of drift.

Sample measurement results

Typical AFM images of SS and Cu samples are shown in Figures 1-2 and Table 2 shows the summary of typical surface roughness measurement values. From these measurements, we found the sample from SS 316L tubing to have a very smooth surface. The tubes are available off the shelf with a maximum 5 µinch (130 nm) Ra surface. But, in the case of Cu tube samples, we had great difficulties imaging the sample despite several attempts, because it is too rough for the AFM cantilever tips we used for SS 316L. It was not easy to scan, particularly imaging areas larger than 20 x 20 µm with model # 1650 AFM tips. But, it was possible to scan the images with model # 1895 AFM tips.

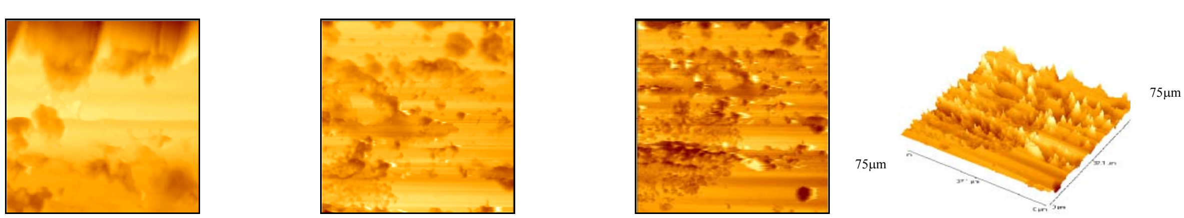
As shown in Figures 1-2, both samples clearly exhibit striations, especially the Cu images, parallel to the longitudinal direction of the tube cut, and these features can be easily seen with a low-magnification light microscope.

Figure 3 shows a typical 2D surface roughness of a Cu tube by profilometer. We measured the roughness of the samples along both the longitudinal and azimuthal directions of the tube. Both SS 316L and Cu tubes exhibited roughness in the azimuthal direction that was much worse than that in the longitudinal direction.



(a) 20 x 20µm (24.64 nm Ra) (b) 50 x 50µm (10.07 nm Ra) (c) 100 x 100µm (16.15nm Ra) (d) 3D - 100 x 100µm

Figure 1: AFM images of the inner surface of stainless steel 316L tube.



(a) 20 x 20µm (297.98nm Ra) (b) 50 x 50µm (317.49nm Ra) (c) 75 x 75µm (207.98nm Ra) (d) 3D - 75 x 75µm

Figure 2: AFM images of the inner surface of OFE copper tube.

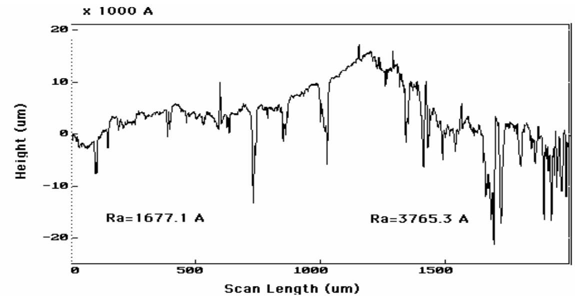


Figure 3: Typical surface roughness profile of a Cu tube along the longitudinal direction.

Table 2: Range of surface roughness measurement values for vacuum chamber materials.

Measurement Instrument	Tube Matl.	Ra (nm)	Rq (nm)
AFM (area)	SS316L	10.1~24.6	14.8~46.9
	OFE Cu	188.1 ~ 424.5	271.4~406.3
Profilometer	SS316L	48.30 ~ 313.4	-
	OFE Cu	71.45 ~ 412.5	-

4 COATING PROCESSES

Electroless plating metal deposition

This technique is defined as a chemical reduction reaction from an aqueous metal salt solution containing a reducing agent. After masking the outer surface of tubing, it is immersed into the plating bath. No external power supply is needed. In the narrow-long application, two problems are expected. First, it would be very difficult for an electrolytic reaction to occur on the inner surface of the narrow-long SS tubing. Second, deposition rates are generally much lower than electroplating rates, so it might not be easy to plate a 10 μm Cu layer. Also, non-uniform thickness is expected. This process requires further research.

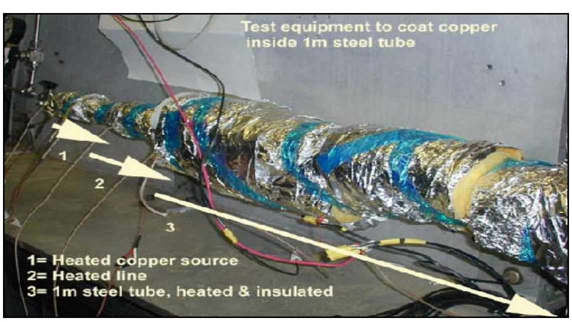


Figure 4: Equipment setup for copper coating by a CVD process inside a steel tube.

Chemical vapor depositions (CVD)

These vapor deposition techniques are based on homogeneous and/or heterogeneous chemical reactions. This process would be a strong candidate to complete the Ni and Cu coatings. As shown in Figure 4, copper coating has been tested with a one-meter-long tube at CVD Manufacturing, Inc. (Toronto, Canada). To deposit a layer of Cu film by CVD, two chemicals, such as copper (II) hexafluoracetyacetonate [$Cu^{II}(hfac)_2$] and copper (II) acetylacetonate, were tested under the conditions listed in Table 3. It is easy to transport $Cu^{II}(hfac)_2$ at low temperature, however, the deposition rate is very low, and this material is also costly. After working on several tests with this material, we found it did not work well in our application. Using copper (II) acetylacetonate, a Cu film was also deposited under the conditions listed in Table 3, and the carrier gas (Ar + H_2) was passed through a bed of copper precursor to bring the vapor into the reaction chamber. The advantage of this material is that it is free from fluorine, and a high purity copper film can be achieved. It also deposits at a much higher rate than materials containing fluorine. A high deposition rate is essential for the long tube deposition. However, the vapor was stuck at some places inside the tubing, particularly at the joints (both tubing ends), because the temperature is lower at those points. Using the enhanced distribution of a uniform temperature, we can achieve more uniform thickness coverage inside the tube as shown in Figure 5.

Table 3: Deposition conditions for Cu CVD.

	$Cu^{II}(hfac)_2$	Cu^{II} acetylacetonate
Reactor Temp.	~ 70 (°C)	~ 190 (°C)
Deposition Temp.	275 - 330 (°C)	~ 400 (°C)
Vapor Pressure	1 - 10 Torr	
Conversion to Copper	Ineffective	Effective

(a) Inlet view (b) 10x (c) 60x

Figure 5: Tube section views of a copper-coated surface.

5 SUMMARY & FUTURE WORKS

The surface roughness of SS and Cu tubing has been measured. Copper coating has been tested with a one-meter-long tube. Uniform thickness coverage inside the tube was achieved by controlling the temperature distribution. Work is continuing to get a uniform Cu film with a 1-m-long SS 316L tube, by optimizing temperature and insulation. Eventually, a full 3.42-m-long tube will be tested. In addition, electropolishing of 3.42-m-long OFE copper tubes will be tested at Delstar Metal Finishing, Inc. (Houston, TX). We expect the finish should be approximately 1/2 of the as-drawn surface roughness and that electropolishing will aid in reducing the surface roughness and outgassing rate for Cu tubing.

REFERENCES

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[2] P. Emma, Proceedings of PAC 2001, Chicago, pp 241-244 (2001).

[3] LCLS Conceptual Design Report (2002), SLAC-R-593.