RESOLVING THE METAL SPUTTERING ISSUE OF A HENE LASER

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ABSTRACT

HeNe laser is a type of gas laser which uses Helium and Neon gases as its gain medium. Some of the common applications of this device are particle counters, wafer interferometer and in laboratory demonstrations in universities. It is an old technology but still preferred due to its long lifetime and stable output.

One of the challenges encountered by the authors of this paper was the occurrence of metal sputtering, after 4 years of manufacturing this device in the Philippines. Metal sputtering is a defect wherein some metal parts are being eroded due to bombardment of high energy ions and the atoms of the metals are vaporized and deposited on top of other surfaces. For the case of HeNe lasers, most occurrences of metal deposits are found on output coupler (OC) mirror.

Several hypotheses were proposed, the resolution of which involved mostly process changes to improve the power output of the lasers. Those investigations have been discussed in this paper. After extensive studies, the root cause was finally identified to be the surface roughness of the glass bore tip. The roughness of the glass generated non-uniformity in the electric field, causing hot spots in the plasma which resulted in metal sputtering. This root cause was supported with high correlation of metal sputtering occurrence on rough bore surfaces, and addressing such with the defined correction and corrective actions have stopped the occurrence of the said failure.

1. 0 INTRODUCTION

Helium-Neon (HeNe) laser is the first gas laser which utilizes Helium (He) and Neon (Ne) as the gain medium. This laser is electrically pumped by a high DC voltage, usually at 10kV. This electrical pumping produces electrons which collide against the He atoms causing the He atoms to be excited to higher energy levels. Once the He atoms are at higher energy levels, the excess energy is being transferred to Ne atoms at ground level. Ne atoms are then excited to its metastable state. At this state, population inversion occurs allowing Ne atoms to release photons through stimulated emission. Following the emission, Ne atoms will fall back to lower energy level until it decays back down to ground state via collision de-excitation with the walls of the glass tube called the glass bore[1].

The construction of a HeNe laser (see Fig. 1) is composed of a gas discharge tube called the glass bore, where anode pin is fused on one side. The glass bore side where the anode pin is located is fused into a large Kovar which provides mechanical stability and hard seal, while the other end called the glass bore tip is being clamped by a rolled finger stock welded onto the cathode mirror-mount. A cylindrical Aluminum (Al) tube which envelops most of the glass bore serves as the cathode. Both ends of the glass bore are sealed by optical mirrors, with the high reflective (HR) mirror located near the anode pin and the OC mirror located on the other end. These optical mirrors are mounted on 4750 alloy mirror-mounts and hard-sealed by ceramic frits. In a technical datasheet from Aircraft Materials, Alloy 4750 is a 48% Nickel-Iron (Ni-Fe) alloy which combines a high saturation flux density with high magnetic permeability and low core loss[2]. The Al cathode is then enclosed by a stainless-steel tube called the laser body. This type of HeNe laser is called a closed-cavity laser.

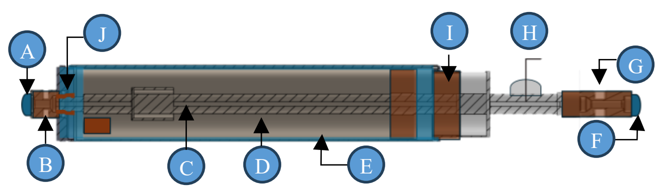


Fig. 1. Construction of a Closed-Cavity Laser. A refers to OC mirror, B is the cathode mirror-mount, C is the glass bore, D is the Al cathode, E is the stainless-steel body, F is the HR mirror, G is the anode mirror-mount, H is the anode pin, I is the large Kovar and J is the finger stock.

On the other hand, another type of HeNe laser is called an open-cavity laser. On this type, the other end has either a Brewster window or an anti-reflective (AR) lens and the OC mirror is external to the laser. The Brewster window is soft sealed to the Brewster stem made from borosilicate glass.

Finger stock is a Beryllium-Copper (BeCu), a non-arcing material with a Nickel (Ni) finish that is cut into desired length, for this case is 15 fingers, and circularly rolled and spot welded into the cathode mirror-mount. This will then hold the glass bore tip and serves as support to prevent the glass bore from freely moving on the tip end.

Previously, the initial problem resolved by the team was the mechanical leak followed by the low power output, which is beyond the scope of this paper. After resolving those issues, another problem occurred which was the metal sputtering.

Metal sputtering is the process where positively charged ions are accelerated toward the target material knocking out the surface atoms which will then be deposited on the substrate. An inert working gas, usually Argon (Ar) is used to facilitate sputtering process[3].

The metal sputtering initially occurred on device X which was an open-cavity laser with AR lens on the cathode mirror-mount. The center of OC mirror visually turned dark and opaque. A few months later, customer feedback was received on another device, (device Y), which was a closed-cavity type. Upon characterization of the returned device Y, it was observed that the laser still had a salmon pink plasma but was not lasing. Further inspection revealed that the OC mirror had a circular cloudy appearance when viewed from outside the laser, suggesting a possible metal sputtering defect.

Three qualified glass bore suppliers were used for this product line. The glass bore raw materials came from a single manufacturer and distributed by Excelitas to the three suppliers which assembled them into desired glass bores. Supplier 1 supplied the glass bores for devices X, Y and Z which are top volume devices, Supplier 2 supplied the glass bore for device A, another top volume device and Supplier 3 supplied glass bore for device B which was a low volume device.

2. 0 REVIEW OF RELATED WORK

In a NASA contractor report (NASA CR-1664)[4], a cathode sputtering occurred in their dual cathode design HeNe laser. The sputtering occurred only in one cathode, and this was replicated in the experiment. The reason why only one cathode sputter was not determined, but the solution adopted was to change the cold cathode material from Tantalum (Ta) to Al. The cathode processing or oxidation was previously tantalum(V) oxide (Ta_2O_5) and was replaced by aluminum oxide (Al_2O_3). In addition, small Al cylinders were placed over the bores between the cathode end caps and the internal bore supports to shield the brazing material at this joint from the discharge[4].

A major cause of failure and decrease in effective life span of gaseous lasers is the sputtering of cathode material. The current density at the working surface of the cathode is being decreased sufficiently to slow down the effects of sputtering and increase the laser life. It has been found that the rate of cathode material removal by sputtering in glow discharge is proportional to a high power of current density[5].

3.0 METHODOLOGY

The following steps were used to investigate and resolve the root cause of metal sputtering:

3.1 Characterization of the problem

Scanning Electron Microscopy – Energy Dispersive X-ray Spectroscopy (SEM-EDX) was used to characterize and identify the metal sputtering defects. The information from this technique was used to localize where the issue was happening within the HeNe laser.

3.2. Evaluation of Potential Factors

From the results of metal sputtering characterization, the potential factors were identified using brainstorming and 5 why's analysis with focus on major process changes since there was no material changes recorded prior to the outbreak of metal sputtering.

3.3. Root Cause Identification and Corrective action.

After identifying the potential factors in metal sputtering, evaluations were performed to determine the root cause. Having successfully determining the root cause of metal sputtering, corrective action was identified and verified for effectiveness by turning the problem on and off.

4.0 RESULTS AND DISCUSSION

4.1. Characterization of Metal Sputtering

From the initial open-cavity device X, SEM-EDX was performed to identify the elements deposited on the AR lens. A good AR lens sample, to serve as a reference, and a metal sputtering sample were prepared. Optical and SEM inspection showed that the good sample had a transparent material while the no good (NG) sample had a mirror-like surface deposited on its center part, as shown on Fig. 2.

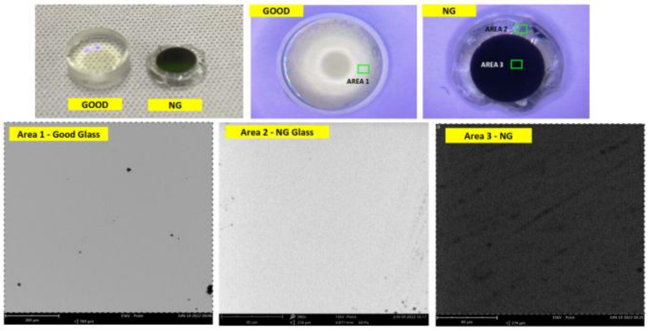


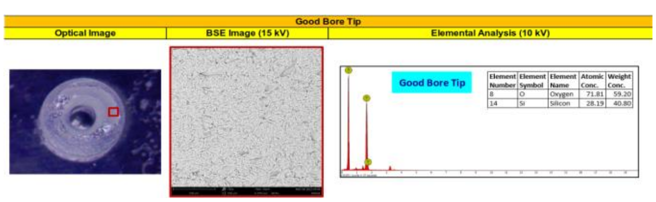
Fig. 2. Optical and SEM Images of a Good and NG lens. Images on top show the good lens (Area 1) as a transparent material while NG lens has a mirror-like deposit on the center (Area 3) and a transparent material around it (Area 2). The images on the bottom are SEM images of the 3 areas, with Area 1 and 2 having brighter image contrasts as compared to Area 3 with darker image contrast which may indicate another type of material deposited on the surface.

Table 1. Summary of Elemental Composition of Good and NG Samples

Sample Name	Area No.	Condition	Elemental Composition (in % weight) - EHT 15kV				Total
			Si	O	Ni	Fe	
Good Glass Filter	1	Reference	52.80	47.20			100
NG Glass Filter	2	Reference	50.56	49.44			100
	3	NG Area - Mirror Like Surface Finish	7.83	10.62	47.01	34.55	100

Table 1 showed that Area 1 from good sample and Area 2 from NG sample were found to be mainly composed of Silicon (Si) and Oxygen (O). Area 3 on the other hand, is found to be mainly composed of Nickel (Ni) and Iron (Fe) with Si and O as minor elements, confirming that another material was deposited on the center of the NG sample.

On the returned device Y (closed-cavity type), the tip of the glass bore was also analyzed using SEM-EDX. Samples for good and NG glass bore tips (sample #1 and #2) were investigated. Optical images (see Fig. 3) revealed that the good sample had a translucent, relatively even and dull tip surface while the NG samples had a translucent, relatively even and slightly reflective tip surface. SEM inspection revealed an irregular and rough surface with minimal dark spots for good samples, irregular and rough surface with few dark spots for NG sample #1 and irregular surface with indications of surface grinding with uneven topology and presence of streak lines for NG sample #2. Elemental analysis showed that the good sample was mainly composed of O and Si, while the NG samples were mainly composed of Ni and Fe, with O, Carbon (C), and Si as minor components.



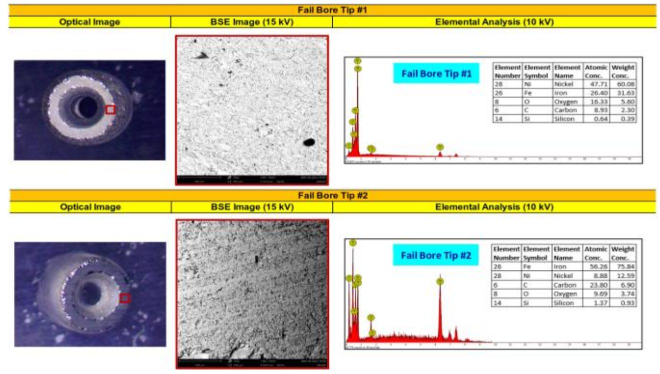


Fig. 3. Optical, SEM Images and Elemental Analysis of a Good and two NG glass bore tips. Images on top show the good glass bore tip which has a translucent, relatively even and dull tip surface with elements mainly composed of O and Si. Images at the center and bottom show the NG glass bore tip samples which have translucent, relatively even and slightly reflective tip surface. SEM image of the 2nd NG sample reveals indications of surface grinding with uneven topology and presence of streak lines. Elemental analysis of the two NG samples shows that the surface is mainly composed of Ni and Fe, with O, C and Si as minor components.

Based on the results of SEM-EDX analysis on two different devices, the metal deposit found on both the AR lens and glass bore tip was mainly composed of Ni and Fe. The location of this lens and the glass bore tip were both on the cathode side of the laser. On this side, the material containing Ni and Fe was the cathode mirror-mount which was made up of alloy 4750, consisting of 48% Ni in Fe. This confirmed that the cathode mirror-mount became the target in the sputtering process that was happening inside the HeNe laser and the glass bore tip and the OC mirror or AR lens acted as the deposition substrates.

4.2. Evaluation of Potential Factors

After the identification of the cathode mirror-mount as the source of the metal deposit, the team focused on understanding the cathode side of the HeNe laser where the cathode mirror-mount, glass bore tip and OC lens (or AR lens) were all closely located. Looking at historical changes, however, there was no change in materials involved on the area of concern. There were two major and one minor process changes that were implemented which were suspected to trigger the metal sputtering: 1. Inline Argon (Ar) plasma cleaning, 2. reduction of finger stock length from 15 to 14 counts and 2. Hydrofluoric (HF) cleaning of glass bore. The team initially hypothesized that there was an interaction happening during the inline Ar plasma cleaning and the loose finger stock brought about the reduction of its length, and / or the implementation of HF cleaning of glass bore.

On 13 batches produced with both inline Ar plasma cleaning and HF cleaning of glass bores, all processed with reduced length of finger stock to 14 fingers, 7% rejection due to metal sputtering was noted.

4.2.1. Inline Ar Plasma Cleaning and Reduction of Finger Stock Length

The implementation of inline Ar plasma cleaning had significantly increased the yield of HeNe lasers in terms of power output. This was a cleaning method where assembled HeNe lasers were cleaned by the bombardment of Ar gas. In this process, assembled lasers were mounted on the vacuum manifold. Prior to the preconditioning of the lasers with He and Ne gases, the lasers were being filled with Ar gas with pressure of 3.3 Torr. The lasers were powered up for 5 minutes allowing the ionized Ar gas inside the laser tubes to bombard the capillary tube and other parts of the laser to clean the lasers internally. It would then be vacuumed to remove the Ar gas and whatever organic impurities that were cleaned off inside the lasers. After this cleaning process, preconditioning and final gas fill would follow.

This cleaning process was being implemented for around 2 years until the sputtering occurred. However, a recent change in finger stock length could have been interacting with the Ar plasma cleaning resulting in the metal sputtering process.

Finger stock length was previously comprised of 15 fingers which was causing the non-concentricity of the glass bore against the cathode mirror-mount due to overlapping fingers when rolled. This resulted in output power variation and instability in device A. Hence, to achieve the desired concentricity, the length was reduced to 14 fingers. With this length the overlap was removed allowing the glass bore tip to be placed in the cathode mirror-mount at equal distances around its perimeter. The change was later fanned out to other HeNe devices.

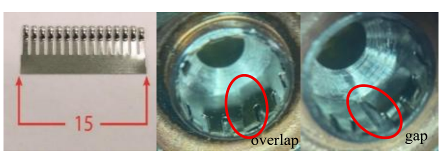


Fig. 4. From left to right: finger stock original length of 15 fingers; finger stock original length when rolled and assembled into mirror mount with overlap; finger stock reduced into 14 fingers, with no more overlap but with gap.

After this change was implemented, there were some samples which showed a gap in the finger stock material around the glass bore, as shown in Fig. 4. Based on the team's hypothesis, this gap was causing an arcing once the ionization took place during the inline Ar plasma cleaning due to the high voltage supply. The electrical arcing would then sputter the Ni and Fe components of the cathode mirror-mount and through time, those components would be deposited on the glass bore tip and on the OC lens.

To eliminate the inline Ar plasma cleaning without compromising the benefit of improving the power output, offline Ar plasma cleaning was introduced. This was the typical Ar plasma cleaning process which used a chamber and the glass bores which were not yet assembled into laser were placed inside the chamber and bombarded with Ar plasma.

To simulate the finger stock with varying length, an experiment was conducted with 3 legs, 5 samples each. Note that inline Ar plasma cleaning was also removed on this experiment.

Leg 1 – standard (STD); length: 15 fingers (with overlap) to avoid the electrical arcing
Leg 2 – unit under test (UUT) 1; length: 14 fingers (no overlapping of fingers but with gap) which was expected to produce metal sputtering
Leg 3 – UUT 2; no finger stock at all, which was expected to be the worst-case scenario and would produce metal sputtering.

The result, however, did not show any significance as no metal sputtering defect was observed on any of the evaluation legs. The finger stock length was retained to 14 fingers. Refer to table 2 for the result of experiment.

Table 2. Results of Metal Sputtering with Varying Length of Finger Stock

Leg	Description	No. of Metal Sputtering Failure
STD	with overlapping fingers	0
UUT 1	with gap	0
UUT 2	no finger stock	0

4.2.2. HF Cleaning of Glass bore

Since the hypothesis on electrical arcing due to the gap on the finger stock was disproven, the next process which was also recently implemented was investigated. This was a newly added chemical cleaning of glass bore which was also dealing with power output improvement. On this cleaning method, the HF was suspected to be causing surface modification on the glass bore which could result in packets where contamination could easily set. These contaminations would later interact with the plasma during the HeNe laser operation and would trigger the metal sputtering.

Three lots were processed with no inline Ar plasma cleaning and no HF cleaning, each lot comprised of 15 units. No metal sputtering occurred on the first 2 lots, but on the 3rd lot, 1 metal sputtering failure was detected, as shown on Table 3.

Table 3. Metal Sputtering after Removal of Inline Ar Plasma Cleaning and HF Cleaning

Lot No.	No. of Metal Sputtering Failure
1	0
2	0
3	1

4.2.3. Visual comparison of old and new glass bore tips

The third hypothesis investigated by the team was the visual appearance of the glass bore. To compare the cathode side of devices with metal sputtering (devices X and Y) to other devices without the occurrence of metal sputtering (devices Z and A), visual inspection under low power microscope revealed that the glass bore tips of devices X, Y and Z were rough while device A has a distinct smoother surface. The team searched for older batches of glass bores for devices X, Y and Z. Old batches of lasers used in other evaluations were recovered. Glass bores were supplied 2 years ago. Under low power microscope, a smooth surface finish was observed for old batch as compared to the recent batch. It was also noted that there was no historical record of metal sputtering on any of the HeNe lasers. Refer to Fig 5.

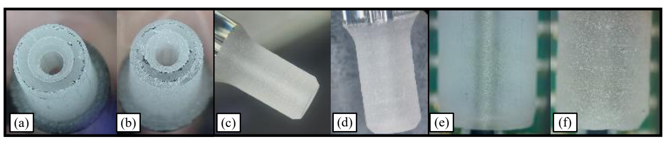


Fig. 5. Glass bore tip images of old and new batch: (a) edge of the tip of old batch showing smooth edge and finely grinded inner surface; (b) edge of the tip of new batch showing irregular rough portions on the edge and roughly grinded inner surface; (c) smooth outer surface of old batch; (d) rough with streak lines outer surface of new batch; (e) magnified image of (c) showing smooth surface; (f) magnified image of (d) revealing rough surface

Another important finding seen on an evaluation build was that device Z had signs of metal sputtering occurring due to visible darkening of glass bore tips, see Fig. 6. The AR lens had no metal deposit because of the structure of this laser on the cathode side. It had a Brewster stem attached to the cathode mirror-mount. The AR lens was soft sealed on the Brewster stem. Due to this structure, the AR lens was farther from the cathode mirror-mount and was not reached when sputtering was initiated.

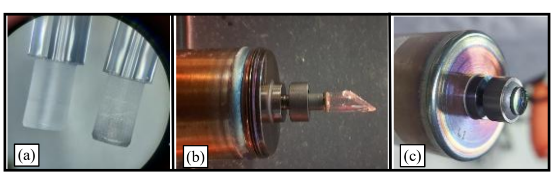


Fig. 6. (a) Device Z glass bore tip images of old (left photo) and new batch (right photo), showing darkening on tip of the new batch as a result of metal sputtering (b) cathode side of device Z showing the Brewster stem which extends the AR lens farther from the bore tip, which explains why metal sputtering did not manifest on the AR lens and, (c) cathode side of device Y showing the OC lens is directly mounted on top of the mirror mount, hence closer to the glass bore tip in which metal sputtering is always visible on the OC lens as foggy or cloudy spot on the center.

On the other hand, device A from old evaluation samples had a smooth surface finish on the glass bore tip which was still comparable to the recent build with no reported metal sputtering.

Those findings pointed to single supplier, Supplier 1, which showed that the recent glass bore supplied had a rough surface finish on its tip, both externally and internally, and all devices X, Y and Z with glass bores coming from this supplier were encountering metal sputtering.

Table 4. Summary of Devices, Glass Bore Suppliers and Surface Roughness Appearance and Metal Sputtering Occurrence

Devices	Glass Bore Supplier	Has rough glass bore tip surface?	Has metal sputtering issue?
X	1	Yes	Yes
Y		Yes	Yes
Z		Yes	Yes
A	2	None	None
B	3	None	None

4.3. Root Cause Identification

Series of investigations and evaluations have proven that the rough surface of the glass bore tip is causing the metal sputtering. Several literatures were researched by the team to understand the phenomenon. From various studies in different areas, it is mentioned that rough surfaces (asperities) can serve as local field enhancers resulting in irregularity in the electric field distribution and hot spots when plasma is generated. In HeNe lasers, the rate of sputtering is proportional to a high power of current density[5].

Fig 7 shows the electric field enhancement as a function of the root-mean-square surface roughness amplitude. The field enhancement refers to the ratio between the strongest electric field (typically occurring at sharp and high asperity tips) on the rough surface, divided by the electric field for flat surfaces with the same average surface charge[6].

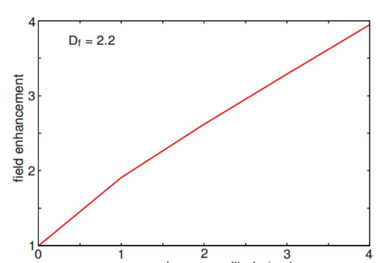


Fig. 7. The maximal electric field enhancement for random rough surfaces, as a function of the root-mean-square surface roughness amplitude[6].

A study was performed to investigate the mechanism of hot spot formation on the plasma-facing materials (PFM) which is a critical issue in the maintenance of high-performance plasma on the Experimental Advanced Superconducting Tokamak (EAST). It was found out that the hot spots appearing in the discharges were toroidally localized which was attributed to the existence of small bulges in a few lower divertor tiles that lead to a larger contact area with the magnetic field lines; accordingly, more electrons could attack these tiles along the magnetic field lines, resulting in excessive local heat loads on these tiles[7].

4.4. Corrective Action

An immediate correction developed by the team was to rework the inventory of glass bores by fire polishing the rough glass bore tip. Initially, there were 4 lasers out of 11 lots (133 lasers) which encountered metal sputtering and low power. The defect rate of metal sputtering was reduced from 7% to 3%. To fine tune the fire polishing process, a drop pin as well as microscope inspection at low magnification was added. The drop pin was to screen out potential glass bore tips which collapsed during fire polishing resulting in low power since the capillary became constricted. The microscope inspection was to screen out glass bore tips which still have some roughness on its surface to be subjected again to fire polishing (see Fig. 8). This mitigation had reduced the metal sputtering to 0%. This, however, was only effective for closed-cavity laser device Y. For devices X and Z, which were open-cavity devices, the alignment process was too difficult for the fire-polished glass bore tips.

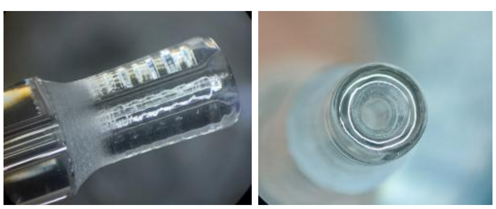


Fig. 8. Glass bore tip after fire polishing to eliminate the rough surface; left image shows the side view, and the right image is the edge of the tip.

While the correction was being implemented for device Y, the issue was communicated to supplier 1 for improvement of the glass bore tip roughness. This was initially not part of the requirement in the drawing, hence returning the glass bore inventory to supplier was not possible. Supplier 1 tried to improve the roughness of the surface, however, the workmanship quality that they were previously producing could not be reproduced. This led the team to qualify supplier 3 to produce glass bores for devices X and Z. The surface roughness from this supplier was smooth, and there was no recorded issue of metal sputtering on device B. During the qualification of supplier 3, using device X as the pilot device, no occurrence of metal sputtering was encountered.

5.0 CONCLUSION

Results of the extensive process mapping and material investigations showed that the root cause of metal sputtering was the rough surface finish of the glass bore tip. This roughness causes nonuniformity in the electric field distribution, with criticality on the inner surface as well as on the end or tip of the glass bore, which is adjacent to the mirror-mount, acting as local electric field enhancers. Sharp asperities on rough surfaces directly correlate with electric field enhancement[7]. This principle is believed to be applicable as well on glass bore containing plasma since effectively removing the rough surface by fire polishing has stopped the metal sputtering from occurring. The rough surface attracts and anchors the plasma which can lead to hotspots and high-energy ion bombardment to the nearest metal, which in this case is the cathode mirror-mount made up of alloy 4750. The Ni and Fe atoms from the cathode mirror-mount are sputtered omnidirectionally and due to the proximity of the glass bore tip to the cathode mirror-mount, these atoms cling to the tip and inner surface of the bore leaving metal deposit on that area while some atoms go straight down the axis towards the OC mirror and condenses on the cooler surfaces hence the metal deposit is also seen on the OC lens.

6.0 RECOMMENDATIONS

The surface finish of the glass bore tip needs to be defined with a quantifiable value and make this parameter a critical to quality (CTQ) requirement specified on the glass bore drawing as a counter measure against non-uniform plasma resulting in metal sputtering.

For the closed cavity laser, fire polishing can be done on the glass bore inventory, but it is not recommended to be used for open cavity laser due to the risk of output power failure due to mechanical alignment problems because of glass bore collapsing after fire polishing.

For open cavity laser, qualifying another supplier (supplier 3) which has a better surface quality of the glass bore tip is recommended.

7.0 ACKNOWLEDGMENT

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