Field Emission Dark Current of Technical Metallic Electrodes

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Abstract

In the framework of the Low Emittance Gun (LEG) project, high gradient acceleration of a low emittance electron beam will be necessary. In order to achieve this acceleration, a -500 kV, 250 ns FWHM, pulse will be applied between two electrodes. Those electrodes should sustain the pulsed field without arcing, must not outgas and must not emit electrons. Ion back bombardment, and dark current will be damaging to the electron source as well as for the low emittance beam. Electrodes of commercially available OFE copper, aluminium, stainless steel, titanium and molybdenum were tested, following different procedures including plasma glow discharge cleaning.

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1 Introduction

In the framework of the Low Emittance Gun (LEG) project, an X-ray free-electron laser (FEL) based on a field emitting cathode is expected to deliver six orders of magnitude higher peak brightness than current state-of-the-art light sources, together with a thousand times shorter pulses [1, 2].

To rapidly accelerate the electrons emitted by the electron source, and keep the emittance low, a stable pulsed voltage in the megavolt range is needed. The first project phase is to design and test an ultra high vacuum (UHV) 500 kV pulser using a resonant air-core transformer (Tesla coil) [3]. A pulse of 250 ns (full width at half maximum), -500 kV, working at 10Hz, will be applied between the cathode holder and an extracting anode. During this time, electrode materials should sustain the field without arcing and the dark current should be kept as low as possible. This dark current will ionize the residual gas as well as desorbing neutrals and ions by the known electron stimulated desorption process (ESD) [4, 5]. Those ions will be accelerated toward the cathode and the field emitter array

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(FEA), in other words the electron source, and induce sputtering. It is known that some surfaces are more sensitive than others to very low energy ion bombardment. Measurable damage can already occur at 500 eV [6, 7, 8]. The damage induced, from any kind of energetic ions, will then reduce the electron emission and the lifetime of the field emitter, for example in GaAs photocathodes, used as polarized electron sources for accelerators [9, 10]. During the after pulse, the reversed field will accelerate the ions toward the extracting anodes producing a current of electrons which will also back bombard the field emitter. The gas desorbed can induce a pressure rise which might not disappear before the next pulse. In the worst case, a plasma forms followed by breakdown and sputtering of the anode material to the field emitter cathode. Recent work, and thorough review of over a century of vacuum breakdown research in many areas, [11, 12, 13] is still not sufficient to select electrode materials without application specific testing.

In order to investigate the electrodes material, a DC high gradient test stand was built to test different metals, which were potentially suitable as electrodes in the pulser. The goal is to find the most suitable material, for our needs, which can sustain high field without breakdown, and emits almost no electrons. In situ cleaning by plasma glow discharge was also tested to see whether an improvement was noticeable in the mitigation of the dark current. This technique of gas conditioning to lower the field enhancement factor $\beta$ has already been reported [14, 15, 16] and used successfully in accelerators to process niobium accelerating cavities, see description in [12], as well as for curing other issues [17].

2 System setup and electrode preparation

2.1 System setup

The ultra-high vacuum (UHV) system shown in Fig.1, outside its metal confinement bunker for radiological protection, is pumped by a 150 l/s diode ion pump. The average pressure reached is in the low $10^{-9}$ Torr scale after a quick bake of the ion pump. A more thorough bake brings the pressure down to the mid $10^{-10}$ Torr. An injection line, a leak valve and a Torr capacitance gauge allow the controlled injection of a chosen gas into the system to prepare the glow discharge between the electrodes. In order to clean the anode and the cathode at the same time, a third electrode polarized positively in respect to the test electrodes is used, Fig.2. The distance of this third electrode from the center of the chamber is a constant.

A negative and continuous 0 to 100 kV bias is applied to the cathode through an insulating ceramic, (on the left in Fig.1). The anode is grounded. The capacitance of the system is close to 300 pF, hence the potential energy stored is 1.5 J at 100 kV. The current flowing from the cathode to the anode is measured across a 1 M$\Omega$ resistor with a digital Fluke$^{\text{TM}}$ voltmeter. The gap separation between the electrodes is adjustable via a translation feedthrough and is controlled with a mechanical comparator. The sagging due to the weight at the end of the rods means that the two electrodes are not centered on each other. We do not expect this off centering to be of any consequence to the high voltage processing. However, it explains the off center damages seen on cathodes. Accurate measurement of the current to the 50 pA level is achieved.
2.2 Electrode choice

Given the long history of research on vacuum breakdown, it seems that the choice of the electrodes should be easy. However, as there is no universal quantifying theory to explain the process of vacuum breakdown depending on the material, and its surface state (physical and chemical), it is necessary to do our own testing for our own application. In order to pick the most appropriate material, we study some elemental properties. Many tables of elements are then compiled in order to make an informed choice. In our case, the electrodes should sustain a DC pulse of 500 kV and not produce or have a low electron dark current. Also a FEA will be installed in the middle of the cathode. If any arcing occurs, sputtered, or vaporized, anode material will deposit on the FEA. This can lead to destruction of the FEA, and the necessity to exchange it; in our system this is a complex and time-consuming procedure. Table 1 compares the secondary electron yield (SEY) the sputtering rate, the melting point, and the tensile modulus of the candidate elements.

From Table 1, Cu and Au appear to be bad candidates. Results obtained with RF waveguide support this point [22]. Despite its good electronic and ionic properties Al should be discarded, as the combination of melting point and elastic modulus is low compared to other materials. Al will probably coat a FEA thoroughly in case of arcing, as we also found with a gold coated anode. The FEA coating problem further implies that spark processing to reach high gradient, despite being efficient, should be avoided [23, 24], unless it is possible to protect the FEA. Some of the other materials which look good in this table, can probably be discarded, due to their yield strength versus the temperature or their electrical or thermal conductivity. Also the choice of the cathode and anode should be made separately as a good cathode material might not be so well suited as an anode. The respective choices depend on the geometry of the system, and the removal of any heat generated by the dark current.

2.3 Electrode preparation and testing

All our electrodes tested have the same shape, see Fig 3 & 4 for the cathode and anode, respectively. The mean roughness was, by design, defined to be less than $R_a \leq 0.2\mu$m. In Fig 4 the copper anode, has a hole in the middle. This hole was made to mimic the behaviour of the extracting anode of the 500 kV pulser. None of the other electrodes have this hole. The $R_a$ of the electrodes was checked after high gradient testing.

The electrodes were cleaned using acetone and alcohol in an ultra-sonic bath, before installation in the UHV system. This is the ”as received” state. Unless specified otherwise none of the surfaces have been mirror finished. All materials were commercially obtained from Goodfellow\textsuperscript{TM}. Technical materials refer to commercially available material, which is exposed to air before installation.

Ti and Mo electrodes were fabricated by the same machining company. Electrodes were thoroughly cleaned in acetone and alcohol before use. Ti electrodes were installed after cleaning and tested, and Mo electrodes were vacuum fired at 900°C for 3 h. After Mo testing, Ti electrodes were also vacuum fired and reused. From the literature, it was shown that heating up the material is beneficial in improving the breakdown strength [25].

The processing histories of the materials tested are summarized in Table 2. The procedure of high gradient conditioning is the same for all the cathodes. The voltage between the electrodes is applied for a given gap, 4 mm, 3 mm, 2 mm, 1.5 mm and then 1 mm.
The voltage is raised slowly, waiting for stable conditions, by discrete steps, to 60 kV and then the gap is diminished with a reduced voltage equal to the previously obtained static electrical field. It was found that above 70 kV arcing sometimes happened somewhere else in the system.

During conditioning, soft breakdowns might occur. During those breakdowns, current is measured and the pressure can increase by a factor 10. When observed, the voltage is, usually, manually reduced. The pressure recovers in a minute or two, and the voltage is again raised slowly to the previous level.

In this study, we do not reproduce quality preparation achieved in [26]. Instead, our aims were to see what is the behaviour of a technical material prepared using a less stringent procedure. Once the electrodes are installed under vacuum, our intention is to use plasma glow discharge (PGD), known to be an efficient way of cleaning surfaces and removing the contamination which can promote field emission. We do not think the exceptional surface preparation achieved by the procedure in [26] will survive an aggressive PGD.

Plasma glow discharge was usually applied after we reached 1 nA of current at 1 mm gap from the as received state. The gases injected for the PGD are usually a mixture of He and Ar, with a composition of 50% He and 50% Ar. Sometime pure Ar is used. The total pressure range was between \( \sim 0.15 \) Torr and \( \sim 0.25 \) Torr. Noble gases are chosen to avoid chemically attacking the surfaces. Helium is chosen because, for the same energy, its sputtering potency is less than Ar. The gases come directly from a compressed gas cylinder and are injected via a leak valve. A +400 V to +600 V bias is applied between a third electrode, Fig.2, and the two electrodes to be tested. The pressure and the energy of the ions in the PGD are adjusted, so that the plasma wraps around the electrodes. The distance between the three electrodes are around 6 cm and the time of the PGD can last between 40 to 60 minutes.

Finally, as it is known from literature that pressure can affect the breakdown onset threshold, and that dark current appearance is affected by the gas species [11], the system is baked not only after air venting but also after each plasma. By this means we minimize any role that the pressure and the gas composition would have in FE or arcing.

3 Results

Before presenting results obtained with our electrodes, it is of importance to bear in mind results obtained by Furuta et al [26, 27] and Diamond [25, 28]. According to Furuta’s publication, the design of their electrodes are equivalent to ours. They have obtained, for stainless steel, Cu, Ti and Mo with mirror finished surfaces, the results summarized in Table3. Those results have been obtained not only with mirror finished surfaces, but the assembly of their system and the mounting of their electrodes, were done in class 1 and class 10 clean room condition, respectively.

All the current vs electric field plots presented in [26] and in this work can be fitted using \( I = c E^2 e^{-a/E} \), see Fowler-Nordheim equation (11), with I current, c and a constants, and E applied electric field. From those fits F-N parameters, area and the field enhancement \( \beta \), can be extracted.

\[
I = A \cdot \frac{1.5 \cdot 10^{-6}}{\Phi} E_s^2 \cdot e^{\frac{1844}{\Phi}} \cdot exp \left( \frac{-6.83 \cdot 10^7 \Phi^\frac{3}{2}}{E_s} \right)
\] (1)
where \( E_s = \beta \cdot E \) and the work function, for Mo, \( \Phi \) is taken equal to 4.2 eV. However, we will not go further into the comparison between our measurements and theory, because the goal of this paper is to report on practical surface conditioning procedures to achieve stable operation under a high electric field. It is also to report on the erosion of the materials upon the field processing.

3.1 Aluminium Results

3.1.1 Al-Al electrodes

Pristine, as received Al electrodes were tested. The first test after a thorough bake of the chamber led to a dark current of 1 nA at a gap of 1 mm for a field of 7.1 MV/m. The gap between the electrodes was set at 4 mm and the electrodes were conditioned overnight by applying 29 kV and drawing 7 nA of current. The next day the dark current increased to 13 nA. Several dark current curves were then produced and compared to the as received test, Fig.5. The obvious conclusion is that our DC electrical conditioning did not lead to any improvement.

We next tested cleaning and conditioning using an He plasma of 0.26 Torr. The sputtering rate of 500 eV He ions on Al is 0.16 \(^{[6]}\). The 1 nA at 1 mm gap was reached for a field of 13.5 MV/m. Subsequent He plasma continued to improve the results. However, a few breakdowns occurred during the voltage processing. An ArGD at a pressure of \(~0.1\) Torr produced the best results which are presented in Fig.6. The 1 nA at 1 mm gap (full circles) was reached for a field of 42 MV/m. When leaving the system at this level of field and dark current further improvement, decrease of dark current over time, is observed Fig.6 full circles. In subsequent tests, also with different materials, this improvement was occasionally observed. However, in some cases the current increased to more than the double the previous value.

In the next test an He-Ar plasma was used to clean the same electrodes. The behaviour, after pumping out the noble gases, was that no FE was observed until breakdown. The Al electrodes held stably (12 hours) a field of 42 MV/m without dark current at 1.5 mm gap. Whilst the field was at 45 MV/m an arc occurred and an emission current of 350 nA could be measured. Nevertheless, damage due to this and further breakdowns during the voltage processing, were not severe; the current at 1 mm, for a field of 41.5 MV/m was still only 1 nA. Finally, the best result obtained by He-Ar GD, was a field of 52 MV/m at 1 mm without dark current. However, at some point an arc more violent than the previous ones, damaged the cathode so that no more GD was able to restore the holding of the high electric field. A summary of the performance obtained with Al electrodes is shown in Table.4.

3.1.2 Mirror Finished Al Cathode

We then replaced the damaged Al cathode by a pristine mirror like finish Al (6082) cathode, machined to an \( R_a \) of 3 nm. The previously damaged mushroom anode was reused, after wiping with alcohol before reinstallation in the UHV system. The damage on the anode was localized around the summit of the anode, and resembled the right-hand picture in Fig.7.

With this configuration, the as received system held stably without dark current, up to an electric field of less than 36 MV/m. At this value, an arc occurred. Inspection of
the cathode through the viewport of the UHV system showed pitting damage. An He-Ar
GD was then applied to cure and clean the electrodes. Results are summarized in Table 4.
The column labelled <0.05 nA shows the field strength held without measuring any FE.
The system held 90 MV/m electric field at 750 µm, and broke down at 92 MV/m. The
vacuum arcing was so severe that no further PGD was able to restore such fields. Final
damage to the Al electrodes is shown in Fig.7. The high field sustained shows that the
breakdown is cathode initiated as the cathode was pristine and the anode was already
severely damaged.

3.2 Copper results

Oxidized copper electrodes were tested solely after a PGD. Even after a PGD and the
voltage processing, the electrodes are still very oxidized. Cleaner spots around the hole
of the anode were observed at the end of the testing. Damage on the cathode was also
visible. The electrodes were then cleaned by chemical etching by use of a phosphoric
acid based solution Polynox®. They were subsequently rinsed with tap water and after
drying, cleaned with ethanol. A last test was conducted by installing a mirror diamond
turned OFHC Cu cathode ($R_a \sim 3$ nm) and the already used Mo and then a SS anode.

3.2.1 Cu-Cu electrodes

The results obtained seem to show that there is no influence from the anode hole in the
achievement of the high gradient, as our results are similar to what was obtained in [26],
see Table 3 for clean copper.

In comparison to Al electrodes, craters in the Cu were neither as deep, nor as extended :
see the 2 spots in Fig.3 compared to damages in Fig.7. All breakdown damage on the
Cu anode remained localized around the hole of the mushroom. That suggests two
possibilities without excluding a combination of the two. The energy in the arc was not
sufficient to vaporize the Cu materials, by melting and sputtering the melted Cu, despite
the fact that Cu has a higher sputtering rate than Al. Or the field was not strong enough
to pull out droplets of Cu which could have then been vaporized [29].

3.2.2 Mirror finished Cu cathode

As results from Al seemed to indicate that the breakdown is cathode initiated, a com-
bination of a mirror finished cathode with the previously used Mo (vacuum fired ) and
stainless steel(SS) anodes was tested. Those anodes had sustained damaged far less sig-
nificant than the Al anode pictured in Fig.7. Results of the Cu-Mo conditioning are
shown in Table 5. The conditioning of the ”as received” electrode followed the ”break-
down processing” or spark processing scheme, until a more severe breakdown brought the
Cu cathode to emit at the level of 800 nA, at 3 mm gap. During the first 500 eV ArGD,
small breakdowns could be seen on the Cu cathode, which were probably dust burning
away. Results obtained after plasma processing improved the situation but not to the
level of the two clean Cu electrodes. It was expected that higher fields could be reached,
as in the case of using two Cu electrodes, Table 5 or two Mo electrodes (see Table 6).

The Mo anode was exchanged for a SS anode, and the Cu cathode was turned 180°
on its axis. Because the anode arm sags, damage on the cathode is not localized on the
center of the anode, hence allowing a pristine area to be exposed. The maximum field
held with this pair was 11 MV/m at 3 mm gap, after an ArGD. From these last results, no conclusion should be drawn on the coupling of this last pair as the Cu cathode was already exhibiting an oxide color. The presence of the oxide can be due to oxygen present in the ArGD, or from oxygen being released from the Mo anode during high voltage conditioning see §3.3.5. The copper oxide is present from the center of the Cu sample to 5 mm from the sample circular edge. Microscopy and surface analysis did not reveal any material transfer from the anode (Mo or SS) to the Cu cathode.

3.3 Stainless steel, titanium and molybdenum results

Main results obtained, at 1 mm, for stainless steel (SS), Ti and Mo are summarized in Table 6.

3.3.1 Stainless Steel

SS electrodes were electrically processed the same way as Al electrodes. After plasma treatment, the best field achieved was 68 MV/m with dark current below the 10 pA detection limit. The final breakdown, was not recoverable by the use of a PGD. Upon removal of the electrodes, damage was located at the top of the mushroom. However, craters were not as deep or as wide as for Al electrodes (in Fig.7). The damage is less extended than that observed on the Cu electrodes. If we look at the data in Table 1, this is not surprising. Effectively, both the melting point and the Young’s modulus of SS are far above copper values. However, as tiny amounts of vaporized or sputtered material from the anode can be prejudicial to the working of FEAs, avoiding even soft breakdowns seems to be a good strategy.

3.3.2 Titanium

In the case of Ti, we have observed after plasma treatment, a stable field holding at 52 MV/m without FE. Above 53 MV/m, dark current appeared and reached 1 nA at 62 MV/m, cf Fig.8 (diamonds). The field held at this value for a few minutes until arcing, which brought the current above 1 µA. The field was then reduce to 35 MV/m in order to get a 1 nA current value, cf Fig.8 (squares.) This current value decreased over 56 hours of 35 MV/m field processing. A few MV/m were then gained to bring back the current to 1 nA.

It is interesting to mention that after a soft breakdown leading to dark current emission around 1 µA, sometime no rise in pressure is detected. At a pressure of 2.10⁻⁹ Torr, gas released by ESD process can in principle be detected. A simple calculation will show that such a current, 1 µA, will produce a gas flux of ∼3.10⁻⁹ Torr.l.s⁻¹, hence an increase of pressure of ∼2.10⁻¹¹ Torr; assuming an ESD coefficient of 10⁻² molecule/electron. This is below the resolution of our instrumentation, and of most total pressure gauges.

A subsequent ArGD for 90 minutes at 580 eV under pressure varying from 0.156 Torr to 0.174 Torr was performed. During this PGD, the Ar gas was evacuated several times and then replaced by new Ar coming from the cylinder. The field held after this plasma was 61 MV/m. The voltage was then increased and fluctuations in the emitted current below 50 pA were observed. Between 63 MV/m and 67 MV/m the dark current was fluctuating around 0.1 nA, see Fig.9. Field conditioning over a week showed, as in the case of Al or SS, an improvement in the dark current emission. The final stable electric
field obtained for 1 nA at 1 mm gap is 55 MV/m, see insert in Fig.9. Above this level of field, the dark current does not diminish but it increases with time, Fig.9.

Upon inspection of the electrodes after their extraction from the chamber, damage spots can be seen on both electrodes. Damage is located on the anode around the top of the mushroom, and 4 separate spots can be seen on the cathode spread over a trail of 1 cm length. Damage on the Ti anode is similar to that seen on the SS and Cu anodes, in extension and morphology (melted area).

### 3.3.3 Molybdenum

Vacuum fired Mo electrodes were installed in the system, the best results are summarized in Table 6. A simple 25Hz optical camera was used to view the electrodes, hence the space in between. When running, no light is present in the system enclosure. During the soft events, a flash is seen on the TV screen and a jump in current intensity, below 0.1 nA, is measured sometimes associated with a pressure increase. The flash is localized and takes the full space occupied between the electrodes. During harder breakdowns, sound can be heard coming from the enclosure. After these soft breakdowns, the voltage could still be increased. In order to have a chance to detect breakdown precursor, fast acquisition and very high sensitivity, to single photon, are mandatory. However, such a simple optical system can be used as an interlock protection for our FEL.

As for the Ti electrodes, dark current appears at some voltage, contrary to Al, Cu and SS electrodes where dark current appears only after a breakdown. Raising the field further increased the dark current until breakdown occurred. Dark current plots from as received electrodes(triangles), and after three plasma treatments are presented in Fig.10. The first ArGD pushed the limits of the dark current onset (diamonds) until a hard breakdown occurred, bringing the current into the µA range. The onset and the 1 nA limit was then greatly reduced (squares). The second ArGD enabled partial recuperation from this breakdown (asterisks). A third plasma He-Ar, did not bring any extra improvement (crosses in squares). Mo conditioning from broad electrodes at large gap (> 500 µm) was similar to conditioning with short gaps. Mo reached a higher gradient than Cu but it sparked more to get there [24], hence showing more damage than Cu, Fig.3. From this, it is obvious that a special electrode conditioning procedure must be used to process the Mo electrodes, and thus to protect the electron source (FEA).

### 3.3.4 Titanium vacuum fired

Original Ti electrodes were re-installed after vacuum firing and the results, for comparison with non fired Ti, are presented in Table 6. After vacuum firing the Ti became gray black. This color can indicate TiH$_2$ or TiO$_2$ in the rutile form, or Ti$_3$O$_5$. Damage, all localized on the top of Ti anode, can be seen in Fig.4. The involuntary coating is removed by the severe breakdowns sustained by both electrodes.

### 3.3.5 Surface analysis

Given the rather poor performances in field holding for the Mo electrodes, compared to literature values, and the colour of the Ti electrodes, it is suspected that the vacuum firing degraded the Mo properties instead of improving them. The pressure in the vacuum furnace was probably around 10$^{-5}$ Torr. Ti and Mo cathodes were sent for surface analysis, X-ray photoelectron (XPS) and Auger (AES) spectroscopy. Upon AES analysis, the
surfaces of both electrodes exhibited high contents of carbon (C) and oxygen (O), higher than normal air exposure. Nitrogen (N) is also present on the Mo surface. Nitrogen cannot be seen on Ti as Ti and N overlap under AES analysis. Under XPS analysis, a shift of about 5 eV to higher binding energy, for both Mo 3d_{5/2} and Ti 2p_{3/2} is observed. Such shift can be the mark of TiO_{2} and MoO_{3}. The Mo shows no discoloration, suggesting the formation of a thin trioxide film. The conclusions are, first of all a small air leak might have been present in the furnace. Secondly, a bad heat treatment will bring the opposite results in terms of field holding.

4 Conclusions

Plasma glow discharge is a very effective way to enhance the DC field holding in between two broad electrodes. It also permits restoration and sometimes improvement of the DC field limit achieved after a breakdown event leading to dark current emission. This dark current follows the FN law.

The downside of such treatment, for Al, Cu and SS electrodes, is that the surfaces hold the field until breakdown with no or little warning. No increase in pressure is recorded, but sometime some current variation in the tens of pA might appear. Such fluctuations can be the sign of a forthcoming breakdown, if any, but the time scale can vary from minutes to hours. In the hunt for the breakdown precursor, in the framework of an interlock for the 500 kV pulser, a highly sensitive and fast photomultiplier will be tested in this 100 kV DC test stand.

For Ti and Mo electrodes dark current appears and increases when raising the voltage until breakdown occurs. However, during the processing a few sparks occur, sometimes in a "spitfest" regime. Those sparks are beneficial as they condition the surface. Dark current at a level of 1 nA can either drift to hundreds of nA, fall back to less than a hundred pA or stay stable. So far, the prediction for its evolution is only empirical.

Finally we have, without stringent procedures, matched or exceeded results obtained by other labs. However, results for non mirror finished Ti and Mo were below the ones obtained elsewhere. In the case of Mo, it is suspected that the vacuum firing contaminated the Mo as it did for Ti, leading to poorer performances than usually reported in the literature.

In order to find the Grail material, which will hold our requested field without emitting dark current, Niobium seems to be a material of interest. Ion implantation, with nitrogen, is known to harden materials [31, 32]. It may be possible that this technique of hardening can be useful to increase the breakdown threshold of soft materials, as it seems to have for harder ones [33]. Dark current from electrodes can be lowered by depositing a pure monolayer of oxygen on the surface, which will increase the work function of the electrodes. However, and in the framework of an accelerator electron source, this layer might have to be regenerated frequently as back bombardement from residual gas ions will clean the surface.

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Table 1: Secondary electron yield maximum [18], sputtering yield by 500 eV incident Ar [6] and self-sputtering rate at 500 eV of different elements [19][20].

| Elements | SEYmax | Atm/Ar inc | Self Sputter rate | Melting Point °C | Young Modulus GPa |
|----------|--------|------------|-------------------|------------------|-------------------|
| Cu       | 1.3    | 2.3        | > 1               | 1083             | 110               |
| Al       | 1.0    | 1.05       | < 1               | 660              | 69                |
| Au       | 1.4    | 2.4        | > 1               | 1063             | 78                |
| Ti       | 0.9    | 0.5        | < 1               | 1668             | 116               |
| Mo       | 1.25   | 0.6        | < 1               | 2610             | 329               |
| Zr       | 1.1    | 0.65       | < 1               | 1852             | 68                |
| Fe       | 1.3    | 1 (SS 1.3) | ~ 1 [21]          | 1536             | 200               |
| W        | 1.4    | 0.57       | < 1               | 3410             | 411               |
| Ta       | 1.3    | 0.57       | < 1               | 2996             | 186               |
| Nb       | 1.2    | 0.6        | < 1               | 2415             | 105               |

Table 2: Measurement history of air-exposed dark current electrodes.

| Cathode | Anode          | As received | Plasma (He - Ar) | n\textsuperscript{th} Plasma |
|---------|----------------|-------------|------------------|-------------------------------|
| SS      | SS             | Yes         | Yes              | Yes                           |
| Al      | Al             | Yes         | Yes              | Yes                           |
| Al mirror Finished | Al (sme as abv) | Yes         | Yes              | Yes                           |
| Cu oxidized | Cu oxidized   | -           | Yes              | Yes                           |
| Cu Polynox\textsuperscript{TM} | Cu Polynox\textsuperscript{TM} | Yes         | Yes              | -                             |
| Ti      | Ti             | Yes         | Yes              | Yes                           |
| Mo vac fired | Mo vac fired | Yes         | Solely Ar        | Yes                           |
| Ti vac fired | Ti vac fired  | Yes         | Solely Ar        | Yes                           |
| Cu mirror Finished | Mo vac fired | Yes         | Solely Ar        | Yes                           |
Table 3: Field gradient (MV/m) between electrodes obtained at 1 mm gap for 1 nA of dark current or with no field emission (FE), second row.

|       | SUS | Cu | Ti | Mo | Mo - Ti | Al | Nb |
|-------|-----|----|----|----|---------|----|----|
| 1 nA | 36  | 47.5 | 88 | 84 | 103     | -  | -  |
| No FE | -   | 70  | 60 | -  | -       | 85 | 92 |

Table 4: Electric field in MV/m held in between two Al electrodes at 1 mm gap for the given dark current in nA.

| State / Dark Current | Al - Al | Al mirror finished - Al |
|----------------------|---------|-------------------------|
| As Received          | < 0.05 nA | 1 nA                   |
|                      | -        | 7.5                     |
| After Plasma         | 52       | 30                      |

Table 5: Electric field in MV/m held in between Cu electrodes at 1 mm gap for the given dark current in nA. (*) obtained at 3mm gap

| State / Dark Current | Cu oxidized | Cu clean | Cu-Mo |
|----------------------|-------------|----------|-------|
| As Received          | < 0.05 nA   | 1 nA     | < 0.05 nA | 1 nA |
|                      | -           | 24       | 18.2 (*) | 13.8 (*) |
| After Plasma         | 32          | 29.3     | 21.6   | 25.4 |

Table 6: Electric field in MV/m held in between two SS two Ti and two Mo electrodes at 1 mm gap for the given dark current in nA.

| State / Dark Current | SS As Received | < 0.05 nA | 1 nA |
|----------------------|----------------|-----------|------|
| After Plasma         | 68             | 35        |      |
| Ti As Received       | 50             | 46.6      |      |
| After Plasma         | 63             | 67 (0.1nA)|      |
| Ti Vac Fired         | 29.6           | 32.5      |      |
| After Plasma         | 39             | 41.4      |      |
| Mo As Received       | 37             | 45.2      |      |
| After Plasma         | 44             | 61.3      |      |
Figure 1: Dark Current -100 kV DC test stand.
Figure 2: Dark Current -100 kV DC test stand. Zoom over the area containing the cathode (flat electrode) the anode (mushroom) and the plasma electrode located at 7 cm from the center of the system.
Figure 3: Cleaned Cu cathode after high voltage testing, left. Damaged Mo cathode, right picture. Damage can be clearly seen.

Figure 4: Three anodes used for HV testing, Ti on the left (grey black colour, after vacuum firing), Mo in the center and Cu on the right. Pictures taken after HV testing. Damage can be seen on the Ti electrodes.
Figure 5: Dark current of Al electrodes after a system bake at 190°C for 100h and after electrical conditioning of 29 kV at a 4 mm gap drawing 7 nA of current from the cathode to the anode.

Figure 6: Dark current of Al electrodes after an Ar Glow Discharge, following the previous He processing and high field conditioning.
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