COMPARISON OF HIGH GRADIENT ACHIEVEMENT FOR DIFFERENT METALS IN DC AND PULSED DC MODE

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Abstract

For the PSI-XFEL project, an advanced high gradient low emission gun is under development. Reliable operation with an electric field, preferably above 125 MV/m at a 4 mm gap, and in presence of an UV laser beam, has to be achieved in a diode configuration in order to minimize the emittance dilution due to space charge effects. In the first phase, a DC breakdown test stand was used to test different metals with different preparation methods at voltages up to 100 kV. In addition high gradient stability tests were also carried out over days in order to prove reliable spark-free operation with a minimum dark current. In the second phase, electrodes with selected materials were installed in the 250 ns FWHM, 500 kV electron gun and tested for high gradient breakdown and for quantum efficiency using a 266 nm UV laser.

100 KV DC SYSTEM

The ultra-high vacuum (UHV) chamber shown in Fig.1, is described in detail in [1]. The UHV system comprises a diode ion pump of 150 l/s, an injection line, a leak valve and a capacitance pressure gauge. The gauge measures gas injection (Ar, He or a mixture of both) in order to prepare for plasma glow discharge (PGD) between the electrodes ($\sim$ 20 minutes, 500 eV).

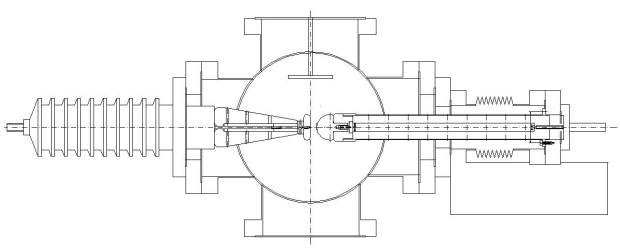

Figure 1: Diode configuration of the 100 kV DC chamber. The cathode is flat the anode is hemispheric and the third flat electrode above is used for plasma glow discharge.

A DC negative bias of 0 to 100 kV is applied to the cathode through an insulating ceramic, (on the left in Fig.1). The anode is grounded. The potential energy stored in the system is 1.5 J at 100 kV. The current flowing from the cathode to the anode is measured across a 1 MΩ resistor with a Keithley multimeter and recorded with Labview^{TM} software. The gap separation between the electrodes is adjustable with a translation feedthrough and is measured with a digital micrometer. A photomultiplier (PMT) is used to detect X-ray (XR) activity.

Non Polished Electrodes

A first set of results was published in [1] and is summarized in Table 1. The electrodes were in general not polished and their average roughness (R_a) is below 200 nm. The highest gradients were obtained usually after the first in-situ PGD cleaning, sometimes after a second one. The values quoted for 1 nA were usually obtained after arcing. After arcing, field emission (FE), also called dark current, appears for lower gradient. A subsequent PGD can often restore the gradient without FE.

Table 1: DC gradient in MV/m before breakdown between cathode (Cthd) - anode (And) at 1 mm gap, unless specified otherwise, for the given dark current in nA.

Cthd-And	Dark Current / State	As Received	After PGD
SS-SS	$<$ 0.05 nA	40	68
	1 nA	42.5	35
Ti-Ti	$<$ 0.05 nA	50	63
	1 nA	46.6	67 (0.1nA)
Ti-Ti Vac Fired	$<$ 0.05 nA	29.6	39
	1 nA	32.5	41.4
Mo-Mo Vac Fired	$<$ 0.05 nA	37	44
	1 nA	45.2	61.3
Cu-Cu Oxidized	$<$ 0.05 nA	-	32
	1 nA	-	29.3
Cu-Cu Etched	$<$ 0.05 nA	24	55
	1 nA	26	19
Cu-Mo	$<$ 0.05 nA	18.2 (3mm)	21.6
	1 nA	13.8 (3mm)	25.4
Al-Al	$<$ 0.05 nA	-	52
	1 nA	7.5	30
Al-Al (*)	$<$ 0.05 nA	36 (2mm)	73
	1 nA	29	31
Nb-Nb	$<$ 0.05 nA	-	10 (4mm)
	1 nA	-	5.5 (4mm)

SS: Stainless Steel (*) Mirror finished - Damaged anode

The PGD between the electrodes is obtained by biasing positively up to 500 V the upper third electrode and connecting to ground the anode-cathode pair [1]. This configuration cleans properly the electrode pair. Applying the

bias to one electrode and then to the other one, usually results in transferring contaminants from one to the other electrode. However, in DC mode a breakdown is usually cathode initiated. Therefore, cleaning the cathode last can still be beneficial in reaching high gradient.

Most of the metals tested in this first set reached their breakdown gradient without arcing. Ti and Mo sustained a few micro-breakdown before arcing. Micro-breakdown in this system is characterized by a surge in pressure, followed by a burst (a few seconds) of FE current. A definitive breakdown is defined and characterized by a sustained vacuum activity, pressure is usually ten times higher than during normal operation, and the FE current is such that the 100 kV power supply cannot hold the voltage. Electric gradient values are then recorded when the FE current is 1 nA, to compare with literature [2].

Polished Electrodes

Electrodes were polished or diamond turned by commercial companies capable of producing high quality optical mirrors. The average roughness, R_a, of the polished electrodes was below 50 nm, and below 10 nm for Al, Cu and SS. The obtained breakdown gradients were compared to those obtained for broad polished electrodes [2, 3, 4]. Nb, Ti and Mo electrodes were given high temperature (HT) treatment and the Nb electrodes were treated with buffered chemical polishing (BCP). After BCP, grains up to 10 mm size were visible. HT treatment reduces the numbers of field emitters with a sufficiently high temperature [5].

Table 2 summarizes the best results. PGD almost invariably improve breakdown gradient. Electrodes installed "as-received" were only cleaned with alcohol before being installed in the vacuum chamber. The values quoted for 1 nA, were usually obtained after arcing, hence the lower numbers compare to the <0.05 nA row. In the "as-received" case the values of the field recorded in the 1 nA row are higher, as FE appears before breakdown.

Operation at a given gradient was carried out over periods of days. As an example Fig.2 shows the results for SS mirror finished electrodes at 1 mm gap after PGD. Each data point is an average of 10 measurements, and is recorded in general every 10 minutes. The system was stable at 69 kV for 6 days. A sudden jump of dark current is probably due to a micro breakdown. The drop in voltage at the end of the set is due to a software protection scheme, which switch off the high voltage (HV) power supply when voltage drops more than 1 kV of the set value. The drop in voltage is usually due to a higher emission of dark current. The PMT signal usually correlates with FE activity, and is enhanced with increasing vacuum level. In this setup the PMT is placed behind a window and look at the electrodes gap. With a 4 mm gap clear PMT signal can be recorded, but as the gap closes, the amount of XR going through the PMT drops significantly.

For polished SS, the field achieved with "as-received" electrodes is 25 MV/m above that for non-polished SS.

Table 2: DC gradient in MV/m held between a cathode - anode pair at 1 mm gap for the given dark current in nA.

Cthd-And	Dark Current / State	As Received	After PGD
Cu-Cu	< 0.05 nA	20	67.5 (*)
	1 nA	25	67.5 (*)
Cu-Cu New-Used	< 0.05 nA	37	52
	1 nA	41.9	47
SS-SS	< 0.05 nA	65	71
	1 nA	24	25 (0.1nA)
Nb-Nb	< 0.05 nA	20	59
	1 nA	23	20.8
Mo-Mo	< 0.05 nA	32.5 (2mm)	68.5
	1 nA	32	33

(*) Drift from 0.03nA to 8.5nA in 58 hrs

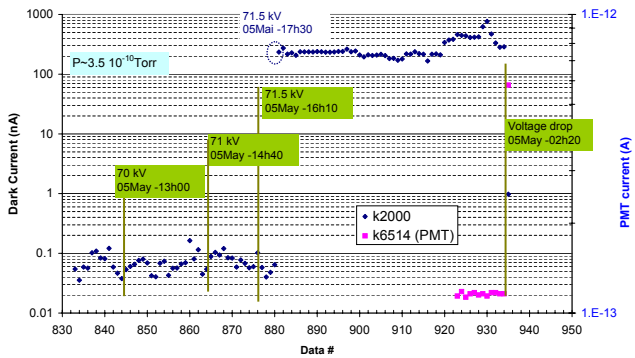

Figure 2: Dark current (label K2000) and PMT level (label K6514) of SS electrodes at 1 mm gap.

However, results obtained for the non polished electrodes and polished electrodes in a DC regime are in general not so different, except for Nb. Polished Mo did not exceed 40 MV/m, without FE, even after two consecutive Ar PGD. In order to reach 68.5 MV/m, the Mo cathode was let producing a 6 μA, 50 kV, dark current for 72 hours. A third Ar PGD of 2 hours followed. When compared to literature an in-situ PGD gives results equivalent to those after careful polishing followed by a ultra pure high pressure water rinsing.

500 KV PULSED SYSTEM

The UHV vacuum chamber and electrodes for the high gradient pulsed tests are shown in Fig.3. The chamber is sealed without bolts, using a differential vacuum system. This permits easy exchange of electrodes. The chamber is integrated into a filtered air cabinet (not shown) to ensure a dust-free environment when it is opened. With a turbo pump, 10^{-7} mbar can be reached in 12 hours, and with two 300 l/s ion pumps, 10^{-8} mbar can be reached within two days. The cathode support includes provision for future mounting of Field Emitting Arrays which are presently under development at PSI [6]. The UHV chamber is integrated with a 500 kV pulser which is described in [7, 8]. The pulser uses thyratrons and an air-core trans-

former (Tesla coil) to generate a damped oscillating waveform with a dominant negative peak voltage. The peak voltage is stable to $\pm 0.1\%$ and is adjustable 0-500 kV. The gap between the electrodes is adjustable 0-10 mm. Both electrodes are made of the same material and have the same profile, which is different from the 100 kV DC system. For quantum efficiency (QE) or electron beam emittance measurements, the emitted electron beam passes through a 2 mm diameter anode hole. The description of the downstream electron beam line can be found in [9].

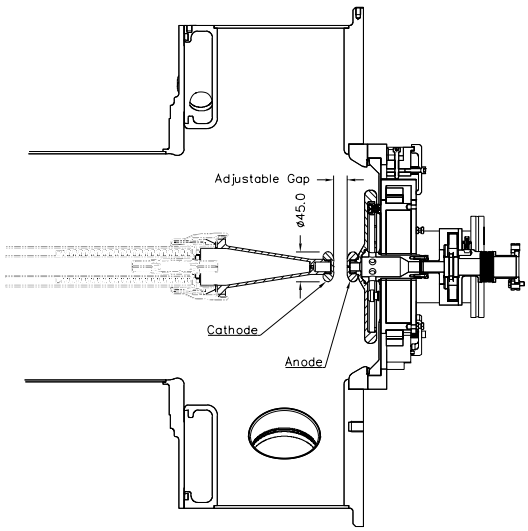

Figure 3: Diode Configuration inside the 500 kV pulser UHV chamber. The cathode is mounted on the left side.

Fig.4 shows a typical pulser operation with a 4 mm gap. The XR signals are delayed with respect to the negative voltage peaks because of an analog filter delay. When a spark occurs, the XR signal saturates as is seen for one event in Fig.4; this high level is used as a machine protection system and will stop the HV pulsing until reset, or at least until the HV is reduced.

Breakdown is characterized by watching the electrode camera, the cathode voltage and XR signals. Considering Fig.4 in more detail, the spark occurred at a moment when the HV was low, suggesting that the previous positive voltage swing may have contributed. The HV is clamped to a flat line with almost zero voltage indicating that the spark turned into a destructive arc and the energy in the pulser was dissipated. The video camera image shows a bright uniform arc column between anode and cathode.

A total of 24 electrode pairs were tested, with evolving skill for polishing and cleaning. The range of breakdown gradients achieved, for gaps varying from 2.5 mm to 6 mm, is shown in Table 3. Although many factors might affect breakdown, the dominant factor for this gradient level is the quality of mechanical polishing. For reasons of cost and ease, most measurements are being performed with 316L stainless steel. Since SS and TiVAl give high gradients and yet are alloys, material purity is not dominant at this gradient. So far, we have not seen any influence of the electrode

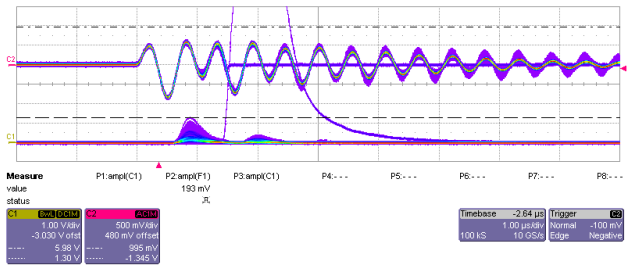

Figure 4: Measured waveform of the HV pulse 280 kV (upper trace) and X-ray scintillator signal lower trace.

geometry, e.g. the anode hole, on breakdown.

Table 3: Summary of peak gradient (MV/m) for gaps ranging between 2.5 mm and 6 mm.

Cthd-And	without laser	with laser
CuCr - CuCr	23	-
WCr - WCr	30	-
Al - Al	46	-
Cu - Cu	74 - 83	41 - 51
Nb - Nb	60 - 83	64
SS - SS	70 - 140	95
TiVAl - TiVAl	70 - 130	-

Earlier attempts with PGD used an external DC power supply to bias the cathode positive or negative. The plasma could be localized in between the electrodes only for a given set of voltage, current and gas pressure, and this was largely independent of the gap between the electrodes. Unfortunately, the energy of the ions was less than 200 eV and this PGD did not give a clear increase in breakdown voltage. Later attempts used the pulser itself, running at 50 Hz to give a kilovolt pulse across the gap. Unfortunately, the large gap current meant that the cathode had only a positive half-cycle of some microsecond, and so far the results from this procedure have not given a clear increase in breakdown voltage.

QUANTUM EFFICIENCY OF METALS

The laser system used to measure the QE of the material is described in [9]. The main parameters of the laser beam are : σ = 6.5 ps rms, λ = 266 nm, energy 12 μJ/pulse at laser exit; energy at the entrance of the accelerator beamline 4 μJ ($\pm$ 0.1 μJ). The energy can droop over weeks, depending on the state of cleanliness of the optics. The short term laser pointing stability at a virtual cathode position was measured to be around 10 μm rms.

As represented in Fig.5, the quantum efficiency (QE) increases with the applied electric field due to the Schottky effect. Indeed analytical formulas [10] based on the three steps model (absorption, excitation and emission of electrons) [11] reproduce quite well the measured data points. The only parameter, in equation.1, that has been adjusted

is the work function, Φ which depends mainly on the surface material and crystal orientation. The reflectivity R, of a given metal, is measured in air.

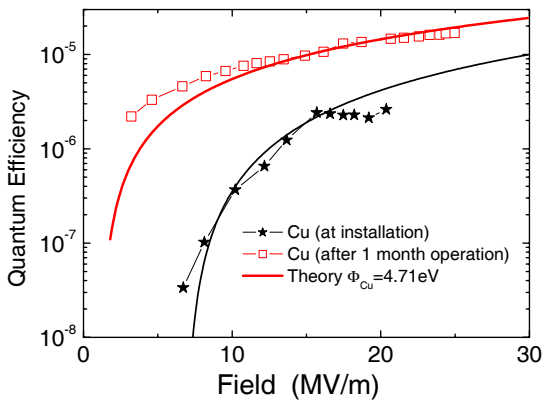

Figure 5: QE increase for a Cu cathode after 1 month of laser and high voltage operation.

$$QE(\omega) = \frac{1 - R(\omega)}{1 + \frac{\lambda_{opt}}{2\,\lambda_{e-e}(E_m)} \frac{E_{ph}\sqrt{\Phi_{eff}}}{E_m^{3/2}} (1 + \sqrt{\frac{\Phi_{eff}}{E_{ph}}})} \times \frac{E_F + E_{ph}}{2E_{ph}} \times \left[1 + \frac{E_F + \Phi_{eff}}{E_F + E_{ph}} - 2\sqrt{\frac{E_F + \Phi_{eff}}{E_F + E_{ph}}} \right] \quad (1)$$

Where E_F is the Fermi energy, $E_{ph} = \hbar\omega$ is the photon energy, λ_{opt} is the laser penetration depth and λ_{e-e} is the electron - electron scattering length and E_m is the energy above the Fermi level. The plotting of eq.1 in Fig.5 shows a good matching with the experimental values. The parameters used for copper [10] are : R_{Cu}(266 nm) = 0.25; E_F = 7 eV; E_{ph} = 4.6 eV; λ_{opt} = 10.7 nm; λ_{e-e} = 2.2 nm.

The difference between the two Cu measurements can be interpreted as a cleaning (contaminants removal) of the surface after one month of operation, no breakdown occurred during that period. QE maximum measured was on the order of 2.10^{-5} at 25 MV/m, which is in agreement with copper based RF photogun [12]. Fig.6 shows the QE of various metals measured with this beamline [9].

Arcing changes the chemistry and topology of the surface; its effect on the QE is seen as soon as the pulser system recovers from the arc. The tendency is that the QE is increased after an arc. In one case, the QE of an SS cathode increased by a factor of four to 4.5 10^{-5} (50 MV/m at 6 mm), in another case with a diamond turned Cu cathode the increase was by a factor of ten to 7 10^{-6} (also 50 MV/m at 6 mm). The highest QE after an arc was with an SS cathode which reached 1.2 10^{-4}; unfortunately, in this case the extracted electron beam no longer had a gaussian cross section. More QE of metals are currently measured using a new laser : 500 μJ, 262 nm, 35 ps FWHM.

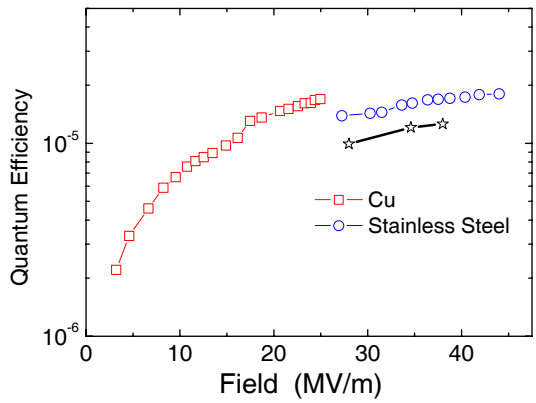

Figure 6: QE of copper, stainless steel and niobium

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