Vacuum breakdown limit and quantum efficiency obtained for various technical metals using dc and pulsed voltage sources

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For the SwissFEL project, an advanced high gradient low emittance gun is under development. Reliable operation with an electric field, preferably above 125 MV/m at a 4 mm gap, in the presence of an ultraviolet 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. The authors show that gradient achieved for rough machined ($R_a < 200$ nm) metal electrodes followed by an argon glow plasma are similar to the one obtained using a mirrorlike electrode ($R_a < 40$ nm). In addition, high gradient stability tests were also carried out over several 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 full width at half maximum, 500 kV electron gun and tested for high gradient breakdown and for quantum efficiency using an ultraviolet laser. Routine electron beam operation, breakdown-free, at 50 MV/m (6 mm gap, 10 Hz repetition rate) at various charges is now achieved using different metal electrodes. © 2010 American Vacuum Society. [DOI: 10.1116/1.3478300]

I. INTRODUCTION

The Paul Scherrer Institut (PSI) is interested in constructing and operating a fourth generation light source before the end of the next decade. This x-ray free electron laser (XFEL), operating at $\lambda = 1$ Å, will be a companion to the existing third generation light source, the Swiss Light Source. The SwissFEL (previously PSI-XFEL) facility, in order to fit the site and the budget constraint, needs a concept which reduces the required beam energy given by the desired radiation wavelength λ according to the spatial coherence criterion, see Eq. (1),

$$\frac{\varepsilon^{(n)}}{\beta\gamma} < \frac{\lambda}{4\pi}, \quad (1)$$

where $\varepsilon^{(n)}$ is the normalized transverse emittance at the undulator entrance and $\beta\gamma$ being the relativistic coefficient.^{1,2} The emittance (beam size $\times$ its divergence) is an important criterion in defining a beam quality. The lowest the emittance, the better the beam quality.^{3–5} The choice of technology envisaged to obtain a low emittance was to use an electron source based on field emission over photoemission or thermionic emission.^{6–8} Emittance simulation studies on a prototype diode electron gun, using double gated field emitter arrays (FEAs) as an electron source, have been performed in accordance to this choice.^{9,10}

To achieve a low emittance, the diode should sustain the highest possible gradient in order to accelerate a high charge density beam and minimize emittance dilution due to space charge effects. The goal is to exceed the typical values of accelerating gradient achieved in state of the art photoguns (~ 100 MV/m accelerating field).¹¹ A review on vacuum

breakdown, as done in Refs. 12–14, over a century of research is not sufficient to select the appropriate material for a specific application.

Metallic electrodes, with different preparation procedures, were first tested in a 100 kV dc system, and the results obtained compared to the literature. Parts of those results, notably the one concerning the nonpolished electrodes, were already presented in Ref. 15. As the diode prototype came on line, high gradient (HG) high voltage (HV) tests on metallic electrodes were carried out with and without ultraviolet (UV) laser. The results, including quantum efficiency (QE) measurements, are reported in this article.

II. 100 KV DC SYSTEM

The ultrahigh vacuum (UHV) chamber shown in Fig. 1 is described in detail in Ref. 15. 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 the absolute pressure of the injected gas (Ar, He, or a mixture of both) in order to prepare for plasma glow discharge (PGD) between the electrodes (~ 20 min, 500 eV, pressure $\times$ distance < 1 Torr. cm). Polished electrodes were treated using only Argon gas, providing ions of 400 eV (ArPGD). The ion current was ~ 10 mA, spreading over a few cm² of electrode. PGDs for the rough electrodes were, at first, a mixture of He–Ar followed by pure Ar.¹⁵

A negative dc bias of 0–100 kV is applied to the cathode through an insulating ceramic (on the left in Fig. 1). The anode is connected to a 1 MΩ resistor through a bayonet Neill–Concelman (BNC) connector vacuum feedthrough. This whole part is grounded. The current flowing from the cathode to the anode is measured across this 1 MΩ resistor with a Keithley™ 2000 multimeter and recorded with LAB-

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FIG. 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.

VIEW^{TM} software. In principle, the HV power supply can deliver up to 1 mA at 100 kV. It is possible to adjust the maximum current allowed to be delivered by the power supply; we have adjusted it around 1 μ A. The potential energy stored in the system is 1.5 J at 100 kV. The gap separation between the electrodes is adjustable with a translation feedthrough and is measured with a digital micrometer. A fast photomultiplier (PMT) (H6780-02 from Hamamatsu^{TM}) is used to detect x-ray (XR) activity. Its current value is recorded using a Keithley^{TM} 6514 electrometer.

Usually one pair of electrodes is tested under UHV condition $P < 5 \times 10^{-9}$ torr. They are then remachined and polished for subsequent tests. In the cases of copper, aluminum, and stainless steel (SS), two different pairs have been used.

A. Nonpolished electrodes

The modus operandi and a first set of results, which are summarized in Table I, were published in Ref. 15. The electrodes were, for the most part, rough machined and their average surface roughness (R_a) is below, but close to, 200 nm. The sequence of test, for either polished or nonpolished electrodes, start by increasing the voltage to 75 kV at 4 mm gap. When reached the voltage is set to zero and the gap is reduced to 3 mm then 2 mm and then to 1 mm. The highest gradients were usually obtained after the first *in situ* PGD cleaning but sometimes after a second. The values quoted for 1 nA were, in general, obtained after arcing. After arcing, field emission (FE), or “dark current,” appears for lower gradients. A subsequent PGD can often restore the gradient without FE.

The PGD between the electrodes is obtained by biasing the upper, third, electrode positively up to 500 V and connecting the anode-cathode pair to ground.¹⁵ This configuration cleans the electrode pair in a similar manner. Applying the bias to each electrode, one after the other, frequently results in transferring contaminants from one electrode to the other. However, in dc mode, a breakdown is generally cathode initiated.¹² Therefore, cleaning the cathode last can still be beneficial in reaching high gradient.

Most of the metals tested in this first sample set reached their breakdown gradient without arcing. Ti and Mo sustained a few microbreakdowns before arcing. Microbreakdown in this system is characterized by a surge in pressure, followed by a burst (a few seconds) of FE current. A defini-

TABLE I. 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.

Material Cthd-And	Dark current (nA)	As received field (MV/m)	After PGD field (MV/m)
SS-SS	<0.05	40	68
	1	42.5	35
Ti-Ti	<0.05	50	63
	1	46.6	67 (0.1 nA)
Ti-Ti vac fired	<0.05	29.6	39
	1	32.5	41.4
Mo-Mo vac fired	<0.05	37	44
	1	45.2	61.3
Cu-Cu oxidized	<0.05	...	32
	1	...	29.3
Cu-Cu etched	<0.05	24	55
	1	26	19
Cu-Mo	<0.05	18.2 (3 mm)	21.6
	1	13.8 (3 mm)	25.4
Al-Al	<0.05	...	52
	1	7.5	30
Al-Al ^a	<0.05	36 (2 mm)	73
	1	29	31
Nb-Nb	<0.05	...	10 (4 mm)
	1	...	5.5 (4 mm)

SS: stainless steel

^aMirror-finished—damaged anode.

tive breakdown is defined and characterized by a sustained vacuum activity. The pressure is often 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 set to 1 nA, to compare with the literature.¹⁶ This explains why values at 1 nA are generally lower than the values without FE (<0.05 nA), as in the case of the etched Cu after PGD, Table I.

B. 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 40 nm, and below 10 nm for Al, Cu, and SS. The term “mirror-finished” will refer to surfaces with an average roughness below 40 nm. The breakdown gradients obtained were compared to those obtained for polished electrodes of broad area.^{16–18} Nb, Ti, and Mo electrodes were, prior to polishing, given high temperature (HT) treatment and the Nb electrodes were treated with buffered chemical

TABLE II. dc gradient in MV/m held between a cathode-anode pair at 1 mm gap for the given dark current in nA.

Material Cthd-And	Dark current (nA)	As received field (MV/m)	After PGD field (MV/m)
Cu–Cu	<0.05	20	67.5 ^a
	1	25	67.5 ^a
Cu–Cu new-used	<0.05	37	52
	1	41.9	47
SS–SS	<0.05	65	71
	1	24	25 (0.1 nA)
Nb–Nb	<0.05	20	59
	1	23	20.8
Mo–Mo	<0.05	32.5 (2 mm)	68.5
	1	32	33

^aDrift from 0.03 to 8.5 nA in 58 h.

polishing (BCP). HT treatment refers to vacuum firing in a dedicated furnace at the Conseil Européen pour la Recherche Nucléaire (CERN) following CERN procedures for each material. One of the criteria in the choice of temperature is to avoid excessive recrystallization.¹⁹ The temperature plateau of the furnace is set at 900 °C for 2 h for SS; Ti, Mo, and Nb at 800 °C for 6 h. Getter materials, such as Ti, are placed inside a separately pumped and degassed vacuum container to avoid any contamination of the electrode by outgassing gas from the furnace. In the case of Nb, after BCP, grains up to 10 mm size were visible. HT treatment, with a sufficiently high temperature, reduces the number of field emitters.²⁰ In this case the temperature chosen for Nb is below this critical temperature, hence the need for polishing. All electrodes are measured as-received after a careful ethanol wipe before

mounting in the UHV chamber. The first PGD is made after the installed as-received cathode either arcs or emits a dark current of 1 nA.

Table II summarizes the best results. PGD almost invariably improved breakdown gradient. Electrodes installed “as-received” were only cleaned with alcohol (ethanol) before being installed in the vacuum chamber. The values quoted for 1 nA were usually obtained after arcing, hence the lower numbers compared 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. After test and under visual inspection, all electrodes retained their mirrorlike appearance, except for the damaged area. No roughness was measured after HG testing.

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 was recorded at intervals of 10 min. The system was stable at 69 kV for 6 days. A sudden increase of dark current was probably due to a microbreakdown. The drop in voltage at the end of the sample is due to a software protection scheme, which switches off the HV power supply when voltage drops by more than 1 kV from the set value. The drop in voltage is usually due to a higher emission of dark current. The PMT signal often correlates with FE activity and is enhanced with increasing vacuum level. In this setup, the PMT is placed behind a window, facing the electrode gap. With a 4 mm gap, a clear PMT signal can be recorded, but as the gap closes, the amount of XR going through the PMT drops significantly. The XR level varies from a few hundred of picoamperes to picoamperes depending of the gap and the vacuum level. With a vacuum level of $\sim 5 \times 10^{-10}$ Torr at 30 MV/m (1 mm gap), the XR current recorded is of a few picoamperes. This can jump by a factor of 10 when pressure jumps of the same amount. This correlates also to an increase of dark current

FIG. 2. (Color online) Dark current (label K2000) and PMT level (label K6514) of SS electrodes at 1 mm gap.

TABLE III. Literature field gradient (MV/m) between electrodes obtained at 1 mm gap: for 1 nA of dark current; without FE; BF with FE; CERN results; this work, after a PGD without FE.

	SS (MV/m)	Cu (MV/m)	Ti (MV/m)	Mo (MV/m)	Mo-Ti (MV/m)	Al (MV/m)	Nb (MV/m)
Furuta—1 nA ^a	36	47.5	88	84	103	...	...
Diamond—No FE ^b	...	70	60	...	...	85	92
Kranjec—BF ^c	79.8 ^d	46.1	48	38.9	...	51.3	...
CERN—saturated BF ^c	800	170	780	420	...	150	400
Tarasova—saturated BF ^f	...	46	55	62	...	45	48
Best BF (this work)	71	67.5 ^g	67	68.5	...	92 ^h	59

^aReference 16.^bReference 17.^cReference 22.^dMeasured at 0.5 mm.^eReference 24.^fReference 12.^g8 nA of dark current.^hMeasured at 0.75 mm.

recorded by the K2000 multimeter. In some instances, the K6514 will display a burst in current without being correlated with a pressure increase or a dark current increase. A microbreakdown hence a burst of XR associated with it would be a good candidate to explain such sudden increase.

In general, and after PGD, results obtained for the non-polished electrodes (Table I) and polished electrodes (Table II) in a dc regime are not so different. The PGD in either cases improves significantly the breakdown field (BF) limit achievable compared to the as-received electrodes.

When comparing field achieved for as-received Nb which was HT treated and chemically polished, Table I, to mechanically polished Nb, one can see that mechanically polished Nb reaches a higher gradient (Table II). The mechanical polishing using the PSI recipe removes the features exposed by the BCP treatment, hence making the surface smoother. The PSI recipe despite not being optimized for refractory metals is still a good start to achieve higher breakdown fields. Polished Mo did not exceed 40 MV/m, without FE, even after two consecutive Ar PGDs. In order to reach 68.5 MV/m, the Mo cathode was run with a 6 μ A, 50 kV, dark current for 72 h. A third Ar PGD of 2 h followed; the best result is shown in Table II. The main action of the PGD is to remove contaminants on the surface, hence changing the work function of the surface of the material with little change of the surface topology.^{12,21}

When compared to Ref. 16, an *in situ* PGD gives results equivalent to those after careful polishing followed by an ultrapure high pressure water rinsing. In general, a PGD treatment used on a commercially mirror-finished or non-mirror-finished electrode gives significant improvement compare to an as-received electrode. A literature comparison, Table III, to our results proves that the BF quality from mirror-finished surfaces, either by polishing or diamond turning, coming from commercial vendors is, nowadays, very satisfying. Microscopy analysis does not show systematic embedded material, roughness achievement is equivalent, and sometimes superior to that, which a research laboratory

can produce. One surprising point is the fact that, in general, PGD on rough material gives some very competitive results compared to highly polished, hence expensive, material.

In early works, it was stated that the less refractory metals seem to reach the highest breakdown field.^{22,23} From results presented in Table III, this is not so evident. Moreover, results from CERN contradict this conclusion with Ti, V, Cr, Mo, Nb, Ta, and W holding higher gradient than soft materials such as Cu and Al, as also shown in much older work.¹² CERN and results cited in Ref. 12 are obtained by doing breakdown conditioning, at CERN between a pointed anode and a flat cathode with gaps around 20 μ m,^{24,25} and for Ref. 12 between different kinds of electrodes separated by gaps varying from 0.3 to 5 mm, hence a very different modulus operandi. In order to compare data presented in line 3 of Table III to other results, the electric field in MV/m has been derived by calculating back from the original voltage.

Different preparation will result in a different enhancement factor (β) and a lower β results in general in a higher BF, although not always.^{16,26} Using β is a convenient way to compare FE quality because it is usually a straight line fit of the data when plotted in a Fowler–Nordheim plot [$\ln(I/V^2)$ versus I/V] and should not present any discontinuity.^{12,22} It is particularly well suited in comparing electrodes of the same materials prepared in an identical way, prior any high gradient testing. However, the intrinsic understanding of β on a “dirty” surface, in an UHV sense, is absent. For example, a variation of the chemistry on the surface implies a variation of the work function. However, as the work function is systematically never measured, but assumed, this variation will be attributed to a change of β in the Fowler–Nordheim equation. Our point is that comparing directly the emission current versus the field applied gives an immediate conclusion. In most of our results, the FE current, before breakdown, is below the detection limit, as in Fig. 2. Hence comparison is not feasible.

The electrodes tested were single material. A mix of different electrode materials is certainly promising for reaching

FIG. 3. (Color online) Measured waveforms of the HV pulse -280 kV (first negative peak) followed by a $+170$ kV (second positive peak) (upper trace, C2) and x-ray scintillator signals lower trace, C1.

high gradient in real dc gun,¹⁶ as one of the hypothesis of the breakdown is material transfer from the anode to the cathode.¹² Unfortunately our pulse, in our pulsed diode system, has an oscillatory behavior with a positive peak amplitude being 60% of the negative peak, Fig. 3. As the effect of the anode cannot be neglected, we have concentrated our effort on single materials in order to propose usable solutions for our needs, without complicating our research.

III. 500 KV PULSED DIODE PROTOTYPE ELECTRON SOURCE

It is known that higher gradients are achieved when using a pulse high voltage compared to a dc system.^{12,27} This is also true in a rf system where the short pulse permits a higher gradient to be reached.²⁸

The original SwissFEL concept was based on a field emitter array producing an electron beam of 5.5 A in 2 ns [full width at half maximum (FWHM)].²⁹ In order to produce an electron beam with no or little energy spread either, a jitter-free square pulse or a longer pulse is needed. The 500 kV, 250 ns (FWHM) pulser, Fig. 4, was initially designed to accommodate such a requirement.

The main driving factor for having HV transformer technology is the compromise between stability and complexity. In the voltage range considered (0.5 – 1 MV), the only available hard switch is a gas switch (spark gap). Self-triggered gas switches are not suitable for large dynamic range because switching parameters depend strongly on operating voltage. Another disadvantage is large switching time jitter and limited life. Triggered gas switches are much more suitable in terms of jitter but require a fast HV trigger pulse or a high power short laser pulse. Switching characteristics of electrically triggered gas switches still depend on applied voltage and to ensure good dynamic range and jitter performance, they require fast trigger voltage pulses with amplitude comparable to the switched voltage.³⁰ This requirement makes such a system impractical. Performance of laser triggered gas switches depends on the properties of the laser trigger pulse. Using lower laser peak power (several megawatts), the jitter performance is still in tens of nanoseconds (peak).^{31,32} Recently, research groups have reported good results with high peak power laser triggered gas switches.^{33,34} In order to get dense enough photoexcited plasma in the

conducting channel, the trigger laser has to provide pulses with tens of gigawatt to terawatt peak power that dramatically increases the complexity and the cost of such a system. Thyatron switched air-core resonant transformer, combined with relatively high primary voltage, gives a good speed-stability engineering compromise and makes it possible to achieve the required amplitude stability to better than 0.1% .³⁵ The linear system ensures large dynamic range of the output voltage, required for such test system. Another reason to use a fully linear technology is the scalability.

A more detailed cross section of the UHV vacuum chamber with the electrodes for the high gradient pulsed tests is shown in Fig. 5. The laser illuminating the cathode is inserted in the middle of the beam line after the UHV valve (Fig. 4) and goes through the 2 mm diameter anode hole. 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 (shown in green in Fig. 4) to ensure a dust-free environment when it is opened. With a turbopump, a pressure of 10^{-7} mbar can be reached in 12 h, and with two 300 l/s ion pumps, 10^{-8} mbar can be reached within 2 days. HG testing of electrodes was done with a high turnover and pressure in the UHV pulser tank was below $P < 10^{-7}$ Torr. During electron beam characterization the pressure was $P < 5 \times 10^{-8}$ Torr. The cathode support includes provision for future mounting of FEAs which are presently under development at PSI.³⁶ The pulser uses thyratrons and an air-core transformer (Tesla coil) to generate a damped oscillating waveform with a dominant negative

FIG. 4. (Color online) Cross section of the 500 kV beam line. (a) SF6 Pressure tank; (b) UHV tank, containing the two electrodes; (c) class 1 clean room; (d) diagnostic lines containing YAG screens, solenoids, Faraday cup, and an emittance monitor (Ref. 38); (e) thyatron; and (f) HV transformer.

FIG. 5. Diode configuration inside the 500 kV pulser UHV chamber. The cathode is mounted on the left side.

peak voltage.^{35,37} The peak voltage, when above 30 kV, is stable to $\pm 0.1\%$ and can be varied from 0 to 500 kV. The gap between the electrodes is adjustable from 0 to 30 mm. Both electrodes are made of the same material and have the same profile, unlike the previous 100 kV dc system. For quantum efficiency or electron beam emittance measurements. The emitted electron beam passes through a 2 mm diameter anode hole. The diagnostic beam line, shown in Fig. 4, includes five solenoids to transport and focus the beam. After the first solenoid, which is mounted on the pulser flange, a wall current monitor is installed. A Faraday cup or a yttrium aluminum garnet (YAG) screen can be inserted in the beam line. They are located 491 mm downstream of the anode. An emittance monitor of 870 mm long fitted with movable pepper pot and YAG screen is used for emittance measurement. It is located at the end of the beam line. The overall length of the diagnostic line from the pulser flange to the end of the emittance monitor is 1470 mm. A more detailed description of the 5 m long beam line, including the 3.4 m long pulser, can be found in Ref. 38.

Figure 3 shows a typical pulser trace with a 4 mm gap. The upper trace labeled C2 is a collection of waveforms of the quasi-dc pulse. The pulse oscillates up to 10 μs ; 8 μs are displayed in Fig. 3. This oscillation, and the superposition of a 950 and a 1800 kHz signal, results from the choice of technology.³⁷ The amplitude of the second positive peak is 60% of the maximum of the first negative peak.

The oscillatory voltage waveform of the pulser, with still a high amplitude of the positive peak, was the reason to concentrate our effort on electrode pairs of the same material in the 100 kV dc test stand. Figure 6 shows the electric field at different locations of the pulser electrodes' surfaces.

An XR scintillator detector is used to detect breakdown. The XR scintillator signals, multiple traces, labeled C1, 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. 5; 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 camera pointing toward the electrodes, the cathode voltage, and XR signals. Considering Fig. 3 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 all energy is dissipated in the spark turning it into a destructive arc. The video camera image shows a bright uniform arc column between anode and cathode and the scintillator signal saturates for a few microseconds. In general, more than 2/3 of the events happen at the first negative voltage peak. The scintillator will saturate, but the pulser will not systematically display a flat line.

A total of 24 electrode pairs were tested, with evolving skill for polishing and cleaning. The reason for developing in-house polishing techniques, instead of buying pairs from vendors, is from the possibility of high turn over in electrode exchange. The range of breakdown gradients achieved, for gaps varying from 2 to 6 mm, is shown in Table IV. Highest gradient were obtained for the smallest gap. For reasons of cost and ease, most measurements were obtained with 316L stainless steel and oxygen free electrolytic (OFE) copper, with typical average roughness below 15 nm. Although many factors might affect breakdown, the dominant factor for this gradient level is the quality of mechanical polishing, mainly characterized by roughness and some microscopy to pinpoint embedded polishing material. The hand polished procedure starts with the use of abrasive paper from coarse to fine grains. For SS, diamond paste of decreasing diamond particles size is then used. For Cu, polishing paste LUXOR™ 0.1 μm is used, instead of a diamond paste; wipe of the paste is performed using ethanol.

Before closing the vacuum chamber, all electrodes are spray cleaned with dry ice, for a few seconds. First results on Nb were obtained with an electrode prepared at CERN, using the BCP technique, which again exposed the big grains of the material. Higher results (83 MV/m) were obtained after hand polishing, which did not expose the underlying grain structure of the electrode so completely, hence reducing the roughness. SS and TiAl achieved the highest gradient although they are alloys. It seems that material purity is not an important parameter. So far, we have not seen any influence of the electrode geometry, e.g., the anode hole, on breakdown rate or breakdown location.

Typical operation for HG achievement, without laser, is shown in Fig. 7 (left figure). The voltage (solid line) for a given gap is raised in steps of a few kilovolts after a given number of pulses. The voltage increases until a breakdown occurs. At this moment the voltage is decreased and ramping up is resumed. This procedure is used with and without laser

FIG. 6. (Color online) Electric field simulation of pulser's electrodes showing a peak value at the anode surface of 119 MV/m for 4 mm gap and 400 kV applied voltage.

operation. In this example, the hand polished SS electrodes did not survive the first breakdown, as gradient could not be restored by subsequent breakdowns. Operation lasted for 31 min. The right figure of Fig. 7 displays a typical laser operation, first at large gap and then at smaller gaps. This procedure is the standard procedure used for all electrodes illuminated with a laser. The corollary of this procedure is that an electrode holding high voltage at small gap will hold the same voltage at large gap. We routinely observe this behavior each time we resume operation, day to day, with the installed electrode pair. The constant voltage plateaus signify gap change or QE measurement. In this example, the diamond turned electrodes broke down at 61 MV/m and the gradient

could not exceed 50 MV/m. Operation lasted for 10 h. The longest operation at high gradient, without breakdown, was obtained with SS electrodes: 80 MV/m for 9 h and extracting 55 pC of electron beam current. Breakdown-free routine operation for emittance measurement at 50 MV/m (6 mm gap) over days is achieved with either Cu or SS electrodes. The simple hand polishing technique used can allow a damaged electrodes to be refurbished in half day and be able to be processed (in general discharge free) to 50 MV/m.

The charge produced by the laser lies between 1 and 80 pC depending on the needs. The goal of this electron gun, in its original concept, is to produce a low emittance beam at high voltage and gradient. During cathode testing, no sys-

TABLE IV. Summary of peak gradient (MV/m) for gaps ranging between 2 and 6 mm.

Material Cthd-And	Without laser field (MV/m)	Duettino ® laser field (MV/m)	Jaguar ® laser field (MV/m)
CuCr-CuCr	23	...	...
WCr-WCr	30	...	...
Al-Al	46	...	50
Cu-Cu	74-83	41-51	50-63
Nb-Nb	60-83	64	...
SS-SS	70-140	95	50-80
TiAl-TiAl	70-130	...	...

FIG. 7. (Color online) Operation with SS 316L and copper OFE electrode. Left figure: Typical operation for HG without laser. Right figure: Typical operation with laser.

tematic emittance studies were done, but still some normalized transverse emittance (geometric average $\sqrt{x.y}$) as function of the beam energy were measured, Fig. 8.³⁹ The beam charge, represented by the circle size, ranges from 10 to 154 pC and most emittances measured lie between 0.5 and 2 mm mrad. Emittance measured with Cu cathodes shows that in general smaller emittance were obtained for small charges. We could not correlate small emittance for high gradient at similar charges, orange circles (labeled gap 6 mm, Cu) in Fig. 8. Results on SS were even more inconclusive.

In the 100 kV dc system, PGDs have shown to be pushing back the onset of the breakdown threshold, even on mirror surfaces. In the pulser, we used an external dc power supply to bias the cathode positive or negative in order to light up ArPGD. The plasma could be localized between the electrodes only for a given set of voltage (200 V), current, and gas pressure (usually a few Torr), and this was largely independent of the gap between the electrodes. With such parameters and configuration, the energy of the ions was probably much less than 200 eV. 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 microseconds. PGD treated electrodes did not perform better than untreated electrodes.

As expected, the gradients and voltages achieved for the pulsed diode system (Table IV) with gaps varying from 2 to 6 mm are above the one obtained in dc system with large gap (1–4 mm) (Table III). Moreover dc breakdown test using pulser's electrode design, Fig. 6, with SS and Cu electrodes, prepared similarly as the one installed in the pulser, holding the dry ice spray, has reach gradient similar to gradient quoted in Table III, respectively, 69 and 63 MV/m at 1 mm gap.

IV. QUANTUM EFFICIENCY OF METALS

A collection of quantum efficiency, or photoelectric yield curves for dirty surfaces, in the UHV sense, and for photon

energy above 10 eV, is summarized in Ref. 40. QE for clean and “dirty” copper for wavelength above 20 nm can be found in Ref. 41.

Two laser systems, from Time-Bandwidth,⁴² were used to measure the QE of the metals. The first laser system used to measure the QE of the material is described in Ref. 38. The main parameters of the Duetino® laser beam are $\sigma=6.5$ ps rms, $\lambda=266$ nm (4.66 eV), and energy 12 μJ /pulse at laser exit; the energy at the entrance of the accelerator beamline is 4 μJ ($\pm 5\%$ peak to peak). The main parameters of the second laser system, Jaguar®, are $\sigma=13$ ps (or 35 ps FWHM), $\lambda=262$ nm (4.73 eV), and energy 400 μJ /pulse at laser exit; the energy at the entrance of the accelerator beam line is 200 μJ ($\pm 0.5\%$ peak to peak) without any laser beam shaping pinhole. The short term laser pointing stability, for both lasers, at a virtual cathode position was measured to be around 10 μm rms. The size of the laser beam on the cathode is chosen such that its power density stays below 150 MW/cm², typically the beam size is in the order of millimeters when using the Jaguar® and was halved when using the Duetino®.

FIG. 8. (Color online) Normalized transverse emittance in function of the charge (circled size) and the electric gradient for Cu and SS electrodes (Ref. 39).

FIG. 9. (Color online) QE increase for a Cu cathode after 1 month of laser and high voltage operation.

As represented in Fig. 9, the quantum efficiency increases with the applied electric field due to the Schottky effect. Indeed analytical formulas⁴³ based on the three steps model (absorption, excitation, and emission of electrons)⁴⁴ reproduce quite well the measured data points. The only parameter in Eq. (2) 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 (Table V).

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

where E_F is the Fermi energy, $E_{\text{ph}} = \hbar\omega$ is the photon energy, λ_{opt} is the laser penetration depth, $\lambda_{\text{e-e}}$ is the electron-electron scattering length, and E_m is the energy above the Fermi level. Φ_{eff} is the effective work function, which is the work function Φ_0 of the bare material minus the barrier reduction due to the external field applied, see Eq. (3),

$$\Phi_{\text{eff}}(\text{eV}) = \Phi_0 - \sqrt{\frac{eE(V/m)}{4\pi\epsilon_0}}. \quad (3)$$

The plot of Eq. (2) in Fig. 9 shows a good match with the experimental values. The parameters used for copper⁴³ are $R_{\text{Cu}}(266 \text{ nm}) = 0.25$, $E_F = 7 \text{ eV}$, $E_{\text{ph}} = 4.6 \text{ eV}$, $\lambda_{\text{opt}} = 10.7 \text{ nm}$, and $\lambda_{\text{e-e}} = 2.2 \text{ nm}$.

TABLE V. Reflectivity of metal photocathode at 262 nm wavelength.

	Copper (%)	316L SS (%)	Molybdenum (%)	Niobium (%)
Pristine area	25.4	17	40.5	12
Damaged area	6.4	7.3	...	10.5

FIG. 10. (Color online) QE of copper, stainless steel and niobium.

The difference between the two Cu measurements can be interpreted as cleaning (contaminant removal) of the surface after 1 month of operation; no breakdown occurred during that period, and no laser cleaning was performed. The laser used with this electrode pair was solely the Duetino®. The maximum QE measured was on the order of 2×10^{-5} at 25 MV/m, which is in agreement with copper based rf photogun measurements.⁴⁵ Figure 10 shows the QE of various metals measured with this beamline.³⁸

Laser cleaning can also be efficient if the power density stays below the ablation threshold, in order to preserve emission uniformity at the surface. Some experimental results can be found in Refs. 45 and 46. As in the dc system, where ion cleaning (PGD) has improved the field holding, ion cleaning can also improve the QE,⁴³ the effect being mostly to reduce the work function, by the removal of the oxide of the surface, to equal the work function of the pure material, without drastically changing the surface morphology. 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. Breakdown conditioning will definitely clean the surface and is an efficient process for rf accelerator structure conditioning but is allegedly detrimental for an electrode, which should produce a uniform beam.

The following figures illustrate the effect of breakdown on the QE of Cu, Fig. 11, and SS, Fig. 12. The data were obtained using the Jaguar® laser.

The QEs displayed in the left figure of Fig. 11 were obtained using a prehigh gradient (83 MV/m) conditioned pair of Cu electrodes. On the right figure, pristine diamond turned Cu electrodes were installed. 200 pC could be extracted using 50 μJ of laser intensity. Our electron beam with charges of 10 pC and above is space charge dominated. The collection of all charges on the Faraday cup might not be linear with the laser intensity for gradients below 40 MV/m. Depending of the laser intensity falling on the cathode, the electron emission can be hampered by the field produced by the already emitted electron, even using picosecond long laser pulse. In Fig. 11 (right plot), the QE of a pristine Cu cathode, at 25 MV/m electric field, is twice less when using 205 μJ

FIG. 11. (Color online) QE of Cu OFE class 1 copper after prehigh gradient test (83 MV/m) (left figure) and a pristine pair of Cu electrode (right figure).

of laser energy than when using 17 μ J. We tested the QE of the same diamond turned Cu cathode versus the laser energy, Fig. 13, at 31 MV/m after the electrode pair had sustained few breakdowns. Again for laser intensity in excess of 40 μ J, the process of electron production became inefficient. For gradient in excess of 60 MV/m, linearity with the laser intensity up to 80 μ J is ensured. For a laser intensity up to 34 μ J, QE linearity is ensured from field above 35 MV/m, as can be seen in Fig. 12, right plot, as the QE is identical for two laser intensities 17 and 34 μ J. The QE of pristine SS electrode is slightly inferior, for a given gradient, to the QE of a pristine Cu; see Fig. 12, right figure compared to Fig. 11, right figure. As for Cu, breakdown generally increases the QE and spoils the emittance of the electron beam. However, as for Cu, a few breakdowns (<5) are usually necessary to significantly degrade the beam emittance.

Finally, the 262 nm UV light reflectivity of some electrodes were measured, in air, after breakdown test. The light was collected at an angle of 30 deg. The reflected light in the damaged area (craters) was still very specular except for Nb where strong stray light could be observed. One should then be careful in estimating the QE of a damaged photocathode with Eq. (2) as we did not collect the light over all angles (Table V).

V. CONCLUSION AND FUTURE DEVELOPMENT

In the quest to find a good material, capable of holding high gradient (>100 MV/m) and producing a 200 pC electron beam, we have tested electrodes of different materials and with different preparation procedures. We mainly compared polished and diamond turned (for nonferrous material)

FIG. 12. (Color online) QE of pristine SS electrodes from a commercially polished (left figure) and hand polished (right figure).

FIG. 13. (Color online) QE vs laser intensity, at 262 nm, of a diamond turned Cu for a constant gradient.

electrodes to nonpolished one with and without plasma glow discharge. Those results were also tested versus the results found in the literature. The main criteria being that the material should reach the target gradient and voltage without arcing. Any arcing being detrimental to the emittance of the beam to be produced or could transfer foreign material onto the electron source, effectively deteriorating this one. This is especially true for metals of low melting point such as aluminum.

The important results of the first section is that polishing (<40 nm average roughness) does not give much advantage in the attainment of high gradient compared to rough electrodes (<200 nm average roughness) which have been cleaned *in situ* by an Ar PGD. However, in the absence of PGD, polishing and good cleaning before mounting are mandatory. Nowadays industrial companies do produce electrodes of equivalent surface finish (geometrically and chemically) than in-house production, with suitable and reproducible results for our high gradient needs. The choice to either develop in-house polishing recipe or buy polished electrodes from external vendor depends solely on the turn-over time and price to obtain new electrodes and not on the quality of gradient achieved as they both gave similar end results. The PSI in-house recipe, which is human skill dependent, took 2 months to master and allowed us to refurbish an electrode pair in half day.

The overall high gradient results obtained can be directly of use for dc guns like the 500 kV dc gun used at Jefferson Laboratory, a gun design which is now widespread in the FEL/ERL community.⁴⁷ In this remark, we are of course not suggesting that a steel cathode holding 69 MV/m at 1 mm under dc voltage will hold the same gradient at 10 mm. We are instead suggesting material and possible preparation methods to be used for those guns. One has still to remember that using the “same” preparation techniques does not, unfor-

tunately, necessarily imply the same end results. However, this guarantees still good performances, on routine operation.

In the second part of this work, higher gradients have been obtained using a voltage pulse of 250 ns (FWHM). We have reached the highest gradient with a Ti alloy and SS. Sustained operation with hand polished SS electrodes at 80 MV/m with 55 pC of electron beam extracted was proven for 9 h. It is not understood why the electrode eventually arced, as it is often the case in this field. Operation, using electron beam with various charges, at ~ 300 kV, ~ 50 MV/m for days without breakdown and no measurable dark current is now routinely achieved, with either SS or Cu, polished, electrodes. In most cases, those electrodes did not arc during the voltage increase. Dark currents do exist, as shown by the XR scintillator activity, but the beam is not captured and transported along the beam line.

Cu and SS were found to have QE in the 10^{-6} range when pristine and for field below 80 MV/m. Breakdown usually rises the QE a decade higher, sometime 2 decades, but degrades the quality of the electron beam. The QE stays constant using different laser energies; hence the emitted current scales linearly with the laser energy. This will be true as long as the electric field applied balances the space charge of the extracted beam.

UV (262 or 266 nm) reflectivity of the electrodes drops on damaged areas compared to pristine ones. Rough areas trap more light, which makes the surface look black under visible light, hence increasing the QE. Finally, laser ablation threshold from metals depends strongly on the pulse length. For an UV laser pulse of ~ 30 ns, the fluence threshold is $\sim \text{J}/\text{cm}^2$.^{48,49} For picosecond laser pulse, the threshold starts around a few $100 \text{ mJ}/\text{cm}^2$.^{50,51} Our first attempts to focus the Jaguar® laser beam on a polished Mo cathode, in vacuum and in the presence of high voltage, using a beam radius of $300 \mu\text{m}$ and $75 \mu\text{J}$ of incoming UV light, resulted in a hole $100 \mu\text{m}$ deep in the metal. The gradient did not exceed 18 MV/m (100 kV). It seems that to keep the electrode safe from ablation and keep the system arcing free the fluence, as a rule of thumb, should be below $20 \text{ mJ}/\text{cm}^2$ for picosecond pulses and in the presence of voltage in excess of a few hundred kilovolts.

This beam line was modified by adding a rf structure to match the first phase of the PSI-XFEL concept.^{2,29} Furthermore, HG, QE, and emittance measurement on various material are ongoing.^{52,53}

NOMENCLATURE

ArPGD	= Argon plasma glow discharge
BCP	= Buffered chemical polishing
BF	= Breakdown field
BNC	= Bayonet Neill-Concelman connector
CERN	= Conseil Européen pour la Recherche Nucléaire
FE	= Field emission
FEA	= Field emitter array
FWHM	= Full width at half maximum
HG	= High gradient
HT	= High temperature

HV	= High voltage
K2000	= Keithley ^{TM} 2000 multimeter
K6514	= Keithley ^{TM} 6514 electrometer
PGD	= Plasma glow discharge
PMT	= Photomultiplier
PSI	= Paul Scherrer Institut
QE	= Quantum efficiency
SS	= Stainless steel
UHV	= Ultra-high vacuum
UV	= Ultra violet
XFEL	= X-ray free electron laser
XR	= X-ray

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