HIGH GRADIENT ELECTRODES FOR A DIODE-RF ELECTRON GUN

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Abstract

Tests of electrodes in a diode-RF electron gun for the SwissFEL project are described. An optimum procedure for producing high breakdown strength electrodes was found. High grade stainless steel elliptical electrodes are hand-polished then coated with 2 µm Diamond Like Carbon (DLC) to produce non-emitting surfaces. Photo-emitting surfaces are installed within the DLC coated cathode electrode. With this procedure, operation at gradient >100MV/m and voltage >400kV with immeasurable electron emission is certain, and gradient >300MV/m is possible. The Quantum Efficiency (QE) for several metals in a high gradient were measured; QE values around $4x10^{-5}$ were achieved for Al-Li alloy and Mg. The search for a high gradient resistant photocathode material with high QE is continuing.

INTRODUCTION

The SwissFEL Free Electron Laser project is to build and operate a user facility for experiments using intense, femtosecond, hard X-ray pulses. A determined search is underway to find a practical, low emittance, 200pC electron source for the SwissFEL. The LEG (Low Emittance Gun) test stand was built and commissioned [1][2] to explore one option for this machine. Fig.1 shows the gun with a pulsed diode electron gun followed by a 2-cell RF cavity at 1.5 GHz. The diode has an adjustable gap. The cathode voltage is driven from an HV pulse generator which gives peak voltages adjustable from -30kV to -500 kV. Downstream diagnostics measure electron beam emittance, profile, energy, energy spread and charge. Most measurements are performed using photo-emission with a UV laser[3], although development is also continuing with field emission from Field Emitting Arrays (FEA)[4].

HIGH GRADIENT TESTS

The HV pulse generator consists of three thyratrons in parallel driving an air-core transformer (Tesla coil). This provides a damped asymmetric oscillatory pulse to the cathode. The voltage amplitude is stable to <0.5% rms (determined by the charging power supply), is freely adjustable from 30kV to 500kV, and the jitter is <1ns rms. On one hand, the alternating polarity and low damping of the waveform in Fig.2 seem rather haphazard.

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On the other hand, the Fowler-Nordheim characteristic gives a sharp onset of parasitic emission, so when the second negative peak is ~10% percent lower than the first, breakdown is determined by the first peak only. Because anode and cathode have similar geometry, positive peaks much less than the negative peaks in amplitude also do not give breakdown. There is an unproven suspicion that dielectric charging of the DLC plays a role in breakdown, and so in fact a bipolar waveform may be preferred.

Initially, electrode conditioning was attempted with bare metal electrodes. Breakdown strength with vacuum pressure of $<10^{-7}$mbar was measured, and then gases such as nitrogen and argon were introduced by a leak valve, up to 10^{-5}mbar. There was no change of parasitic emission or breakdown strength with gas pressure. In the following development, little concern was given to gas pressure.

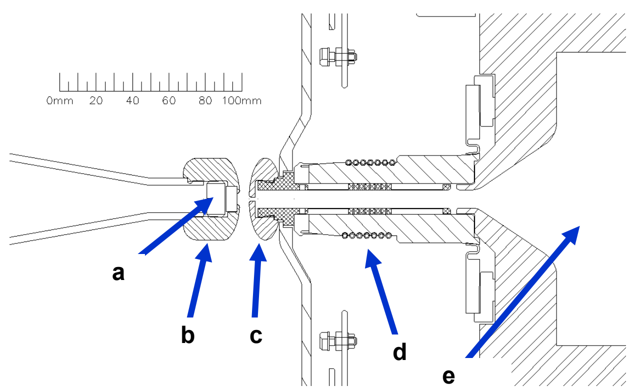

Figure 1: Geometry of diode: (a) metal insert; (b) hollow cathode with DLC; (c) anode with DLC; (d) pulsed solenoid; (e) RF cavity.

There is no conditioning or ramp-up needed for the DLC coated electrodes to reach high gradient. In any case, conditioning is excluded because one arc has sufficient energy to destroy the DLC coating.

The breakdown strength of the electrodes was measured using a three phase test procedure: firstly, anode-cathode gap is set to 1mm and the voltage is ramped up to 50kV (gradient 50MV/m); then the gradient is kept constant (50MV/m) but the gap is increased up to 7mm (350kV). The first two phases are normally completed without any activity on the X-ray scintillator, indicating that the electrodes are defect-free and not prone to shedding particles. In the last phase, the voltage is kept constant (350kV) and the gap is closed down gradually until a breakdown occurs.

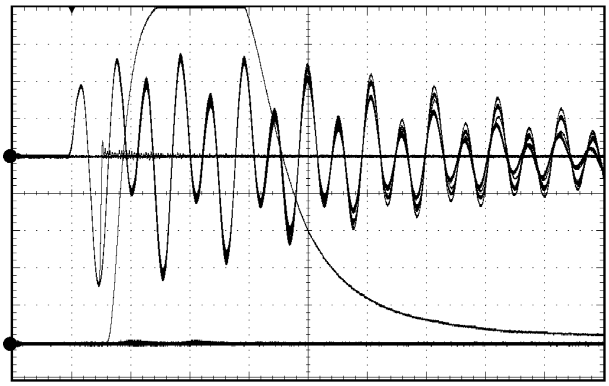

Figure 2: Typical breakdown waveforms. (upper trace: cathode voltage, lower trace: X-ray scintillator signal, 500ns/div).

Fig.2 shows the result of one breakdown test. The cathode voltage trace shows a single arc occurring on the highest negative peak; the voltage is clamped to zero indicating low arc resistance. A directional X-ray scintillator is used to monitor the Bremsstrahlung from the dark current in the accelerating diode. The scintillator trace is flat until the arc event, a sign that parasitic electron emission is minimal; the arc event puts the scintillator into saturation. There is no exact measurement of parasitic current, but shot-to shot, the scintillator signal is often flat, indicating single photon signals; with some gross order-of-magnitude estimates, the parasitic charge emitted into 2π str. should be less than 10pC.

DLC ELECTRODES

This section summarises work being presented in [5]. The Plasma Assisted Chemical Vapor Deposition (PACVD) process permits deposition of hydrogenated amorphous DLC (a-C:H) with custom properties (coating thickness, hardness and conductivity) on virtually any type of metal surface. The influence of five coating parameters on the breakdown strength were explored: DLC layer thickness, DLC layer type (electrical resistivity), base metal, base metal surface roughness and process parameters from suppliers.

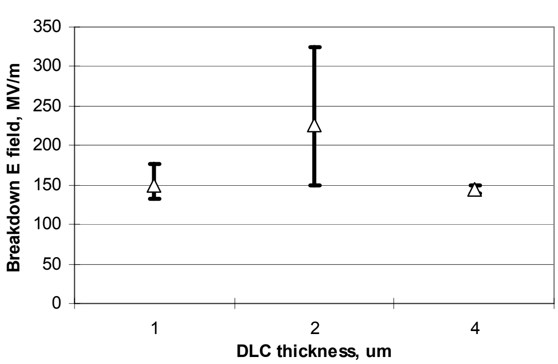

Figure 3: Comparison of breakdown strength with DLC layer thickness.

As example, Fig. 3 summarizes the results for three coating thicknesses from one supplier (coating type: a-C:H, Bekaert). The error bars represent the full span of measured results. For 1μm, the number of breakdown tests was three, that is, three pairs of electrodes. For 2μm, 18 tests and for 4μm, 4 tests were made. The large spread for 2μm is dominated by the bronze samples; stainless steel as a base metal gave more reproducible results. The 2μm thick coating may give the highest breakdown strength simply because the industrial coating process has been optimized for this thickness.

QUANTUM EFFICIENCY TESTS

The success of the DLC coated electrodes made it possible to develop the hollow cathode geometry for holding different photo-emitting materials and FEAs. At higher charge, the measured emittance values in the LEG are determined by the laser transverse profile, and the largest improvements in emittance are possible by sacrificing laser energy density in return for improved transverse laser profile.

The search continues to find a robust photo-emitting surface with higher QE [6]-[8]. The QE measurements were dependent upon the last few strokes of surface polishing. In general, machined surfaces without extensive polishing to remove tens of micrometers are not able to operate in high gradient (>50MV/m). Some metals were not possible to polish finely (Ra <30nm) and some alloy samples had the tendency to "fall to pieces" at lower gradient.

Table 1. Measured quantum efficiency.

	QE (10^{-6})
SS	0.3
Ti	0.7
Cu	1.5
Mo	3.0
TiVAl	3.3
Nb	4.2
Bronze	12
Bronze	13
Bronze	17
Y	19
Al	33
Al	33
Mg	39
Mg	40
Al	40
Al-Li2.5-Cu1.5-Mg1	44
Al-Li2.5-Cu1.5-Mg1	60

For the test procedure, the illumination was from a tripled Ti:Sa laser at 266nm with 4ps rms Gaussian longitudinal profile and the laser spot size on the sample insert was ~1mm FWHM. For each installation of a sample there was the final polish with minimal pressure during a few seconds, followed by alcohol and dry ice cleaning. After installation, the vacuum pump-down was started within 20 minutes. In this way, all the sample surfaces were exposed for approximately the same time to the atmosphere.

In Table 1, the highest QE is for an aluminium alloy containing lithium. The presence of oxygen on the surface plays a role to increase QE with this alloy [7].

The pure aluminium samples emitted more strongly if the surface was not illuminated. Typically, absence of the laser illumination for 2 minutes gave an increase in emitted charge by ~50% on re-application of the laser; the charge then sunk back to the original value over about 2 minutes. This behaviour is interesting but also annoying during operation; any movement of the laser to a new emitting area also gave a transient charge increase.

The QE test procedure included charge measurements with incrementing and decrementing voltage and gap by +/-10% from the nominal center values of 350kVand 6.0mm (i.e. nominal 58.3MV/m on the DLC electrodes, and 30MV/m on the recessed insert due to the hollow geometry). These derivative measurements are vulnerable to errors, and this appears as the spread in data points. The results shown in Fig. 4-5 are for a magnesium insert with the laser energy adjusted to change the emitted charge.

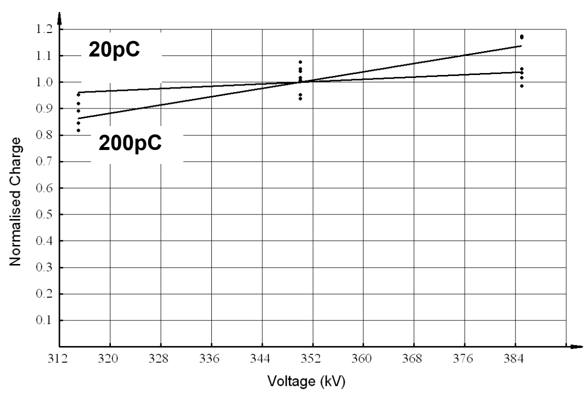

Figure 4: Sensitivity of charge to voltage about the nominal operating point of 350kV and 6mm.

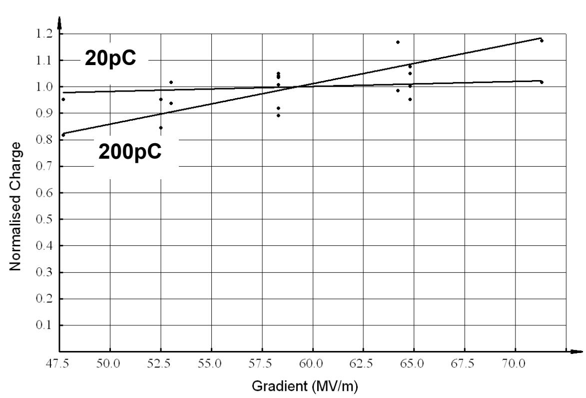

Figure 5: Sensitivity of charge to gradient about the nominal operating point of 350kV and 6mm.

Results for voltage and gradient are shown; the third parameter, the gap, gave little effect on the charge. It is concluded that there is some beam loss at high charge, and little evidence of field enhanced emission. The X-ray scintillator gives little indication of loss at the anode so it may be that an expanding beam is scraped further downstream.

Long-term stability tests have not been made, but routine operation at 350kVover several days with a magnesium insert was possible without measurable drift of emission.

CONCLUSIONS

For non-emitting surfaces of the anode and cathode electrodes, the production of stainless steel electrodes with 2µm DLC coatings has matured. Gradients over 100MV/m at 400kV without breakdown and with very low level of dark current are achieved reproducibly. Many electrodes reach 150MV/m and a couple have reached 300MV/m without breakdown. For photo-emission tests, inserts of different metals were installed within a DLC coated cathode. As photo-emitters, aluminium-lithium alloy and magnesium gave the highest QE, around $4x10^{-5}$. The search to find a suitable photo-cathode insert (high QE, low emittance and capable of withstanding a gradient of >50MV/m) is continuing.

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