

FIELD EMISSION MEASUREMENTS FROM NIOBIUM ELECTRODES*

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Abstract

Increasing the operating voltage of a DC high voltage photogun serves to minimize space charge induced emittance growth and thereby preserve electron beam brightness, however, field emission from the photogun cathode electrode can pose significant problems: constant low level field emission degrades vacuum via electron stimulated desorption which in turn reduces photocathode yield through chemical poisoning and/or ion bombardment and high levels of field emission can damage the ceramic insulator. Niobium electrodes (single crystal, large grain and fine grain) were characterized using a DC high voltage field emission test stand at maximum voltage -225kV and electric field gradient > 10MV/m. Niobium electrodes appear to be superior to diamond-paste polished stainless steel electrodes.

INTRODUCTION

Reliable DC high voltage photoguns with GaAs photocathodes require electrodes free of field emission. This becomes a challenging requirement as the gun voltage and gradient are pushed higher to achieve a brighter extracted beam. Today, there are DC high voltage photoguns operating at numerous locations at voltages between 300 and 500kV, with maximum field gradient ~ 12 MV/m [1] but every photogun program - including those operating at significantly lower voltage and field gradient - occasionally suffers setbacks due to field emission, ranging from disappointingly poor photocathode operating lifetime to catastrophic failure of the ceramic insulator. Most photoguns use stainless steel electrodes polished to a mirror-like finish with diamond grit. The polishing process is laborious and can take weeks to complete. One of the perceived problems with diamond-paste polishing (DPP) is variability in polishing technique, and concern that sharp points can be “rolled over” embedding contamination.

Niobium is used to make superconducting RF cavities and there are many reports of field emission-free operation at field gradients exceeding 20MV/m and considerably higher [2]. Although these results were obtained at ~ 2K and with RF electric fields, it seemed reasonable to evaluate niobium in a DC high voltage configuration and at room temperature. An appealing feature of niobium is that it can be chemically polished, which greatly reduces the preparation time. This work compares field emission behavior of DPP 304 stainless steel and niobium in three different forms: single crystal, large grain and fine grain. Standardized steps were

followed to prepare each electrode, with intention of adopting as many SRF techniques as possible [3]. Also note that these measurements were conducted with an apparatus that closely resembles an actual DC high voltage photogun, in particular, measurements were made with shaped electrodes with a hole in the center to accommodate a photocathode, realistic cathode/anode gaps and maximum voltage - 225kV.

EXPERIMENT

The apparatus is shown in Figure 1. The test electrode attaches to an “inverted” insulator that extends into the vacuum chamber. Each test electrode had a geometry identical to electrodes used at CEBAF for many years [4] with a hole in the middle to accommodate a GaAs photocathode if it were used in an actual polarized photogun. For these tests however, a piece of polished stainless steel was used in place of the GaAs photocathode. The anode was a large flat plate electrically isolated from ground and attached to a sensitive current meter (Keithley electrometer model 617). The anode could be moved up/down to vary the cathode/anode gap and therefore the field gradient. Two different anodes were used for these tests: a 304 stainless steel anode for evaluation of the DPP 304 stainless steel cathode electrode and a fine-grain niobium anode for evaluation of all the niobium cathode electrodes. The stainless steel anode was polished with 600 grit silicon carbide paper and 6um diamond paste. The fine-grain niobium anode was chemically polished.

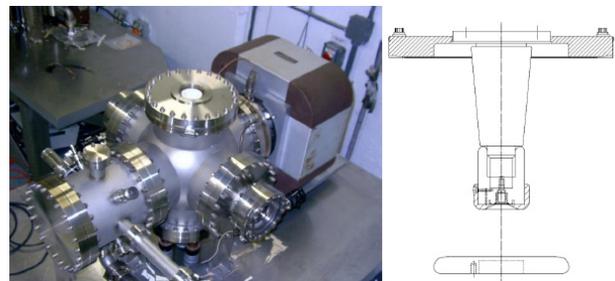


Figure 1: (left) High voltage field emission test stand used for evaluating each cathode electrode, (right) a schematic of the insulator, cathode test electrode and anode used to collect the field emission.

A -225kV high voltage power supply was used for the experiment. The HV power supply and the ceramic insulator accommodate “industry standard” high voltage cables with R-28 connectors. A 100MΩ conditioning resistor was placed in series with the cathode electrode and served to protect the apparatus in case of sudden discharge of stored energy.

Sources and Medium Energy Accelerators

Tech 02: Lepton Sources

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Each test electrode underwent similar preparation steps before installation, described below. Prior to the application of high voltage, the entire vacuum apparatus was baked at 200°C for approximately 30 hours to achieve vacuum level in the -11 Torr range. Vacuum pumping was provided by a 220L/s ion pump and a SAES Getters GP-500 non-evaporable getter pump which was partially activated during the bakeout. Future tests will be performed to determine if vacuum level plays a role in field emission characterization.

An assessment of the field emission properties of each test electrode involved monitoring vacuum level inside the apparatus, x-ray radiation near the apparatus, and anode current while increasing the voltage applied to the cathode electrode. High voltage was first applied to the electrode using the largest cathode/anode gap of 50 mm. Upon successful high voltage processing (defined below), the gap could be decreased to achieve higher field gradient. The smallest gap was 20mm and provided maximum field gradient of ~ 20MV/m when the cathode was biased at -225kV.

The electrodes were high voltage “processed”, which means the applied voltage was increased gradually while maintaining anode current less than a few nanoAmperes. During processing, field emission sites would “burn off” and field emission current would become more stable. An electrode was considered fully processed when field emission current was stable to within a few percent of the average value. It was not uncommon for this to take hours.

High voltage processing was not always successful: sometimes a field emission site (or sites) would be produced that would not “burn off”. This typically happened at the smallest gaps and highest gradients. Elimination of stubborn field emitters often required that the electrode be removed and re-polished.

Diamond Paste Polishing of Stainless Steel

The field emission characteristics of niobium electrodes were benchmarked against those of a “conventional” DPP stainless steel electrode that had been used successfully for many years inside one of the CEBAF 100kV spin polarized photoelectron guns [4]. The DPP stainless steel electrode was manufactured from vacuum arc-remelt 304 stainless steel. After being cut to shape with hydrocarbon-free lubricants, the electrode was polished on a potter’s wheel with silicon carbide paper of increasingly finer grit (300 and then 600 particles/in²) followed by polishing with diamond grit (6µm, 3µm). This produced an electrode with a mirror-like finish. Between each polishing step, the electrode was cleaned in an ultrasonic bath using an alkali solution.

Buffered Chemical Polishing of Niobium

Three different types of niobium electrodes were evaluated: single crystal, large grain (grain size > few cm) and fine grain (also referred to as poly-crystalline, grain size ~ 0.13mm). The single-crystal and large-grain

niobium test electrodes were manufactured from high quality material suitable for SRF cavity fabrication with residual resistance ratio (RRR) values > 250. The fine-grain niobium electrode was manufactured from “reactor grade” material with RRR value ~ 40. The machine shop provided a 32 finish. The electrodes were then chemically etched in a mixture of hydrofluoric (49%), nitric (69%) and phosphoric (85%) acid with mixing ratio 1:1:1 at room temperature. This technique is referred to as buffered-chemical polishing. Typically, the desired surface finish was obtained after ~ 20 minutes immersion in the acid bath, corresponding to removal of 100µm of surface material (surface roughness < 0.5µm for single-crystal and ~ 5µm for fine-grain niobium). Besides taking advantage of the SRF technique of buffered-chemical polishing, other SRF techniques were adopted including high pressure rinsing and vacuum degassing. The steps for preparing a polished niobium electrode were as follows:

- Receive the electrode from the machine shop with surface finish 32
- Silicon carbide polishing with 600 grit paper, if necessary, to remove obvious visible scratches
- Solvent cleaning in ultrasonic bath of alkali solution
- Buffered-chemical polishing to remove ~ 100µm material
- High pressure rinsing (1200 psi) for 20 minutes with ultrapure de-ionized water with resistivity > 18MΩcm.
- High temperature (900°C) vacuum degas for one hour

RESULTS AND DISCUSSION

The field emission characteristics of each test electrode are shown in Figure 2, as a function of bias voltage and cathode/anode gap. All of the niobium electrodes could be biased to higher voltage before the onset of field emission, compared to the DPP 304 stainless steel electrode. Interestingly, the performance of the fine grain niobium electrode was similar to the large grain and single crystal niobium electrodes even though the surface was considerably rougher. To the eye, the fine grain niobium electrode had a mottled “orange peel” finish. Table 1 shows the field gradient at the cathode electrode at which 10pA of field emission was measured on the anode. The variation in gradients associated with each gap is contrary to Fowler-Nordheim predictions and likely suggests the electrodes were not fully “processed”.

Table 1: Gradient (MV/m) with 10pA field emission

Electrode	20mm	30mm	40mm	50mm
DPP304SS	-	5.2	5.4	5.6
FGNb	9.6	8.2	8.1	7.4
LGNb	8.1	6.4	6.5	6.0
SCNb	8.1	7.0	8.1	7.9

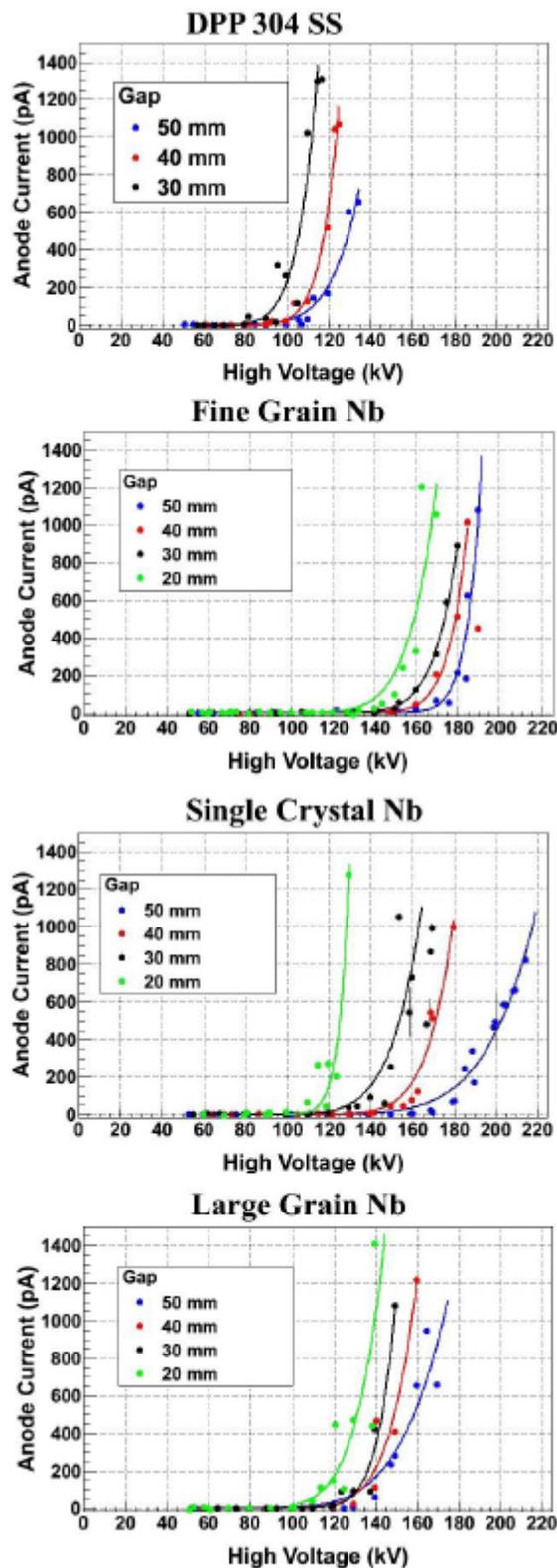


Figure 2: Field emission current vs. cathode voltage for different cathode/anode gaps. The plot title indicates the cathode electrode material.

CONCLUSION

The field emission characteristics of four cathode electrodes similar to those used inside DC high voltage GaAs photoguns were evaluated using a field emission test stand at voltage to -225kV and with cathode/anode gaps between 20 and 50mm. All of the buffered-chemically polished niobium electrodes exhibited smaller levels of field emission than the DPP 304 stainless steel electrode. In terms of field gradient, DPP 304 stainless steel exhibited field emission at $\sim 5.5\text{ MV/m}$ whereas the onset of field emission from niobium electrodes was between 7 and 10 MV/m. Another set of electrodes will be evaluated in the future to improve statistics.

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