A PLASMONIC NIOBIUM PHOTOCATHODE FOR SRF GUN APPLICATIONS

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Abstract

The typical quantum efficiency (QE) of niobium is of the order 1e^{-4}, whilst also requiring UV lasers for emission. This paper presents the results of a plasmonic niobium surface that operates with IR laser via multiphoton emission.

INTRODUCTION

The motivation for the research between RadiaBeam and Jefferson Lab (JLab) stems from the promise of SRF photoinjectors that can provide CW, high-average current electron bunches [1]. Over the past decade the research has branched in two directions. One option is to accommodate a 'warm' photocathode within the superconducting cavity, however this route has presented difficulties with trying to support the cathode away from the superconducting cavity to prevent quenching. A common problem with this is multipactor in the cathode support mechanism. The motivation to overcome these difficulties leads to the second option, where high quantum efficiency superconducting photocathodes can be used. Using a superconducting material, such as Nb or Pb, is beneficial because metals make robust, long lifetime photocathodes. There is no need to support the photocathode as it can be superconducting itself and sit snugly in the cavity back wall. The downside is that metals typically have low QE of the order 1e^{-4} [2]. Improving the effective QE, by surface plasmon resonance (SPR) enhancement and increased laser absorption with nano-patterning the cathode, will overcome this deficiency somewhat and present new operating regimes and opportunities for future photoinjectors.

Recent advances in nano-plasmonics and photocathode research are the basis for a custom developed, nano-patterned cathode (NPC) surface that demonstrated enhanced photoemission of MeV electrons in an RF accelerator. It was shown, in the UCLA experiment, that the charge yield from the NPC was 100x greater than that of flat copper with an ultrashort IR drive laser [3]. The cathode with periodic, nano-scaled surface patterns is designed to make use of the SPR and enhance the multiphoton emission using infrared (IR) photons. Multiphoton emission [4] is the dominant mechanism of emission for laser light whose photon energy is lower than the metal work function and is advantageous for high-intensity laser pulses. The local field enhancement factor is more dramatic for higher n, where n is the minimum number of photons required to exceed the work function [5].

The research program focuses on the following areas:

- Modify and recommission an existing SRF gun for use with a niobium plug photocathode
- Design and build a beamline with the capability of measuring photoemission from the gun in a vertical RF test dewar
- Develop polishing techniques that would provide a flat and smooth surface suitable for nano-patterning with FIB and develop FIB technique for uniform nano-patterning to specification
- Demonstrate multiphoton emission from niobium

RESEARCH PROGRAM

SRF Gun Performance

The photoinjector is an existing 1.6 cell, 1.3GHz niobium cavity. The cavity has been previously measured at JLab with a Pb film photocathode, and its twin has been extensively beam-tested at HZB producing around 35MV/m peak electric field on the cathode in both cases [6]. The cavity was refurbished with light chemical polishing, a new RF set-up, and was tested at 2K with a hand-polished, flat Nb cathode to establish an RF baseline. The maximum gradient on the cathode was calculated to be ~35MV/m, limited by field emission, as shown in Figure 1. For this basic demonstration, the gun was tested without all the ancillary components required for electron beam production and in an inverted orientation.

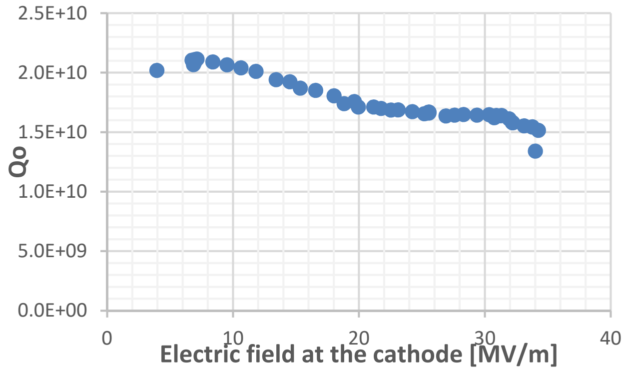

Figure 1: Quality factor as a function of electric field on the cathode.

Cathode Design and Manufacture

The photocathode is situated centrally in the base of the gun, as shown in Figure 2. The plug is sealed to the gun with a ring of indium wire, and the flange bolted directly into the back of the gun to provide a good seal. The original design combined the flange and plug in one piece. This was bulky, difficult to seat and would require large pieces of niobium for several cathodes to be manufactured. The final design was a small removable puck that would sit on a niobium-titanium flange as shown in Figure 2 (bottom, far right). Holes drilled around the puck support in the flange aid with liquid helium flow for cooling in that area. This is to avoid quench from potential laser heating.

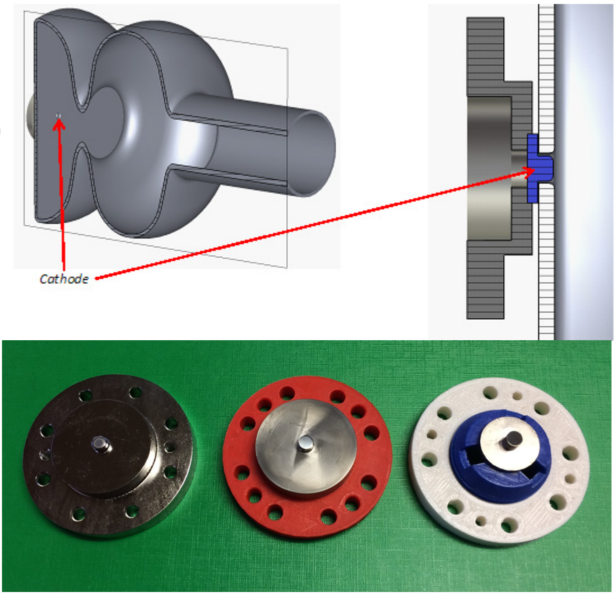

Figure 2: Top: Schematic of the SRF gun with cathode plug. Bottom: Evolution of photocathode design from solid niobium flange (left) to niobium puck held by a NbTi flange (right). NbTi flange reproduced with 3D printed plastic.

Photoemission Beamline Design

In a typical cold cavity RF test, the cavity is suspended from the dewar lid, which also has ports available for RF feedthroughs and vacuum. The dewar is sealed at the lid, evacuated and filled with liquid helium at 2K to a level that covers the cavity inside. Field emission isn't typically measured directly but inferred from x-ray radiation monitors situated around the dewar.

For testing of the SRF gun, it was important to quantify any current from the cavity, either from field emission or photoemission at the cathode. To achieve this a more complex set up was required. The cavity itself needed to be electrically isolated so that current would not drain to ground, whilst still being supported on the test stand. The gun was held with an insulating material, a ceramic break isolated the gun beam pipe from the vertical beam pipe, and 'DC breaks' were used on the RF input and output coupler ports.

The vertical beam pipe served multiple purposes. It was used to provide active vacuum pumping on the cavity during testing. This can be useful if there are small helium leaks and a test can still be performed. Secondly, it was designed to have line of sight to the photocathode in the gun from a laser window port situated above on the warm side of the dewar lid. The third purpose was that the beam pipe would be used as a Faraday cup, collecting charge. To act as a charge collector any electron beam from the gun needed to be steered into the beam pipe with a magnet. For safety, a permanent magnet was preferred over an electro magnet, as any current reaching the laser window had the potential to cause a catastrophic vacuum leak. It was important also to keep the magnet far enough away from the SRF gun, so that stay fields would not be trapped causing quench at low electric field. The final set up of the beamline is shown in Figure 3.

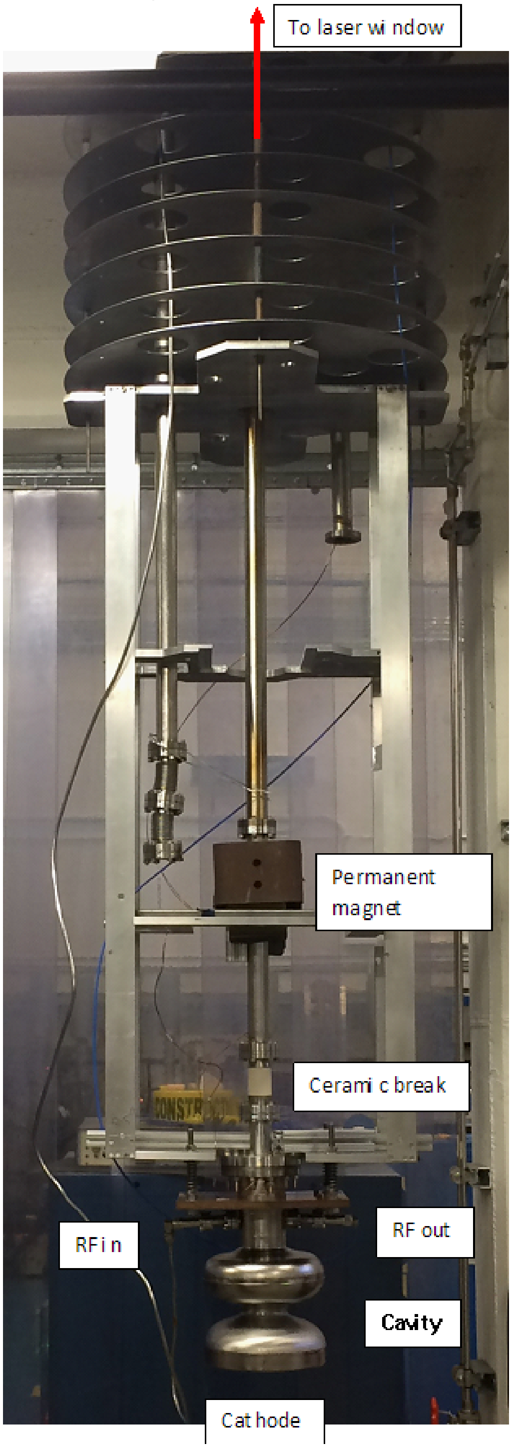

Figure 3: Experimental set up on the test stand.

Without care for cleaning and preparing the cavity, a quick cold test was performed of this set-up to confirm that all components were isolated. Wires were connected to the gun body and the beam pipe to separate pico-ammeters. As expected the cavity developed a field emitter at low gradient, and current measured tracked with radiation observed. Within measurement error it was confirmed that current leaving the gun was collected on the beam pipe.

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RESULTS

Photocathode Surface Preparation

Initially a selection of 1” niobium coupons were polished in-house at Jefferson Lab; some were fine grain, others single crystal. Initial tests made by RadiaBeam for nano-patterning with the FIB showed that the single crystal structure resulted in a much more uniform drilling pattern. For this reason the single crystal pucks were used.

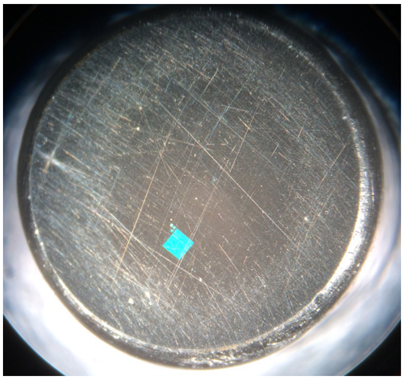

Figure 4: Microscope image of cathode tip. Blue area shows the nano-patterned area.

The first successfully drilled cathode is shown in Figure 4. The nano-patterned area looks holographic to the naked eye as the red wavelengths are absorbed. It can also be seen that the surface is not highly polished and media is still embedded. The theoretical reflectance simulated for the nano-hole pattern is calculated as 1% at a laser wavelength of 1030nm. The reflectance of this cathode measured in the lab at 1036nm was found to be: bare surface: 68.7%, Patterned area: 57%. The discrepancy is considered due to the non-uniformity of the hole pattern. It was clear from these results that to increase the absorption of photons at the desired wavelength that the cathode surface should be improved upon. With refinement to the polishing process a surface roughness, Ra <2nm was achieved, see Figure 5. Two cathodes with a surface finish of Ra~3.8nm had improved reflectance of 50% and 30%.

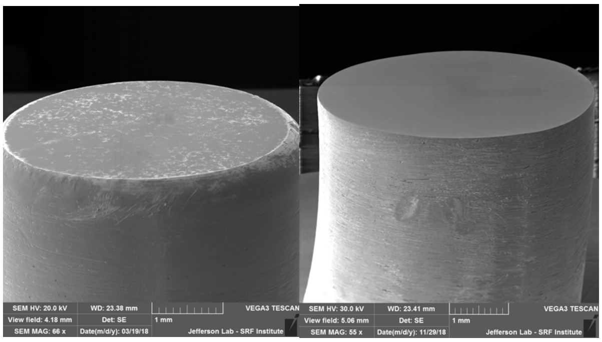

Figure 5: SEM images of cathode tips. Left Ra~2.5nm, polishing media can be seen embedded. Right: Clean, Ra =1.65nm surface.

Room Temperature Cathode Performance

To baseline the performance of the nano-pattern in a lab setting a cathode test chamber was assembled. The first nano-patterned cathode (of Figure 4) was inserted into the cathode test chamber and hydrogen cleaned. The typical work function of niobium is ~4.2eV (296nm). The nano-pattern was tailored to absorb at 1030nm for surface plasmon enhanced emission. To photo-emit at this wavelength would therefore require a 4-photon emission process to overcome this barrier. The order (number of photons) of the emission can be experimentally measured by plotting the charge density as a function of laser intensity, shown in Figure 6. The slope is calculated as 4.65 +/-1.21, which suggests that 4 photon emission is taking place. This corresponds to an ‘effective quantum efficiency’ of 1.4e-5. It should also be noted that with a laser intensity of ~23GW/cm^2 the damage threshold on the surface was reached. This resulted in the surface being ablated.

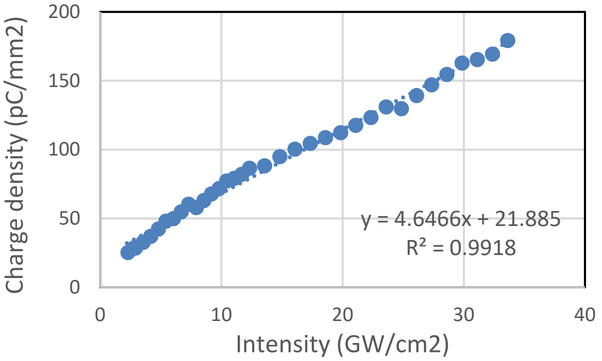

Figure 6: Charge density as a function of laser intensity.

FUTURE WORK

The results of this research are very encouraging. A great deal of progress has been made in refining the techniques and art required to both manufacture and measure emission from nano-patterned niobium cathodes. It is clear from the achievements that there is huge potential in this technology to both simplify SRF gun design and the laser requirements for photoemission. Next steps will include further warm tests of NPCs and ultimately a 2K test in the SRF gun beamline.

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