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DESIGN OF A 200 kV DC CRYOCOOLED PHOTOEMISSION GUN FOR PHOTOCATHODE INVESTIGATIONS

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Abstract

Intrinsic emittance of photocathodes limits the brightness of electrons beams produced from photoemission guns. Recent advancements have shown that an order of magnitude improvement in intrinsic emittance over the commonly used polycrystalline metal and semiconductor cathodes is possible via use of single crystalline ordered surfaces of metals, semiconductors and other exotic materials at cryogenic temperatures as cathodes. However, due to practical design considerations, it is not trivial to test such cathodes in existing electron guns. Here we present the design of a 200kV DC electron gun being developed at the Arizona State University for this purpose. The design is based off the Cornell DC cryogun but can use the omicron paddle-shaped sample holder and is connected in UHV to a suite of surface preparation and characterization chambers designed to test single crystalline ordered surfaces as cathodes. The omicron paddle-shaped holder allows for easy cathode characterization in standard surface science instruments and allows for a large flexibility in terms of the cathode shape and size enabling the study of numerous commercially available and epitaxially grown single crystal materials. Here we present the mechanical, electrostatic and the thermal design of this gun.

INTRODUCTION

Linear accelerator applications like X-ray Free Electron Lasers and Ultrafast Electron Diffraction setups are critically dependent on the intrinsic emittance of the photocathode [1]. Existing photoemission electron guns used for such applications have so far employed polycrystalline cathodes with disordered surfaces and generally operate with the cathode at near room temperatures. Recent studies suggest that an order of magnitude improvement in the intrinsic emittance of cathodes is possible by using single crystalline cathodes with atomically ordered surfaces that have the appropriate electronic band-structure and are cooled to LHe temperatures in ultra-high-vacuum (UHV) [2]. However, existing electron guns do not allow for use of such cathodes without significant modifications to the cathode transfer mechanism. Moreover, existing electron guns are often designed to use a specific size and shape of the cathode restricting the exploration of a wide range of potential single crystal materials that are more easily available in different sizes and shapes as cathodes. To overcome this issue, we are developing a 200 kV DC photoemission gun with a cryocooled cathode (cryogun) at Arizona State University for photocathode research. The design of this gun is based off the design of the 200 kV DC cryogun already in operation at Cornell University [3]. However, the ASU cryogun has a better thermal cooling design allowing for temperatures lower than 20 K at the cathode and has been designed to use a variable size cathode wafer mounted on to an omicron flag style sample holder compatible with several surface science instruments. The cathode transfer system is designed to allow easy UHV transport of the cathode from the gun into a wide range of surface science instruments, photoemission diagnostics and single crystal growth capabilities available at the ASU Photoemission and Bright Beams laboratory [4]. This gun will allow easy investigation of a wide range of both single and polycrystalline cathode materials as ultra-low emittance electron sources. Here we present the mechanical, thermal cooling and the electrostatic design of the ASU cryogun.

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MECHANICAL DESIGN

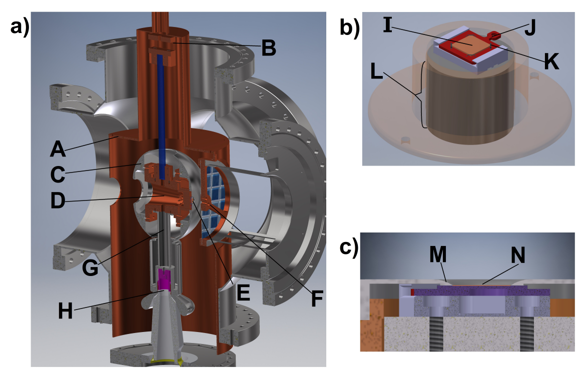

Figure 1: (a) Cross-section of the overall mechanical design of the gun. The cryoshield (A) connects to the cryostat at the copper strap (B). The spherical electrode (C) encloses the copper core (D). The photocathode (E) is inserted into the core and faces the anode (F). The thin wall tube (G) connects the core to the DC plug. A stainless steel collar shields the ceramic covering the HVPS plug from high fields at the triple point junction (H). The design is based on the Cornell DC cryogun [3]. (b) The photocathode (I) strapped onto the omicron paddle (J) using tantalum foil (K) and inserted into the cathode plug (L). (c) A closer view of the electrode and photocathode cross-section, more clearly showing the pierce electrode (M) with the photocathode (N) inserted.

The mechanical design of the ASU cryogun is based off the Cornell DC cryogun with a few modifications to allow for better radiation shielding, a flexible cathode size and a continuous flow cryostat based cooling system.

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The copper core which holds the cathode plug is connected to a continuous flow cryostat (Janis Research Model ST-400 UHV Supertran System) via a sapphire rod. The sapphire rod provides electrical isolation along with a good thermal conductivity between the copper core and the cryostat. The other end of the core is connected to the 200 kV UHV ceramic feed-through via a thin-walled stainless steel tube to minimize heat loss via thermal conduction. Note that stainless steel is a thermal insulator at LHe temperatures. The high electric fields at the high-voltage ceramic-metal-UHV junction have been shielded using a polished-horn like structure to avoid ceramic punch through problems [4]. The copper core is enclosed in polished stainless-steel shells to minimize sharp corners being exposed to large electric fields.

The cathode plug has slots to insert an omicron style sample holder as shown in Fig. 1b. Wafers of variable size and shape can be mounted on the omicron holder using Tantalum strips spot welded onto the Omicron holder. The front stainless-steel shell has a pierce design such that the wafer rests against the opening in the shell when the plug is fully inserted in the gun core as shown in Fig. 1c. The plug is held in the gun core via multi-lam springs which allow for mechanical stability along with increased thermal conductivity [5]. So long as the smallest dimension of the wafer mounted on the omicron sample holder is larger than 10 mm all the sharp edges of the wafer are covered by the pierce design of the shell preventing their exposure to large electric fields. The entire cathode assembly will be enclosed in a polished radiation shield cooled using the cold He gas escaping from the continuous flow cryostat. The shield will have one hole for cathode insertion and another hole for the anode. The anode is a flat plate with a 2.5 mm hole for the electron beam to pass. The gun will be assembled in a 13-inch flange size 6-way cross. The anode will be connected to one of the faces of the cross. The opposing end will be connected to the UHV transfer line of the ASU photocathode research facility [6] for cathode transfer. The cryostat is connected to the top, while the high voltage feedthrough is connected to the bottom. The other two ports will be used for pumping.

THERMAL COOLING DESIGN AND ANSYS CALCULATIONS

The temperature of the photocathode limits the mean transverse energy (MTE) (which is a measure of the cathode intrinsic emittance [1]) to $k_b T$, which tells us that at room temperature we can typically expect an MTE of 25 meV or larger. Ignoring the effects of disorder induced heating [7], this can be lowered to around 1 meV MTE with a LHe cooled photocathode –corresponding to a cathode temperature in the range of 20 K which is the goal for this cryogun. The temperature of the cathode can be controlled to a certain extent by controlling the Helium flow rate through the continuous flow cryostat. In our case, we plan to capture the escaping He gas and channel it into a compact Helium liquefier which can liquify at the rate of 1.2 lit/hr. This limits the maximum He flow rate through the cryostat without allowing the He to escape to atmosphere allowing cold operation of the gun for extended periods of time (weeks) at a stretch.

We simulated the thermal design in Ansys [8] and found the heat extraction values necessary to cool the cathode to various steady-state temperatures. When the top of the sapphire rod connected to the cryostat was set to a temperature of 12 K, the top of the radiation shield was set to a temperature of 80 K and walls of the UHV chamber along with the anode were set to room temperature, it was found that the powers extracted from the sapphire rod and the radiation shield were 2.3 W and 10.5 W respectively at steady state. These power extraction capabilities are within the manufacturer spec of the cryostat for a flow rate of 1.2 lit/hr. As seen in Fig. 2, under these conditions the cathode temperature remains as low as 13.1 K.

It should be noted that in the absence of the radiation shield, in order to maintain the power extraction spec of the cryostat, the cathode (and sapphire rod) temperature needs to be increased to 40 K. The two-inch cathode insertion opening on the back of the radiation shield made little difference on the cathode temperature, only marginally increasing the cooling power necessary to reach the same steady-state temperature. In order to achieve lower cathode temperatures the anode can be thermally connected to the radiation shield, however that increases the complexity in the assembly of the gun.

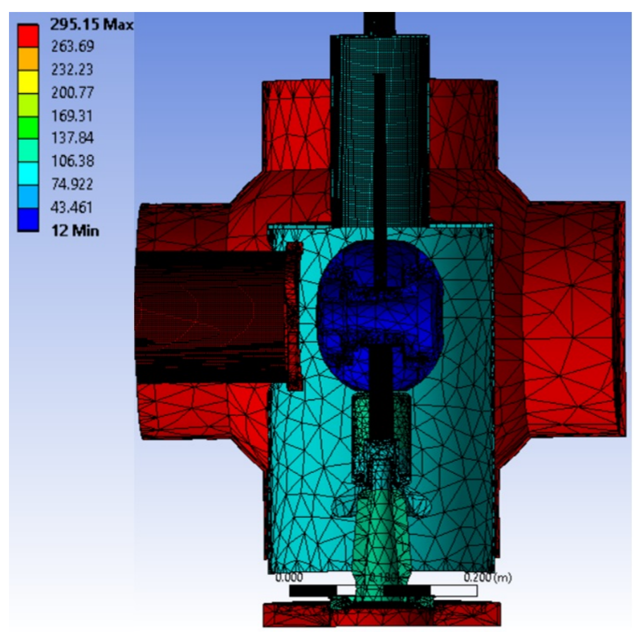

Figure 2: ASU Cryogun steady-state thermal calculations done using a simulation with a cryoshield covering the sapphire rod and electrode. For the Ansys calculations the temperature at the top of the sapphire rod is set to 12 K and the walls of the chamber are set to 295.15 K. The radiation shield is set to 80 K.

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ELECTROSTATICS DESIGN

The ASU cryogun is being developed primarily as a test facility to study cathodes and to serve as an electron source for an Ultra-fast Electron Diffraction (UED) beamline in the future. Along with measuring the quantum efficiency and response time, testing cathode materials involves measuring their intrinsic emittance (or MTE) at large electric fields. Hence it is essential to ensure that the cathode-anode electrode structure can result in large electric fields on the cathode surface and do not exhibit large focusing aberrations at reasonably large beam sizes.

The Cornell cryogun has been designed to result in electric fields as high as 10 MV/m at 200 kV [3] and has negligible focusing aberrations so long as the spot size on the cathode is less than 100 μm rms. The ASU gun design is based on the Cornell cryogun design; however, the redesigned pierce-style cathode will result in lower fields at the cathode surface and result in additional cathode focusing. It is essential to ensure that the reduction in the cathode electric field and the focusing aberrations of the modified cathode are not significant.

Figure 3a shows the equipotential lines calculated in the cathode-anode region using the software POISSON [9]. At 200 kV the cathode field reduces to 8.42 MV/m in the ASU cryogun, while the fields elsewhere on the electrode shell do not exceed 11.05 MV/m. It may be possible to increase the cathode field to 10 MV/m by increasing the voltage beyond 200 kV.

Using the General Particle Tracer (GPT) software [10] we tracked electrons in the cathode-anode electric field calculated from POISSON to calculate the change in the rms emittance from the cathode to the end of the anode. The emittance change should be negligible so long as the focusing fields are linear in nature. Figure 3b shows the change in rms emittance between the cathode and the end of the anode due to the non-linearities in the focusing fields as a function of the rms beam size at the cathode assuming an MTE of 5 meV. From this plot we see that the effect of non-linearities is insignificant so long as the rms beam size at the cathode is less than 100 μm.

CONCLUSION

The design of the ASU cryogun allows for utilizing a wide variety of cathode materials in an electron gun with relative ease. Making use of a radiation shield surrounding the core, the cryogun is designed to reach 20 K cathode temperatures or lower. The cooling power required to reach the sub-20 K range is 2.3 W from the sapphire rod and 10 W from the radiation shield at 100 K. The electrode design was changed to a pierce geometry electrode to allow for flexibility in the size and shape of the photocathode. The electric field at the cathode center is 8.42 MV/m, while the fields elsewhere on the electrode shell do not exceed 11.05 MV/m. Using electron tracking simulations we also show that so long as the rms beam size at the cathode is smaller than 0.1 mm, the effects of nonlinearities in the electrostatic focusing fields are negligible.

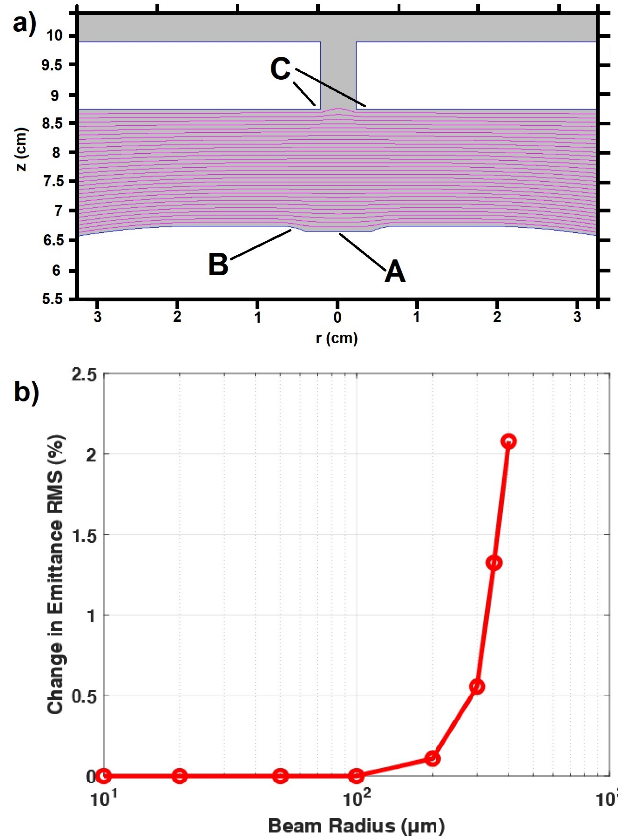

Figure 3: (a) Electrode-static modeling of the same cross-section of the cathode-anode gap as seen in Fig. 1-c. With the electrode voltage set to -200 kV, the equipotential lines computed at the center of the cathode (A) show a 8.42 MV/m electric field. The pierce electrode (B) focuses in front of the cathode, while the anode (C) defocuses. (b) Change in emittance without space charge effects as a function of rms beam radius shows that non-linear focusing due to the cathode and anode is not a significant effect below 100 μm

The detailed mechanical design of the gun is being finalized and we expect the gun to be fabricated and commissioned in the time frame of one year.

ACKNOWLEDGEMENTS

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