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

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Abstract

We present the first results of the commissioning of the 200 kV DC electron gun with a cryogenically cooled cathode at Arizona State University. The gun is specifically designed for studying a wide variety of novel cathode materials including single crystalline and epitaxially grown materials at 30 K temperatures to obtain the lowest possible intrinsic emittance of UED and XFEL applications. We will present the measurements of the cryogenic performance of the gun and the first high voltage commissioning results.

INTRODUCTION

Advances in photoinjector technology has given rise to applications that are heavily dependent on the brightness of the initial photoemitted beam; these applications include X-ray Free Electron lasers (XFEL), ultrafast electron diffraction (UED) and microscopy, electron linear colliders for fundamental physics research, and more [1]. The electron source has recently become key to increased brightness in these devices. Brighter sources will bring next generation improvements to photon and pulse energies for XFELs and bring about the advent of compact XFELs built to fit inside a university laboratory. Similarly they offer improvements to UED to enable studies of crystals with larger lattice sizes. In most photoinjectors brightness follows the following proportionality relationship $B_{4D} \propto E_0^n/\text{MTE}$, where E_0 is the accelerating field gradient, MTE is the mean transverse energy and n is a number between 1 and 2 and depends on the photoinjector design. The MTE can be related to the intrinsic emittance of the cathode via the relationship $\varepsilon_{n,x} = \sigma_x\sqrt{\frac{\text{MTE}}{m_0c^2}}$, where σ_x is the rms spot size of the emitted electrons, m_0 is the rest mass of a free electron and c is the speed of light. Thus, along with maximizing the electric field, minimizing the MTE is critical to obtaining the maximum possible brightness.

There are a number of processes which increase the MTE of photocathodes. First is the excess energy (E_{excess}) or the difference between the photon energy and the cathode work function. At higher excess energies MTE $\approx E_{excess}/3$ [2]. If the photon energy can be tuned to the work function such that the excess energy is zero or slightly negative, electrons are emitted from the tail of the fermi distribution making MTE $= k_bT$, meaning that emitting from a colder source will further reduce the MTE [3]. MTE is also limited by the effects of surface non-uniformities (physical roughness and work function variations) [4], making it critical to use single crystalline atomically ordered cathode surfaces for smallest possible MTE. Finally, other effects of band structure [5], many-body scattering with phonons [6], and non-linear photoemission [7] can contribute to increasing the MTE.

While RF photoinjectors have made huge strides in increasing the accelerating electric field to improve brightness, the photocathode technology they use is wanting. Typically they feature emission from materials with MTE in the few 100 meV range.

In recent years the advances in reducing MTE from photocathodes has been astounding. MTE as low as 5 meV was measured from near-threshold emission from Cu(100) surface cryocooled to 35 K [8]. By effectively using the electronic structure of the surface state of Ag(111), MTE as low as 20 meV with QE as high as 10^{-4} has been demonstrated. For extremely high QE and low MTE, Alkali-Antimonides have shown a lot of promise, but still have not demonstrated the thermal limit for MTE due to nanoscale physical roughness and work function variations or lattice defect states [9]. Methods for synthesizing these materials with atomically smooth flat [10] and ordered surfaces [11] have recently been developed. These methods require growing these films on single crystalline lattice matched substrates and show promise of obtaining the thermal limit along with QE in the 10^{-3} range or better. Future improvements are expected from novel single crystalline materials like topological insulators and Dirac semimetals used as cathodes [1].

Despite these success is measuring such low MTE from such novel single crystalline cathodes, none of the above technologies has ever been tested in an electron gun.

Even though there is interest to use advanced photocathodes in today's photoinjectors, the compatibility in most devices is simply not there. Most RF photoinjectors use the backside plate of the RF cavity, a piece of machined copper, as their photoemission source. New INFN style plugs as retractable cathodes in RF guns are becoming more popular, but they still don't allow for the use of single crystalline materials [12]. Several DC guns are designed to use single crystalline cathodes, especially for using GaAs based cathodes for spin-polarized applications. However, they are designed with a specific size and shape of the cathode that is not a standard easily available from vendors.

Use of single crystal cathodes also requires ultra-high-vacuum (UHV). Most DC guns are designed to achieve and operate in UHV, however, this is often a challenge for RF guns. Recently RF guns with upgraded pumping capabilities operating in the VHF [13] and S-band ranges have demonstrated UHV and can, in principle, use single crystalline cathodes.

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Lowest MTEs have been measured from single crystalline cathodes at cryogenic temperatures. Thus a gun required to test and achieve optimal performance from such cathodes should have the ability to use standard single crystal sizes available from vendors, should have UHV and must have the ability to cryocool the cathode. None of the existing electron guns meet all these needs.

In order to address this need of a cathode test bed for such advanced low MTE cathodes, we have designed and built a 200 kV cryocooled DC electron gun at ASU. The design of this gun is largely based on the Cornell 200 kV DC Cryogun [14], but has a pierce electrode and a redesigned cathode plug to allow use of wafers mounted on omicron flag-style sample holder as cathodes [15]. These holders are a standard in most surface science diagnostic instruments and allows flexibility in the cathode size and shape including the use of 10 mm × 10 mm wafers - the most commonly available size for single crystal wafers. The gun has a continuous flow liquid Helium (LHe) cryostat and has a thermal radiation shield to achieve 30 K temperatures at the cathode. Additionally, the gun is connected to the ASU cathodes research facility. This allows easy UHV transfer of the cathode from the various thin film growth, surface preparation and diagnostics and photoemission characterization UHV chambers into the gun [16]. Figure 1 shows the cross section of this gun, labeling some key parts of the design.

Here we present the cryogenic cooling and first high voltage commissioning results of this DC Cryogun.

CRYOGENIC COOLING

The ASU DC Cryogun is cryocooled using a continuous flow LHe cryostat. The cryostat is connected to the cathode via an electrically insulating, but thermally conducting sapphire rod [14, 15]. The He exhaust of the cryostat is used to cool a thermal copper radiation shield around the cathode to minimize radiation losses. The He exhaust is then pumped into a Cryomech Liquid Helium Plant (LHeP) [17] capable of liquifying He at a rate of 24 lit/day. With this flow rate a stable cathode temperature of 34.5 K was achieved in about 40 hours. This corresponds of a $k_B T < 3$ meV, sufficient to achieve the smallest MTE demonstrated so far [8]. This temperature can be maintained indefinitely due to the loss-free helium liquification using the LHeP liquifier. Figure 2 shows the cathode temperature as a function of cooling time. The temperature is limited by radiative heating effects from the holes in the thermal radiation shield required for cathode insertion and the anode.

The long over 40 hour time required to achieve the lowest cathode temperature is due to the limited heat extraction rate through the sapphire rod and the large thermal mass of the cathode electrodes. Such a long cooling time can be problematic for the use of atomically clean ordered surfaces as residual gas is expected to stick to surfaces being cryocooled for so long even in UHV conditions. To address this we demonstrated insertion of a warm cathode plug into a pre-cooled cathode electrode in the gun. The thermal mass of the

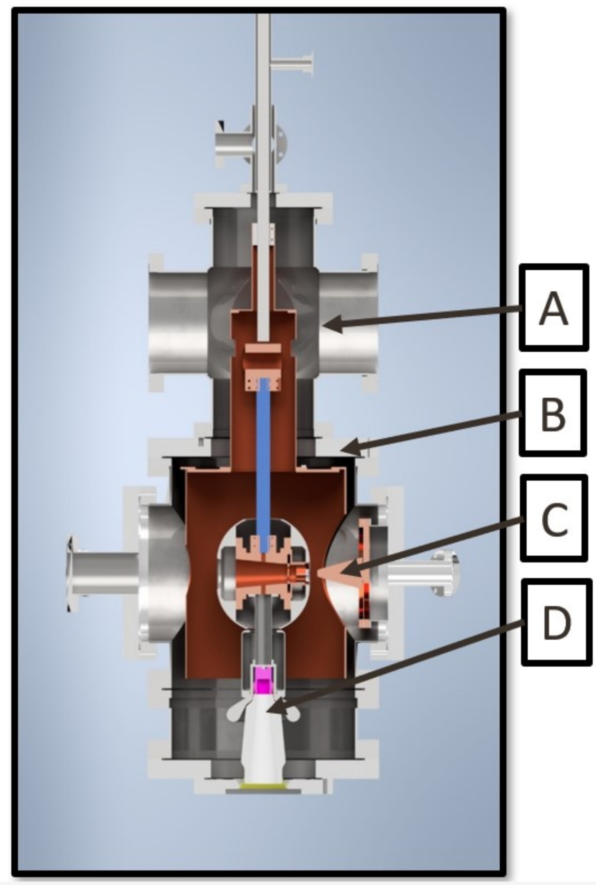

Figure 1: Cross-section of the ASU DC Cryogun. At the top of the gun a cryostat (A) is connected to the electrode via a flexible copper strap and sapphire rod. Surrounding these cold parts is a polished copper cryoshield (B). We show the cathode-anode gap (C) with a omicron paddle compatible plug and a conical shaped anode. This gun's design is based off of Cornell's DC Cryogun and uses the same HV inverted insulator (D) geometry.

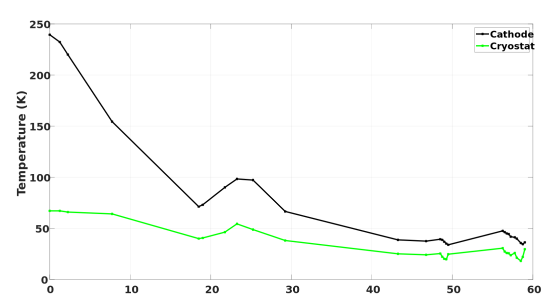

Figure 2: Cooling time of and temperature of the cryogun in calibration with the cryostat temperature. A minimum stable temperature of 34.5 K was achieved after 48 hours of cooling.

plug is significantly smaller and rapidly cools to cryogenic temperatures and reaches 60 K in less than 2 hours and full equilibrium in less than 6 hours. Figure 3 shows the cathode

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temperature as a function of cooling time with the cathode electrode pre-cooled. Further improvements to this can be made by reducing the mass and therefore the heat load of the electrode, core, and cathode puck or by increasing the diameter of the sapphire rod to allow a higher heat transfer rate.

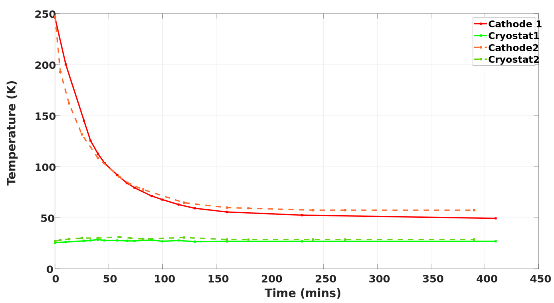

Figure 3: Rapid cooling of the puck of the cathode, reaching 60 K temperatures in 2 hours.

COMMISSIONING TO HIGH VOLTAGE

The electrodes of the gun have been designed to give a cathode field of 8.0 MV/m at 200 kV. The gun also has view ports that allow the laser to be incident on the cathode at 22.5° and 65.0° to the normal of the cathode surface. The larger angles of incidence are required of some cathode technologies [5]. To allow for such large angles of incidence while maintaining a large electric field at the cathode, the anode shape needs to be conical with a very narrow angle. This makes the fields at the anode tip as large as 30 MV/m. Use of such large fields at the anode is non-standard and may impact the high voltage (HV) commissioning process.

All the components of the cathode and anode exposed to large fields were polished in a tumbler with corn-cobb. Then they were finely polished using diamond paste of 1.0 µm. This was followed by a high pressure water rinse. The gun was then assembled in a class 100 clean room. The electron gun was baked out to 120° C and pumped using two SAES NEXTorr D2000-10 pumps [18] to achieve a pressure in the range of $8 * 10^{-10}$ torr.

During the HV commissioning process the HV power supply current, gun pressure and radiation were monitored. HV was increased slowly to minimize the spikes in either of these. Figure 4 shows a plot of voltage over time, where a voltage of 200 kV was achieved within a few tens of hours of conditioning.

CONCLUSION

We have presented the cryogenic cooling per preliminary high voltage performance of the ASU DC Cryogun. This gun will be an ideal test bed for new cathode technologies and can also serve as an electron source for UED experiments. The beamline of the gun will be equipped with a pinhole scanning technique for 4D phase space measurements, solenoids for emittance measurements and a 3.0 GHz deflection cavity for

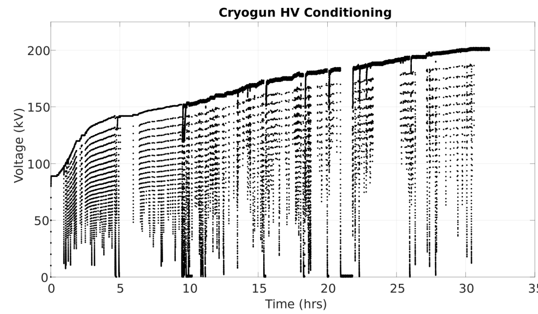

Figure 4: Voltage on the cathode as a function of time during high voltage commissioning.

cathode response time measurements. The phase space and emittance measurements can be used to deduce the cathode MTE. We expect to deliver first beam in fall 2022 with a fully operational cathode characterization beamline by summer 2023.

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