ISBN: 978-3-95450-232-5 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2022-TUYD3

THE QUEST FOR THE PERFECT CATHODE*

J. W. Lewellen†, J. Smedley, T. Vecchione
SLAC National Accelerator Laboratory, Menlo Park, CA, USA
S. Karkare, Arizona State University, Tempe, AZ, USA
J. M. Maxson, Cornell University (CLASSE), Ithaca, NY, USA
D. Filippetto, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
P. Musumeci, University of California Los Angeles, Los Angeles, CA, USA

Abstract

The next generation of free electron lasers will be the first to see the performance of the laser strongly dependent on the material properties of the photocathode. A new injector proposed for the LCLS-II HE is an example of this revolution, with the goal of increasing the photon energy achievable by LCLS-II to over 20 keV. We must now ask, what is the optimal cathode, temperature, and laser combination to enable this injector? There are many competing requirements. The cathode must be robust enough to operate in a superconducting injector, and must not cause contamination of the injector. It must achieve sufficient charge at high repetition rate, while minimizing the emittance. The illumination wavelength chosen must minimize mean transverse energy while maintaining tolerable levels of multi-photon emission. The cathode must be capable of operating at high (~30 MV/m) gradient, which puts limits on both surface roughness and field emission. This presentation will discuss the trade space for such a cathode/laser combination, and detail a new collaborative program among a variety of institutions to investigate it.

NEEDS OF LCLS-II HE

The LCLS-II-HE project will build a new low-emittance injector (LEI) based on an SRF photoinjector to achieve a normalized transverse emittance of 0.1 μm with 100 pC in 3 ps at 100 MeV. This level of performance has never been demonstrated before and is a factor of 3-4 better than the state-of-the-art design of the LCLS-II photoinjector. It will enable the generation of 20 keV photons using an 8 GeV linac, and even harder x-rays when coupled to future superconducting undulators. To achieve this, simulations show that the SRF gun must operate at > 25 MV/m photocathode gradient and that the photocathode must have an intrinsic emittance of ≤ 0.3 μm/mm [1], corresponding to a maximum allowable MTE of 184 meV.

The LEI performance goal has motivated a multi-institutional effort to address the main technical hurdles and explore the parameter spaces. The cathode MTE vs temperature and wavelength will be explored at moderate gradients for a selection of materials. The most promising will be tested in RF guns at LBL and UCLA. A DC HV test will also be explored. Each of these will be described in the following sections.

GENERAL APPROACH

Our collaboration is designed to both capitalize on leading-edge capabilities at our respective laboratories, while concurrently using multiple techniques to perform the desired characterizations. Our measurements will thus naturally be "cross-checked" as we progress through our experimental program. The approach not only provides additional confidence in our measurements, but will also provide insight as to the source of any discrepancies between measurements.

Broadly speaking, we expect the first year of the effort will focused on low-field measurements, and on preparing for the start of high-field measurements (e.g. standardizing growth recipes, transfer chambers, etc.) Year 2 will see the start of high-field measurements. The third and final year will continue both low- and high-field measurements on the most promising materials.

LOW FIELD MEASUREMENTS

Our low-field measurements will begin with Cs_3Sb cathodes grown using various recipes on polycrystalline metal or single crystal Si substrates as well as on lattice matched (to Cs_3Sb) substrates like SiC and STO using different growth techniques (sequential deposition, co-deposition and layered growth followed by re-crystallization). Other alkali-antimonides such as K_2CsSb and Na_2KSb will also be investigated. The spectral response and MTE will be measured from these films. The MTE of photocathodes will be measured at low gradient in two locations, Cornell and ASU, to ensure reproducibility.

At ASU, MTE will be measured in the PhotoEmission Electron Microscope (PEEM) by measuring the transverse momentum distribution in the k-space imaging mode. MTE will also be measured at room and cryogenic temperatures in the 200kV DC cryogun at ASU [2]. The PEEM and the 200kV DC gun are connected to the growth chamber in UHV. The surface topography and work function variation of the films will be measured using an Atomic Force Microscope and a Kelvin Probe Force Microscope connected in UHV to the growth chamber [3]. The topography and work function variations will be correlated to the MTE measurements to investigate the effects of surface topography on MTE.

Cornell has a dedicated molecular beam epitaxy (MBE) growth chamber including real-time structural analysis of the photocathode during growth via reflection high energy electron diffraction (RHEED) (Figure 1) and has

* Work supported by the Department of Energy Contract DE-AC02-76SF00515.
† lewellen@slac.stanford.edu

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demonstrated epitaxial growth of alkali antimonide compounds, reproducing the work demonstrated in [4].

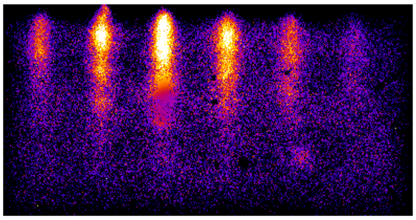

Figure 1: Reflection high energy electron diffraction (RHEED) pattern of an epitaxial cesium antimonide photocathode taken during growth in the Cornell MBE chamber. Vertical streaks are indicative of lattice ordering and surface smoothness.

The Cornell MBE chamber is equipped with a vacuum suitcase that transfers omicron-paddle-style pucks to the Cornell cryogenic transverse energy meter (cryo-TE-Meter). The Cryo-TE-Meter is a 10 keV DC gun whose cathode electrode can be cooled down to 20 K during operation. The downstream beamline has a solenoid and scintillating view screens to perform solenoids scans of emittance. A common source of error in solenoid scans of this kind is the projected emittance growth due to stray skew quadrupole moments [5]. We have developed a 4-dimensional phase space mapping system in the TE-meter that can be used to diagnose skew quadrupole moments and correct them with dedicated corrector magnets. This system will also serve as a useful cross-check on solenoid scans.

QE and intrinsic emittance will be measured as a function of temperature, ranging from 20 K to room temperature, and photon energies above and below threshold. The simulated ultimate resolution of the Cryo-MTE meter is 5 meV MTE. The MBE and Cryo-TE-meter have successfully demonstrated several growths and test transfers of alkali antimonide photocathodes into the TE-meter gun.

HIGH FIELD MEASUREMENTS

High-gradient photocathode tests are essential for characterizing the emission of dark current from the photocathode surface under relevant operating conditions. Excessive dark current must be avoided in a superconducting linac as it can quench superconducting cavities or generate large amounts of damaging radiation.

Ideally, such testing would be performed in an SRF photoinjector; however, there is no suitable gun available. Our collaboration is thus planning on conducting measurements on two very different RF guns, using cathodes fabricated at a single location, to serve as "proxy" environments, as well as exploring DC-based testing options for complementary studies.

DC High Field Measurements

DC high field tests of cathode performance have the potential to enable direct quantization of the field emission from the surface in very good vacuum, without the complication of an RF source. A challenge occurs if the 'beam' will be dumped locally, as the test will be dominated by electron stimulated desorption (ESD), and Bremsstrahlung may cause secondary photoemission. ESD can largely be avoided by keeping the electron energy below 300 eV [6]. A proximal probe system, such as the AFM instrument at ASU is well suited to characterize the effects of high field on dark current. The sample biased to 30V with the tip at 1 um from the sample can give electric fields as high as 30 MV/m. The AFM allows biasing of the sample while measuring a sample emission current using a picoammeter. This current will be measured as a function of the tip-sample distance to get a measurement of the dark current under high DC electric fields. This can be performed at various locations of the sample to get an idea of emission uniformity.

The collaboration is also exploring use of facilities at the Center for Functional Nanomaterials, which has a precision nanoprobe that will enable a similar measurement to the ASU AFM but over a larger scan area. A LEEM with in situ cathode growth capability is being constructed by a team in Leiden University in collaboration with IBM, and the SLAC team will participate in measurements there that will image the field emission uniformity, but only to 15 MV/m. Here ESD is avoided by removing the electrons from the vicinity of the cathode before they are dumped.

Photocathode Production for High Gradient Tests

The baseline plan is that the photocathodes for the high gradient tests at LBNL and UCLA will be produced at SLAC using the existing LCLS-II deposition system. This system was commissioned to grow Cs_2Te photocathodes on INFN style plugs for the LCLS-II. It has four physical vapor deposition sources that are reconfigurable to produce different materials following either sequential or co-deposition recipes. Importantly, the production recipes that the collaboration will use must be generic enough that the implementation of equivalent growth processes at any of the collaborating institutions will be straightforward, otherwise the compilation of photocathode test results may be inconsistent.

An alternate plan being considered is to subcontract the production of photocathodes for the high gradient tests using an industrial partner. In this scenario, the partner company would produce the photocathodes on INFN style plugs and package them in small vacuum transport canisters. These transport canisters would then be opened in vacuum using a dedicated UHV unpacking system that would allow the plugs to be transferred to compatible suitcase carriages. Both baseline and alternate options are being investigated.

Finally, the INFN plugs will be redesigned to make their top detachable and mount it on an omicron sample holder to measure it in the UHV AFM at ASU. This will allow measurements of the topography of the cathodes grown on the INFN plugs and tested under high field conditions at Pegasus and HiRES beamlines.

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High-Gradient RF Testing at Pegasus

The UCLA Pegasus facility [7] is a natural testbed to characterize the performances of advanced photocathode in a high gradient RF environment. The system is based on a pulsed high-gradient (up to 100 MV/m peak field) UCLA/SLAC/BNL style S-band 1.6 cell gun, recently equipped with a load-lock chamber. Preliminary beam operation with an alkali antimonide cathode grown at Cornell and ground-shipped to Los Angeles was demonstrated in the Fall of 2021 [8]. Notably these cathodes have resulted in an increase of two orders of magnitude for QE and beam charge with respect to the baseline values from a copper cathode, enabling the study of novel modalities in the superradiant THz FEL [9].

One of the advantages of the high frequency S-band gun for photoemission studies is the ability to change the injection phase and therefore the launch field anywhere between 20 and 60 MV/m, without otherwise altering gun parameters and thus maintaining a constant baseline for, as an example, dark current. The phase can be used to modulate the cathode work-function by Schottky effect, as previously demonstrated [10]. Eventually this knob could also be used close to the photoemission threshold to better differentiate between the different domains in the cathode and elucidate the effect of the field on surface roughness.

High-Gradient RF Testing at HiRES

The HiRES accelerator facility is a unique CW RF test stand for high brightness photocathodes [11], concurrently providing accelerating gradients in excess of 20 MV/m, MeV-range beam energies, high average currents, and vacuum levels compatible with extended operations of high quantum-efficiency cathodes. Taking advantage of the cathode exchange system (load-lock), the beamline diagnostic suite has been used over the years to characterize semiconductor cathodes [12] and dark current emission [13] in continuous RF operations. Such cathodes have also been used to produce high density beams for application in ultrafast science [14].

The main goal of the tests at HiRES is to characterize emittance, dark current and lifetime of different cathodes produced by the collaboration, in conditions as close as possible to the future operation of the LEI electron gun. To such purpose, the accelerating field in the HiRES VHF electron gun will be increased via modification of the cathode plug geometry. Indeed, by varying the plug insertion depth in the RF cavity, the longitudinal field at the cathode plane can reach values in excess of 25 MV/m. This modification will also produce an associated defocusing effect (which will need to be accurately determined to characterize the beam emittance) and a change in the field profile at the interface between the plug and the cavity wall. Both effects are expected to have consequences on the final beam emittance and on the total dark current transmitted along the beamline. In particular, reshaping of the cathode plug corners could provide beneficial effects in minimizing the total dark current generated by the source. The presence of multiple solenoid lenses downstream the electron gun allows for imaging of the cathode plane on a scintillating screen, providing a quantitative tool for spatial localization and comparison of dark current sources for the different geometries.

CONCLUSION

The energy of a photon generated by an X-FEL is

$$E_\gamma = \frac{2hc\gamma^2}{\lambda_u\left(1+\frac{1}{2}K^2\right)}, \tag{1}$$

where E_γ is the photon energy, h is Planck's constant, c is the speed of light, γ is the Lorentz factor of the electron beam, λ_u is the undulator period and K is the normalized undulator magnetic strength. For an X-FEL to saturate at a desired wavelength, other conditions must be met: the beam emittance and energy spread must be small enough, and the peak current of the beam, high enough. Both unnormalized emittance and fractional energy spread scale inversely with γ, so it appears natural to push to harder photon energy by increasing the beam energy.

In the first generation X-FELs, such as LCLS-I, the intrinsic electron beam quality was generally determined primarily by the "structural" characteristics of the electron gun; and both the unnormalized emittance and fractional energy spread could indeed be usefully decreased with higher beam energy. Improving the cathode properties (e.g. MTE) would not have resulted in substantially better performance of the X-FEL as a whole.

Even absent the presence of other constraints (both physics and fiscal) on extending towards arbitrarily higher energy, the relative scaling of photon energy versus beam quality, with beam energy, suggest this approach cannot be used indefinitely. Indeed, the upcoming generation of X-FELs, such as LCLS-II-HE, will use lower beam energies, combined with intrinsically brighter beams, to achieve lasing and saturation in the hard X-ray regime. Under this paradigm, the properties of the electron source – the cathode – are at least as important as the "zero-MTE" performance of the gun in determining the intrinsic beam quality. The move towards higher duty factor operation places constraints on other aspects of cathode performance, such as dark current and field emission; and the guns in which they are used, are more sensitive to contamination by the cathode itself.

Optimizing the next-generation beam sources as systems, therefore, requires more comprehensive performance characterization of candidate cathode materials, with improved fidelity to expected operating conditions. This work seeks to address that knowledge gap. We also expect the techniques and partnerships developed for this work will help to facilitate development and evaluation of new cathode materials, and will help to improve consistency of cathode performance.

ACKNOWLEDGEMENTS

The authors wish to acknowledge advice and assistance from many in the materials science community, including Jean Jordan-Sweet and Rudolph Tromp of IBM, Piero Pienatta of SLAC, and Percy Zahl and Erik Muller of BNL.

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