- ## Introduction

GaAs-based photocathodes are the state-of-the-art electron source for the production of highly spin polarized electron beams used in planned and existing large scale accelerators facility for high energy (e.g. ILC) and nuclear physics experiments (CEBAF, Electron-Ion-Collider, LHeC), as well as in small scale accelerators like spin-polarized low energy electron microscopy and spin polarized transmission electron microscopy to investigate magnetic properties of condensed matter [1-6].

Since the discovery of spin polarized photoemission from bulk GaAs in the 1970's, several studies have aimed to increase the degree of spin polarization. It has been shown that straining the GaAs crystal lattice results in the breaking of the energy degeneracy of heavy and light holes in the valence band. This allows energy-tuned transitions to excite electrons to into vacuum with very high spin polarization (above 90%) with quantum efficiencies that are at most of 1% [7]. A collaboration led by the JLab group demonstrated that employment of strained GaAs/GaAsP superlattice (SL) structures with a distributed Bragg reflector (DBR) outperform all previous cathode configurations, producing electron beams with spin polarization above 80% and quantum efficiencies larger than 6% [8]. Recently, the Cornell University photocathode development group has been investigating new methods to produce NEA activation on bulk GaAs and on superlattice structures based on GaAs/GaAsP. The Cornell group demonstrated that activating layers based on Cs-O-Sb and on Cs-Te can provide one order of magnitude longer lifetimes with respect to the standard Cs-O activation layer without any spin depolarization and with minimal losses in the quantum efficiency [9-11]. However, these last demonstrations were only performed with low beam energies, and at low currents and small extraction fields.

- ## Proposed Research

Bare GaAs-based photocathodes (like the SL with DBR) cannot produce spin polarized electron beams, as the photon energies which produce spin selective excitation are too little to overcome the outmost GaAs layer work function. Instead, the work-function of the GaAs at the vacuum interface must be lowered with an activating dipole layer on its surface which is strong enough to generate Negative Electron Affinity (NEA). NEA is typically achieved by depositing just under a monolayer of Cs-O or Cs-NF3 on the photocathode surface. However, these activation layers are extremely sensitive to poor vacuum conditions and require extreme vacuum levels (in the range of 10^{-11} Torr or below). Even at such low pressures, their operation at moderate to high average beam currents (from few microamperes to few milliamperes) often results in a rapid quantum efficiency degradation over time (1/e decay measured from days to hours, respectively) [12].

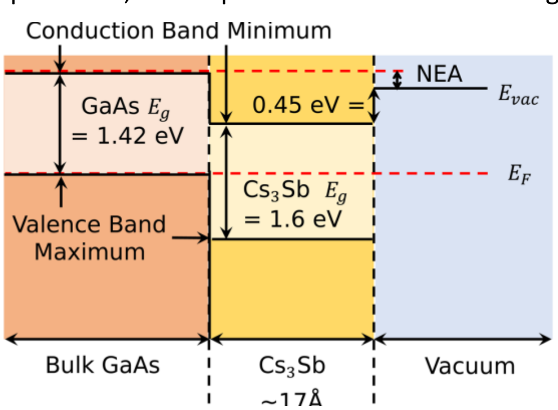

Figure 1.Schematics of the electronic band alignment enabling the NEA conditions in the presence of a heterostructure based on GaAs and Cs3Sb [11].

Recent experiments from the Cornell group have demonstrated that alternative methods to produce NEA at the vacuum interface based on the formation of a heterojunction between the GaAs based photocathodes and other semiconductors like Cs2Te or Cs3Sb (figure 1) can yield a more robust NEA layer than the one achieved with Cs-O or Cs-NF3 [9-11]. With a proper choice of the activating layer thickness operational lifetimes can be extended up to an order of magnitude without any loss in spin polarization and with minimal losses on the efficiency of the photoemission process (figure 2) [11].

If the lifetime improvements, so far measured only at low electric field, low energy and low charge per bunch, translate to realistic gun conditions (high current, high energy), this technology can pave the way to the realization of future facilities based on high average current Energy Recovery Linacs to deliver highly intensity spin polarized beams. Furthermore, the possibility of delivering high current polarized electron beams for extended periods of time enable the production of spin polarized positron at low beam energy [13]. Finally, this could broaden the application of spin polarized cathodes beyond conventional high voltage DC guns, to less forgiving but potentially higher brightness guns like high field SRF guns. We propose a dedicated set of experiments, both via surface science analysis at Cornell, and in a state-of-the-art photoinjector tests at a test beamline at Thomas Jefferson National Accelerator Facility to study precisely this question.

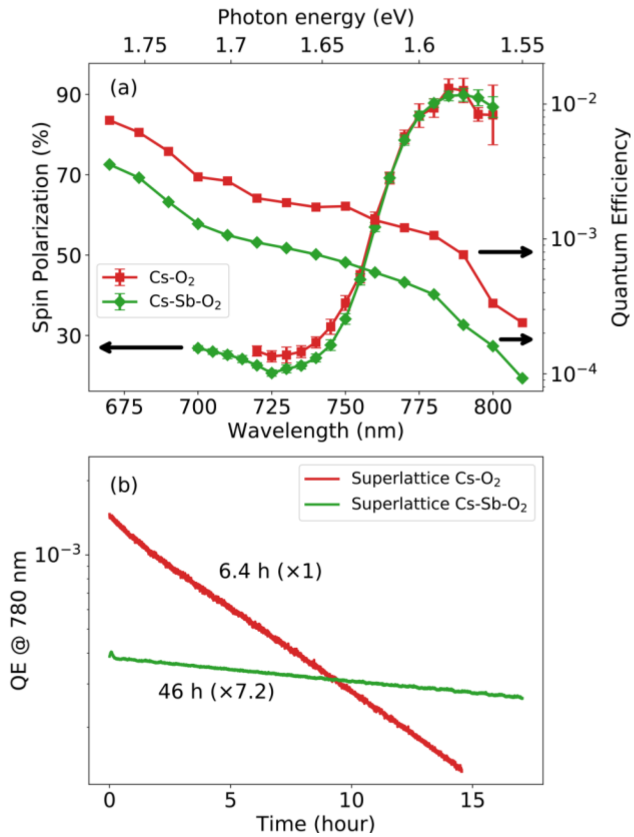

Figure 2. Quantum Efficiency, electron spin polarization and lifetime measured for the same GaAs-based superlattice photocathode activated to NEA using Cs-O and Cs-Sb-O [11].

The proposed program will proceed along two parallel directions: we will install the required thin film evaporation sources in one of the JLAB photocathode growth suites, so that activating layers based on Cs-Sb-O and Cs_2Te can be grown on site at JLAB at their Upgraded Injector Test Facility (UITF). We will then perform NEA activation experiments of GaAs photocathodes using these new methods using the already developed methods based on the Cs-O-Sb and Cs_2Te in the attempt to replicate the results obtained at Cornell University at JLAB. Upon successful growth at JLAB, we will perform photoemission characterization of the activated samples in the UITF beamline including lifetime measurements and polarimetry at the gun beam energy of 200 kV and with high currents up to 3 mA, limited by the high voltage power supply. The UITF beamline will be modified, upgraded with a high energy Mott polarimeter which will be recommissioned with an updated electronics and data acquisition system. Jefferson laboratory team members are world leaders in the production and characterization of high intensity polarized electron beams and they have the unique required experimental facilities, hardware and know how to perform this experimental program. Both bulk GaAs and GaAs-based superlattice samples will be used to produce electron beams at high average current and high polarization. Post-mortem studies will be performed on the samples after their extended use in the gun in order to understand how the new activating layers behave in presence of the intense ion back-streaming that in DC gun usually drastically limits the lifetime of the photocathodes, which is one of the major roadblocks preventing operating at high average current above few mA.

In parallel to the photoemission studies performed at Jefferson Lab, the Cornell group will also continue to perform detailed photocathode studies aimed at extending our understanding of the heterostructure activating layers. Additional thin film growth experiments will be conducted in Cornell University photocathode laboratory. To gain a better understanding of the electron transport, we will use advanced surface analyses techniques like photoelectron spectroscopy and atomic force surface microscopy to analyze the activating layers in conjunction with traditional photoemission studies that characterize quantum efficiency and spin polarization. Specifically, we will study the effect of a segregated

Cs-O layer on the performances of the GaAs photocathodes activated to NEA using Cs2Te. The results obtained in this parallel effort can be used to readily implement new methods of activation in the photoemission experiment at JLab. Furthermore, we will attempt transfer of these photocathodes using a vacuum suitcase to perform surface analyses studies and we will measure their robustness with respect to such procedure.

- **Statement of work**

As discussed in the previous section we plan to perform proposed research in two parallel efforts: the primiary effort will seek at demonstrating the performances of the new activating layer in a real photoinjector beamline equipped to perform high current and spin polarization measurements by transferring Cornell University growth techniques to JLab. The second effort will support the operations at JLab seeking to further improve the performances of the photocathode by exploring the phase space of the growth conditions for the activating layers made with Cs, Te and oxygen, which can outperform the previously developed materials in terms of robustness, and at the same time to perform surface studies aimed at revealing details of such activating layers.
There will be a total of six task that will be carried out within this proposal.
At Jefferson Lab:

A. **We will retrofit one of the JLab growth chambers with the required elemental sources to be able to activate GaAs based photocathodes using the new robust methods developed at Cornell University;**
    - The alkali antimonides growth chamber will be retrofitted with an oxygen leak valve and a Te evaporator to perform the NEA activations procedure developed at Cornell University;

B. **We will perform growth experiments aimed at optimizing the process parameters to the JLab growth chamber;**
    - The growth procedures developed at Cornell University will be applied to the growth system at Jlab and process parameters optimized for the different growth conditions;

C. **We will install a high energy Mott polarimeter in the beamline of the Upgraded Injector Test Facility and we will commission a new data acquisition system.**
    - The Mott polarimeter already in hand at Jlab will be installed into the beamline and a new data collection system will be built and commissioned;

D. **We will perform high current runs aimed at demonstrating that the new methods of activations provide extended operational lifetimes without compromising electron spin polarization.**
    - Activated GaAs-based selected photocathode will be moved into the gun to produce a spin polarized electron beam at sustained current operation to estimate the operational lifetime;
    - Polarization of the electron beam will be measured at the gun beam energy using the Mott polarimeter;

At Cornell University:

E. **We will perform a dedicated set of experiment to study the role of a possible segregated Cs-O layer at the interface between GaAs and the NEA activation layer grown using Cs2Te.**
    - NEA activation will be performed using two parameters: the oxygen exposure and the tellurium thickness;
    - QE, Electron Spin Polarization and lifetime will be measured and trade-offs estimated;

F. **We will perform transfers of activated photocathode using a UHV suitcase from our growth chamber to a surface science UHV facility capable of performing atomic force microscopy,**

photoelectron microscopy and capable to measure the quantum efficiency to determine the degradation of the surface induced by the transfer.

- Selected samples will be transferred using a UHV suitcase to another lab to estimate their robustness against short distance transfer and vacuum transfer;
- Atomic force microscopy and photoelectron spectroscopy will be used to study the chemical composition and morphology of the activating layers;

- **Description of the results, products, transferable technology, and expected technology transfer path.**

In summary, this proposal seeks to **demonstrate the reliable operation, in a realistic accelerator setting, of robust NEA activating layers for GaAs-based photocathodes designed for the production of intense highly spin polarized electron beams, and to further explore the possibilities of improving the robustness of GaAs with an approach based on the formation of heterojunctions**. If successful, this proposal can pave the way to the production of unprecedented high average current electron beam which will have multiple impact in expanding the capabilities of existing facility (like CEBAF or FRIB) and open the way to the realization of other facilities (like LeHC, and EIC based on ERLs) requiring sources of high average current spin polarized electron beams. Furthermore, other future facilities (like ILC) and small scale experimental microscopes designed to study magnetic properties of materials and surface can take advantage of longer operational lifetime that can be achieved with these new methods.

We expect to publish the results in peer reviewed journal and to disseminate the results at relevant conferences and workshops, as well as to train a graduate student in the growth and characterization of these new activating layer and in the operation and characterization of photocathodes in a state-of-the-art photoinjector facility.

- **Cost, schedule, and measurable milestones for the proposed research**.

The present proposal consists of 6 tasks as detailed in section 3. Table 1 reports the estimated scheduled for the six tasks over the performance period of 12 months.

Table 1. Estimated schedule of the activities part of this proposal. In red the tasks that will be performed at the photocathode laboratory at Cornell University, In blue the activities that will be carried at JLab. The key personnel responsible for each task is also reported.

TASK/month	1	2	3	4	5	6	7	8	9	10	11	12
A - Growth system upgrade @ JLAB (Mamun)												
B - Growth experiments @ JLAB (Mamun)												
C - Mott Polarimeter Installation @ JLAB (Suleiman)												
D - Electron beam production @ JLAB (Hernandez-Garcia)												
E - Cs2Te growth studies @ CU (Cultrera)												
F - Surface studies of NEA layers @ CU (Cultrera)												

Task A– estimated cost and milestones:
Growth system upgrade at Jefferson Lab (estimated cost $29,894.20)

- Install an oxygen leak valve and a Te evaporation source in one of the JLab growth chamber;

Task B– estimated cost and milestones:

Growth experiments at Jefferson Lab (estimated cost $46,612.34)

- Demonstrate activation to NEA using the methods developed at Cornell University;

Task C– estimated cost and milestones:
Mott Polarimeter Installation at Jefferson Lab (estimated cost $76,599.85)

- Install the Mott polarimeter on the beamline of UITF;
- Recommission the electronics for data acquisition for the Mott polarimeter;

Task D– estimated cost and milestones:
Electron beam production experiment at Jefferson Lab (estimated cost $53,274.57)

- Perform characterization of lifetime at high average current;
- Measure polarization at the gun energy;

Task E – estimated cost and milestones:
Cs2Te growth studies at Cornell University (estimated cost $46,449)

- Perform photoemission measurements (QE, spin polarization and lifetime) at low electric field as function of the Cs2Te thickness;
- Perform photoemission measurements (QE, spin polarization and lifetime) at low electric field as function of the exposure to oxygen;

Task F– estimated cost and milestones:
Surface science studies of NEA layers at Cornell University (estimated cost $46,449)

- Study the robustness of the activating layer (in terms of QE) when samples are transferred using a UHV suitcase;
- Study the morphology and composition of the activating layers;

APPENDIX 3: BIBLIOGRAPHY & REFERENCES CITED

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APPENDIX 4: FACILITIES & OTHER RESOURCES

CORNELL UNIVERSITY:

The photocathode infrastructure at Cornell includes the alkali antimonide cathode growth and characterization vacuum complex – that will be be dedicated to this proposal. Analysis techniques such as Scanning Auger Spectroscopy, Low Energy Electron Diffraction (LEED), Reflected High Energy Electron Diffraction (RHEED can be used to characterize the surface properties of the specimens. Spectral response, photoemission uniformity, lifetime measurement, electron spin polarization and intrinsic emittance are used to characterize the quality of samples and to relate to the growth conditions.

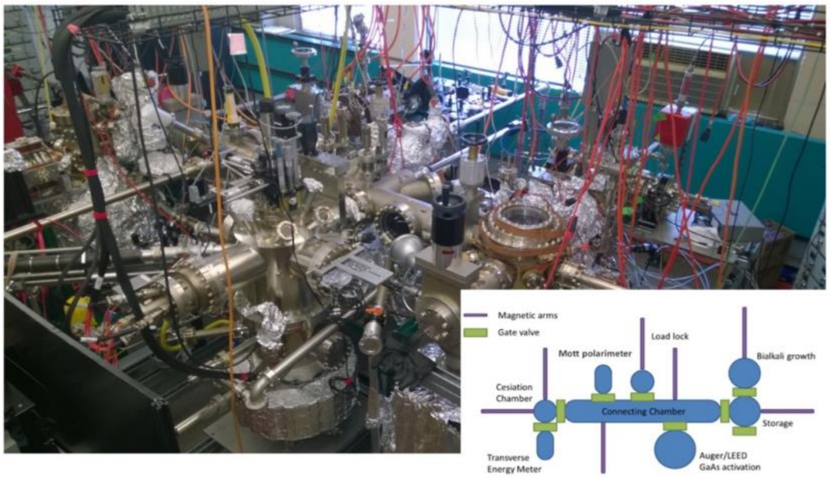

Figure 3. The main UHV installation operated in Newman laboratory showing the infrastructure for the photoemission studies at Cornell University.

In Newman laboratory, we have a well-equipped machine shop for fabricating ultrahigh vacuum components, including welding, brazing and heat treating.

Furthermore, substantial use is made of the facilities of the Cornell Nanofabrication Facility (CNF) and the Cornell Center for Materials Research (CCMR). These laboratories have public user facilities for device fabrication and materials and device characterization including Atomic Force Microscope, X-ray Photoemission Spectroscopy in a single unit for photocathode material characterization.

JEFFERSON LAB:

The growth chamber installed at UITF gun and beamline will be modified to activate photocathode with the new recipes including the new required evaporation sources.

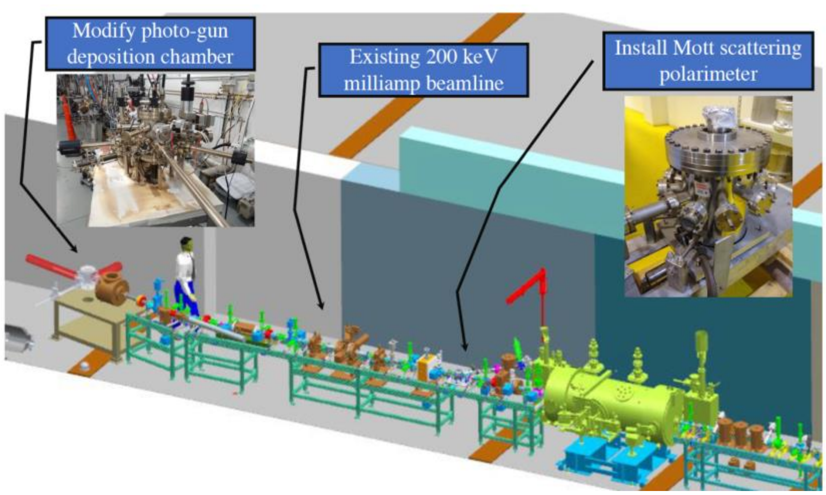

Figure 4 The Upgraded Injector Test Facility (UITF) at JLab

Then the gun and beamline will be used to measure lifetime at high average current from a 200 kV dc-photo gun, and finally to measure the electron spin polarization in a Mott scattering polarimeter.

APPENDIX 5: EQUIPMENT

The vacuum chambers and all ancillary systems (vacuum pumps, vacuum gauges and RGA) for the growth of Sb and Te film and for their reaction with alkali metals and oxygen will be made available to the experimental plan.

Additional equipment available to this study includes a supercontinuum fiber laser source with ps pulse duration tunable from 400 to 850 nm and a large number of low power CW laser diodes operating in the visible and IR range of the spectrum.

APPENDIX 6: DATA MANAGEMENT PLAN

Expected Data. The data produced will include measurements of photocathode performance, RGA spectra, growth recipes and history details. Extensive use of computer-controlled data recording techniques is employed and the entire process is fully controlled with LabView control software and data processing using MATLAB. The detailed results of the research will be published in peer-reviewed journals and all growth performance data (made available upon request) will be included as part of the complete dataset.

Data Format. An electronic logbook ELOG (backed up daily) is maintained to record the daily activities and experiments performed. The data themselves will be stored in ASCII or binary formats (using typical MATLAB and LABVIEW I/O standards and functions) for large size sets. Data snapshots will be stored in individual directories with appropriate time stamps. Indexing of the experimental data (metadata) will be available in each directory and the main parent directory, along with documentation in the hardcopy notebooks according with accepted standards in the lab. Metadata standards are enforced so that the experimental conditions can be unambiguously associated with the growth conditions, dates and times, processing and analysis techniques, and any other information deemed necessary to fully understand the data analysis flow and results.

Access to Data and Data Sharing Practices. We expect that all the data gathered and results derived during this project will be freely available to interested parties. All significant results will be published in peer-reviewed journals, our data and simulations will be made available to the interested laboratories upon request.

Policies for Re-Use, Re-distribution. Data reuse and redistribution will be in accordance with Cornell University and DOE standards. Data will be allowed to be reused without expressed consent from the PI but requires statements of attribution and disclaimers that the originators of the data are not responsible in any way for re-use or novel interpretations or results. Disclaimers and policies for deposit, access, withdrawal, ownership, privacy and preservation of data will follow closely those for the eCommons@Cornell depository found at http://ecommons.library.cornell.edu/policy.html and discussed below.

Archiving of Data. All electronic logbooks and experimental disk space is regularly backed up and archived with daily incremental and full monthly backups. Cornell Accelerator Lab has been maintaining such data for many decades of successful accelerators' operations. To guarantee redundant access and persistence, the PI may also archive all key project data in the eCommons@Cornell repository. This Digital Repository is powered by opensource project DSpace and is open to anyone affiliated with Cornell University as a place to capture, store, index, preserve and redistribute materials in digital formats that may be useful for educational, scholarly, research or historical purposes. eCommons@Cornell is a service of the Cornell University Library that provides long-term, open access to a broad range of Cornell-related digital content of enduring value. All work deposited in eCommons will be assigned a persistent identifier and a persistent Web address (URL), guaranteeing that data will be accessible independent of the hosting location or domain of the repository.