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Technology to Establish a Factory for High QE Alkali Antimonide Photocathodes Phase I

Final Report

Topic 6: High Quantum Efficiency Photo-Cathodes

Subtopic b: Other

Phase I grant Award Number: DE-SC0013276

I. Identification and Significance of the Problem or Opportunity and Technical Approach

A. Introduction

Intense electron beams are key to a large number of scientific endeavors, including electron cooling of hadron beams, electron-positron colliders, secondary-particle beams such as photons and positrons, sub-picosecond ultrafast electron diffraction (UED), and new high gradient accelerators that use electron-driven plasmas. The last decade has seen a considerable interest in pursuit and realization of novel light sources such as Free Electron Lasers [1] and Energy Recovery Linacs [2] that promise to deliver unprecedented quality x-ray beams. Many applications for high-intensity electron beams have arisen in recent years in high-energy physics, nuclear physics and energy sciences, such as recent designs for an electron-hadron collider at CERN (LHeC) [3], and beam coolers for hadron beams at LHC and eRHIC [4,5]. Photoinjectors are used at the majority of high-brightness electron linacs today, due to their efficiency, timing structure flexibility and ability to produce high power, high brightness beams.

The performance of light source machines is strongly related to the brightness of the electron beam used for generating the x-rays. The brightness of the electron beam itself is mainly limited by the physical processes by which electrons are generated. For laser based photoemission sources this limit is ultimately related to the properties of photocathodes [6].

Most facilities are required to expend significant manpower and money to achieve a workable, albeit often non-ideal, compromise photocathode solution. If entirely fabricated in-house, the photocathode growth process itself is laborious and not always reproducible: it involves the human element while requiring close adherence to recipes and extremely strict control of deposition parameters. Lack of growth reliability and as a consequence, slow adoption of viable photoemitter types, can be partly attributed to the absence of any centralized facility or commercial entity to routinely provide high peak current capable, low emittance, visible-light sensitive photocathodes to the myriad of source systems in use and under development. Successful adoption of photocathodes requires strict adherence to proper fabrication, operation, and maintenance methodologies, necessitating specialized knowledge and skills. Key issues include the choice of photoemitter material, development of a more streamlined growth process to minimize human operator uncertainties, accommodation of varying photoemitter substrate materials and geometries, efficient transport and insertion mechanisms preserving the photo-yield, and properly conveyed photoemitter operational and maintenance methodologies.

AES, in collaboration with Cornell University in a Phase I STTR, developed an on-demand industrialized growth and centralized delivery system for high-brightness photocathodes focused upon the alkali antimonide photoemitters. To the end user, future photoemitter sourcing will become as simple as other readily available consumables, rather than a research project requiring large investments in time and personnel.

An excellent photoemitter meeting the above requirements, as currently implemented at Cornell University, is sodium potassium antimonide Na_2KSb from the family of alkali antimonides. Recent work at Cornell [7] has shown that this material can meet the requirements of operation at high average currents for extended periods (days to weeks at 10's of milliamps minimally with many months of "dark" lifetime) with low emittance and excellent time response. A similar photocathode material, CsK_2Sb has demonstrated generating ultra-low emittances when the laser wavelength is tuned to the photoemission threshold of the photocathode [8]. Adoption of these photoemitters for routine use is limited by their availability and integration into the supply-stream. Routine availability will be addressed by generating a commercial-grade growth system, capable of handling the various substrate and geometry requirements of individual laboratories. The growth technology will be enhanced via additional process streamlining by adding a control system to eliminate operator effects. Close work with the end users will result in self-contained, reusable vacuum transport systems for moving the photocathodes from the growth system to the point of use and operation and maintenance methodologies appropriate to both the photoemitter and the facility where it is destined. For example Brookhaven National Lab has a program LeRHIC to demonstrate electron cooling of ions. This program will use a DC gun purchased from Cornell and antimonide photocathodes for electron production. AES plans to be a supplier to BNL for this program.

Figure 1 shows the layout of the growth chamber and transfer suitcase that AES plans for Phase II. A Puck insertion chamber is also included that will be used for storage of blank pucks as well as cathodes that do not meet the quantum efficiency minimum during processing

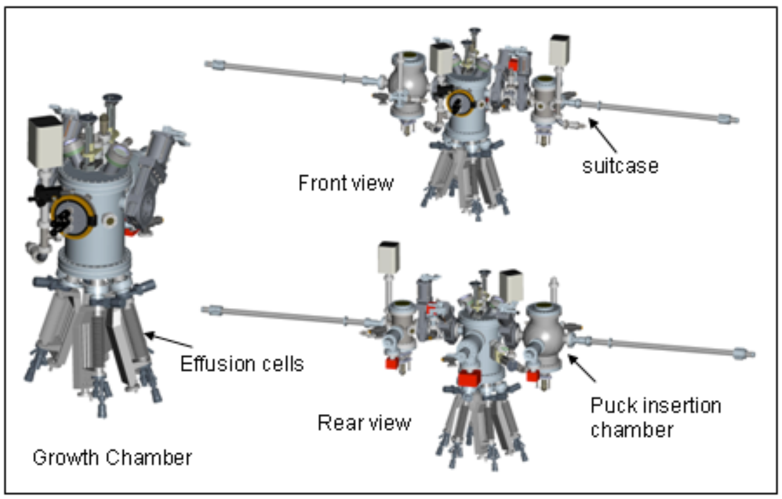

Figure 1, AES MBE based Growth Chamber and Transport Suitcase

Figure 2 shows the hardware at the Cornell facility. This is their first generation test facility. The AES facility is based on the general layout of this facility with industrialized components, for example effusion cells with self contained cooling that are used in the processing industry.

Figure 2, Cornell Growth Chamber, Storage Chamber and Transfer Suitcase

Figure 3 shows Cornell's second generation growth chamber on the left and effusion cells and Pnuematic actuator on the right. The pnuematic actuator is used to operate the shutters that cover the effusion cell when emission of that material needs to be stopped. This second generation system is used to implement engineering improvements such as a cooling jacket on the growth chamber to isolate the effects of the operating effusion cell.

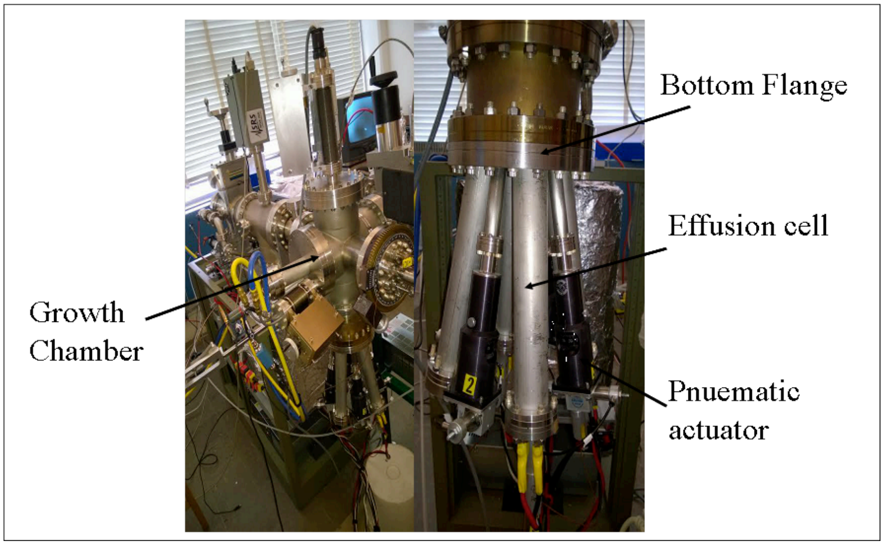

Figure 3, The growth chamber is shown on the left side, the right side shows the bottom flange hosting the effusion cells and the pneumatic actuators for the shutters, Cornell System.

On the left side of figure 4 are the view ports that are used to illuminate the cathode surface for QE measurements. On the right is the translator that moves the substrate heater assembly into place.

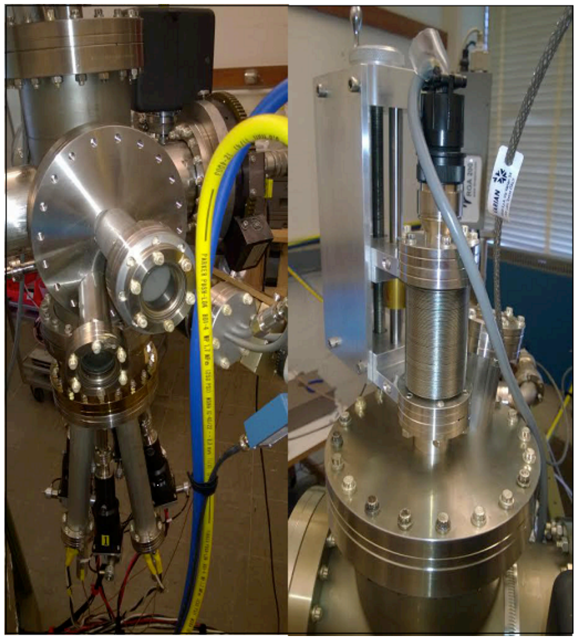

Figure 4, View ports to illuminate the cathode surface are placed on a side flange (left side) and translator hosting the substrate heater assembly on the top flange (right side), Cornell System

Figure 5 is a CAD layout of the internals of the growth chamber. The effusion cell alignment to the center of the substrate is shown. In this next generation chamber the translation of the substrate is horizontal. This is similar to the AES layout, which includes a storage chamber that holds multiple substrates.

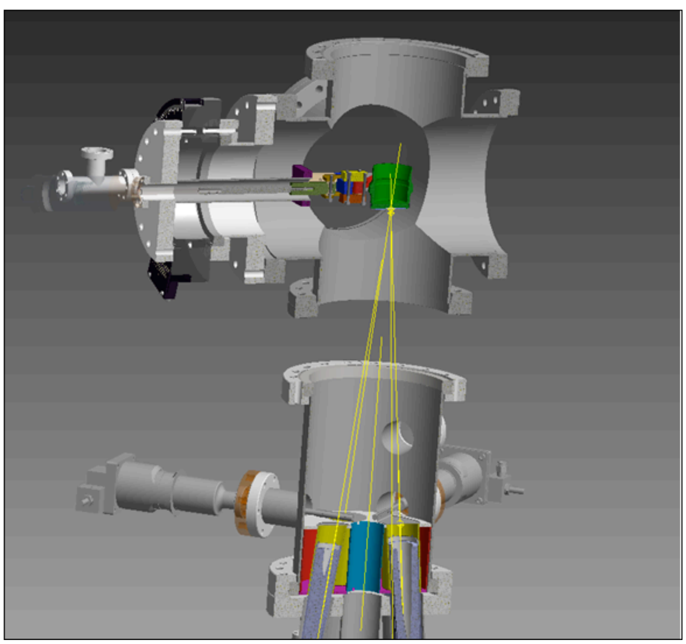

Figure 5, Internal Layout of Effusions Cells aligned to center of substrate

Phase I of this effort was an STTR with Cornell University. Cornell passed along their detail drawings and test results showing the success of the MBE type growth chamber. AES has taken this information and industrialized the effusion cells by designed the chamber with industrial effusion cells develped by Veeco. These cells have individual cool jackets and though more expensive than the research type cells that Cornell uses, are more robust and are expected to last longer. These cells also use shaped exit geometry which gives a more uniform distribution of metal on the substrate surface.

The next two figures show the results that Cornell has achieved using the hardware shown above. The results are for Cesium Potassium Antimonide and for Sodium Potassium Antimonide are shown In figures 6 and 7. Systematic characterization of the cathodes was performed. This included looking at 1/e lifetime for stored cathodes and 1/e lifetime for high current cathodes. This is in line with the expected operation of the Cornell ERL. The cathodes showed a storage 1/e life of 13 months. This enables the making cathodes ahead of their intended usage decreasing down time of the DC gun. For high current operation Cornell generated the active cathode surface off center to decrease the effects of ion back bombardment. Figure 6 shows tests of cesium potassium antimonide running at high current, 60 mA for 25 minutes with a projected 1/e lifetime of 30 minutes. Sodium potassium antimonide showed the ability to run current In the 60 mA range with a QE between 4% and 5% for multiple hours, figure 7 upper right. These two alkali antimonide photcathodes show very good and similar characteristics with the sodium potassium antimonide showing increased life.

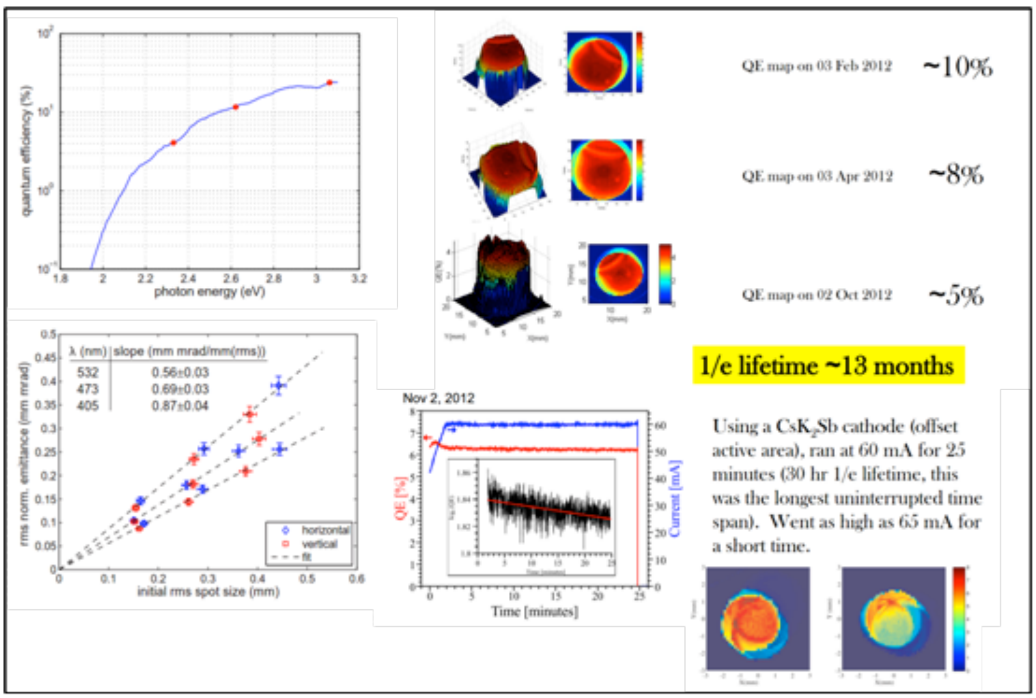

Figure 6, Cornell Grown CsK2Sb cathode tests

The standard electro-optics designation for the bi-alkali antimonide Na_2KSb photoemitter is S-24 [16]. It is currently utilized as a high temperature photosensitive component, operable up to 175°C, in modern photomultiplier tubes [17]. The chief advantage of the bi- and multi-alkali photoemitters over the mono-alkali type is both their increased sensitivity and the fact that they are responsive to the visible light.

The principal advantages of the Na_2KSb photoemitter based on Cornell measurements [7] are:

1) High QE associated with relatively low intrinsic emittance in the visible at ~530 nm, which is in the range of wavelengths generated by a frequency doubled solid state or Yb fiber based laser (see figure 1);
2) Demonstrated sub-ps response time (see figure 2);
3) High temperature stability due to the comparatively low volatility of K and Na compared to Cs, the Na_2KSb photoemitter retains its cohesiveness up to temperatures in excess of 150°C. This also implies an overall longer lifetime at room temperature where the alkali metals have small, but significant vapor pressures (see figure 3).
4) Demonstrated ruggedness in delivering extremely high average currents in Cornell photoinjector with a 1/e lifetime evaluated to be about 2.5 days at 65 mA average current. This photocurrent level represents the world record in terms of average current ever extracted from a photoinjector (see figure 4).
5) Flexible substrate: though principally grown on phototube faceplate compatible materials (e.g., glass, quartz, MgF_2, etc.), bi-alkali photocathodes have been successfully grown on other materials including stainless steel [18] and silicon [19]. The flexibility in the conformity of this polycrystalline photoemitter allows its use in virtually all of the currently employed photoinjectors.
6) Scalable size: The size of the photoemitter can be easily scaled down to minimize stray emission by masking during growth, i.e., partial coverage of the actual substrate.
7) Demonstrated ruggedness with respect to transport between different vacuum systems by means of suitable vacuum suitcases.
8)

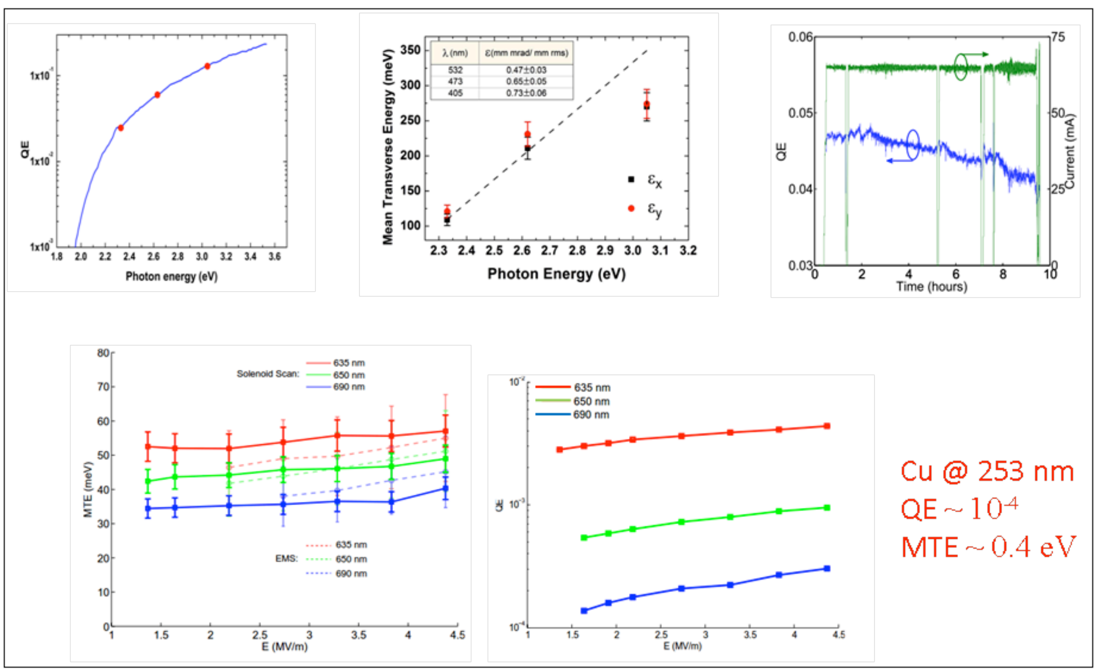

Figure 7, Cornell Grown Na2KSb Cathode Tests

Cornell has been looking at different metal sources for many years while exploring methods to grow cathodes. Figure 8, is a table of pros and cons that they have developd for different sources. Although pure metals are unstable in air Cornell has been able to use a simple inert gas purged glove box to transfer the metal to the effusion cell and to insert the effusion cell

Into the growth chamber. They have concluded that pure metals result in a better cathode. Figure 9 shows the glove box and loading of pure metals at Cornell.

	PROS	CONS
SAES	Air stable Stable flux	Few mg per charge High temperature
ALVATEC	Larger capacity than SAES	Air sensitive High temperature
AZIDES	Very high capacity Air stable	Flux unstable High nitrogen gas load
PURE METALS	Very high capacity No contamination	Air unstable High saturated pressure

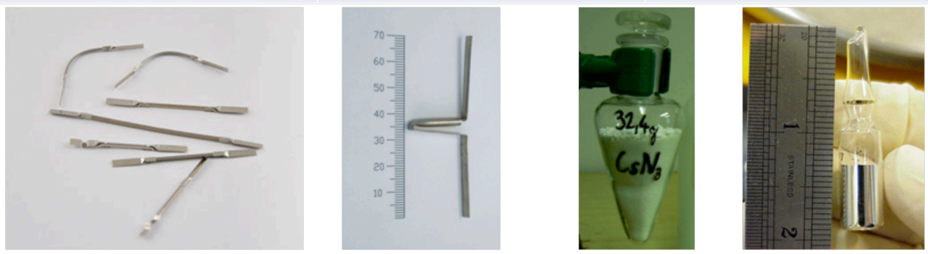

Figure 8, Comparison of Alkali Metal Sources

Figure 9, Loading of Pure Metals at the Cornell Facility

Cornell has developed two different growth procedures for these types of photocathodes over the last few years. A sequential procedure where the antimonide is grown, followed by potassium and either cesium or sodium as the final layer. The second procedure is a co-deposition procedure where the alkali metal, potassium, is grown with antimony then additional antimony is grown with cesium or sodium. The sequential method is simpler to perform but requires more material, the co-deposition method requires fine control of the fluxes. Cornell has not seen any dependency of QE on the method. AES will develop its control procedure based on the simpler sequential method.

Figure 10 shows the recipe for growing CsK2Sb on a puck. Cornell has shown good success growing the cathode material directly on a stainless steel puck. The surface where the cathode material is to be grown is polished to the nm range. Heavy oxides are removed in an acid bath. The puck is heated to 550ºC to 600ºC for at least 24 hours to outgas the surface. The puck is allowed to cool down and growth procedures begin during this cool down. When the puck temperature drops to 160ºC antimony is evaporated on the surface. A calibrated quartz microbalance thickness monitor is used to measure the growth of antimony to 20 nm this occurs when the puck is at about 140ºC. Then potassium evaporation is started and QE is measured. The light sources used for measuring the QE of the cathode are a small solid state laser emitting about 0.7 mW at 532 nm and a 200 W enhanced metal arc lamp coupled to a monochromator and silver plated concave mirror to illuminate the surface of the cathode with wavelength ranging from IR to UV. The light power is measured using a powermeter coupled with a UV enhanced Silicon photodetector. As the potassium is deposited the QE rises till it reaches a plateau. At this point potassium deposition is stopped. When the puck temperature reaches 100ºC, cesium evaporation begins. QE rises steadily and slowly and cesium evaporation is stopped when QE is steady, this occurs when the puck temperature is below 60ºC. The sodium potassium antimonide cathode

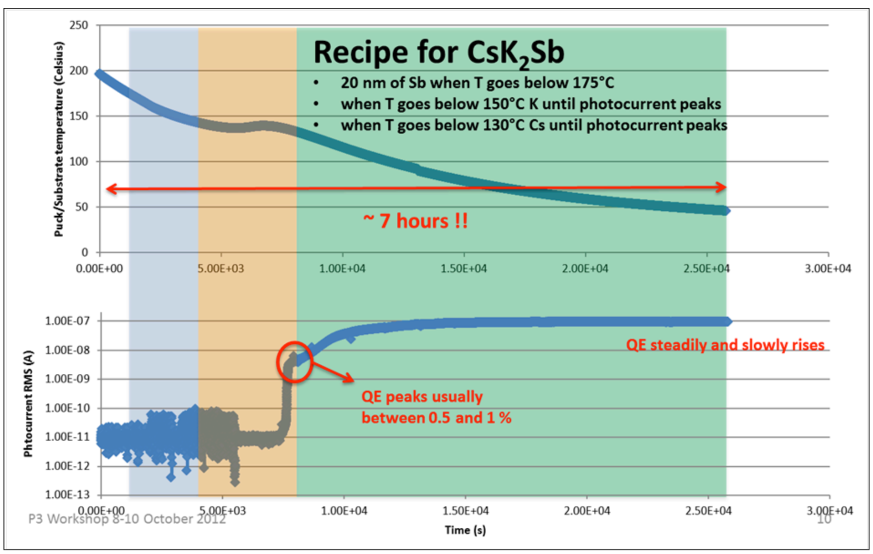

Figure 9, CsK2Sb Growth, Time and Temperature

The temperatures shown in the top of figure 10 are temperatures of the effusion cells and the puck temperature. The pure metal recipe for growing sodium potassium antimonide is different than for the cesium cathode. After baking of the puck it is cooled to near 100ºC. At this time the antimony cell is heated and antimony is evaporated. The quartz microbalance thickness monitor is used to measure the growth of antimony to 20 nm. At about 1.5 hours after the antimony cell is initially heated its growth is complete and the cell heater power is turned off and the shutter is moved to cover the cell. The potassium cell is heated and its shutter is opened evaporating potassium to the cathode surface. While potassium is growing on the cathode surface its QE is measured until QE reaches a plateau. At this point the potassium effusion cell heat is turned off and its shutter is closed and the sodium effusion cell heater is turned on and its shutter is opened. Similar to cesium potassium antimonide the sodium cell is left on until the QE becomes constant.

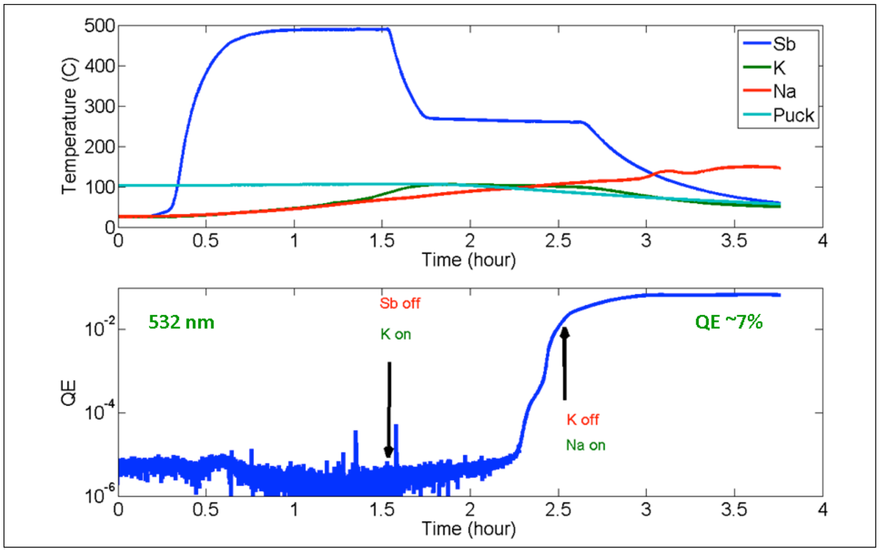

Figure 10, Pure metal source growth of NaKSb, Time and Temperature

It is clear that by measuring the thickness of antimony with a calibrated quartz microbalance thickness monitor and measuring QE to determine the optimal thickness of potassium and sodium (cesium) the system can easily be controlled by instrumentation and control software. Figure 11 shows the output screen for the first test of their computer controlled growth process. Here Cornell used temperature measurements and thickness measurements to grow the cathode. This method produced excellent QE of 2.5% (without Shottky Effect) as measured in the growth chamber.

Computer was programmed to analyze substrate temperature during the cooling And to perform Sb, K and Na deposition of predetermined thickness each within a predetermined range of temperatures

2.5% QE @ 532 nm were achieved

Figure 11, First Test Results Cornell

Figure 12 shows a schematic of the equipment needed for controlling the cathode growth process. The mechanical chopper breaks up the light source to a known frequency. Stray light entering the chamber can be subtracted from the photoemission measurements. This allows accurate determination of QE.

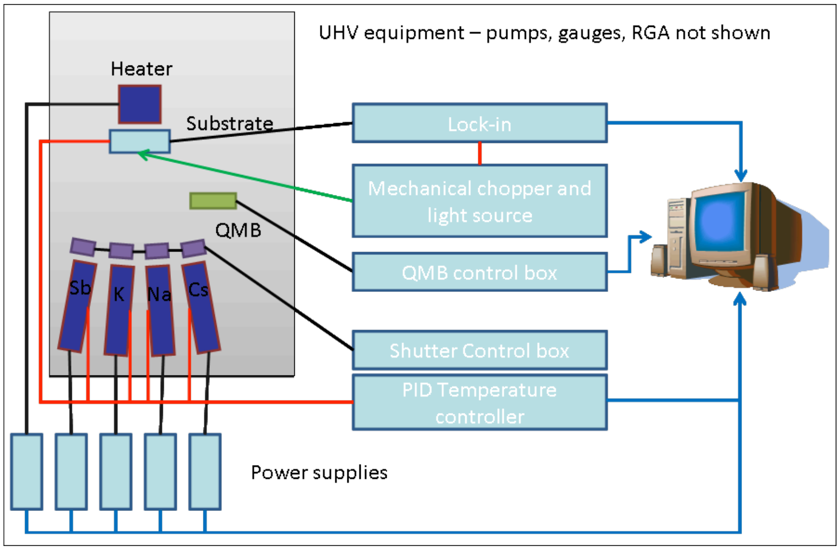

Figure 12, Schematic of simple control system for cathode growth

Cornell has provided AES through the phase I STTR with the requirements and general layout of the hardware required for Molecular Beam Epitaxy (MBE) growth of alkali antimonide photocathode material on a substrate. AES has developed an industrialized version of the growth chamber and transfer suitcase. Cornell has had success growing these cathodes on stainless steel as well as silicon substrates. A centralized photocathode facility producing reliable photocathodes will require a system that is operator independent by including a computer controlled growth process. By using industrialized effusion cells the throughput of the factory will increase by minimizing downtime. AES has full engineering capability and can offer customized pucks, substrates and transfer suitcases. The growth procedure was derived from those used for photomultiplier tubes. The computer control system will use the sequential growth method since it is simpler and results in excellent QE. The operator of the growth system will only be required to monitor the process to determine that it is performing as expected and that the instrumentation is working.

One of the main Phase I tasks for AES was to develop a cost for the growth hardware including the control system. The following table lists the hardware and cost based on sub-assemblies. The total cost before burden and contingency is $458,696.

Assembly	Quantity	Item	P/N	Item Cost	Total Cost
Assembly 1530-00010 contains:					***$458,696***
	1	Sub-Assembly	1530-00020	$231,274	$231,274
	1	Sub-Assembly	1530-00030	$61,467	$61,467
	1	Sub-Assembly	1530-00040	$13,864	$13,864
	1	Sub-Assembly	1530-00050	$42,656	$42,656
	1	Supporting Sub-Assemblies and Parts:		$81,000	$81,000
	1	Spare Parts:		$28,435	$28,435

Sub-Assembly 1530-00020 contains:					***$231,274***
	1	Sub-Assembly	1530-00060	$106,190	$106,190
	1	Sub-Assembly	1530-00070	$105,725	$105,725
	1	Sub-Assembly	1530-00080	$19,359	$19,359

Sub-Assembly 1530-00030 contains:					***$61,467***
	1	Sub-Assembly	8_IN_STORAGE_CHAMBER_AES_MOD	$5,000	$5,000
	1	Sub-Assembly	TURNTABLE-8INCH		$0
	1	Sub-Assembly	PRESS_PTATE_ASSEMBLY	$1,653	$1,653
	1	Part	MDC150008	$129	$129
	1	Sub-Assembly	TRANSLATOR_ASSEMBLY	$6,735	$6,735
	1	Sub-Assembly	VAT48236	$10,220	$10,220
	1	Sub-Assembly	CF_TEE_150-3	$125	$125
	1	Sub-Assembly	LESKER_L-0275	$90	$90
	1	Part	HPS_CCG	$1,463	$1,463
	1	Sub-Assembly	RGA_INFICON_ADAPT	$150	$150
	1	Part	INFICON_RGA - 200 amu	$17,865	$17,865
	1	Part	INFICON_ELECTRONICS	$0	$0
	1	Sub-Assembly	233847	$4,940	$4,940
	1	Part	NEXTORR_D_500-5	$12,097	$12,097
	1	Sub-Assembly	VARIAN951-5027	$1,000	$1,000
	3	Sub-Assembly	234_VIEWPORT		$0

Sub-Assembly 1530-00040 contains:					***$13,864***
	1	Sub-Assembly	6WAY_4_5_TO_2_75_REDUCING_CROSS	$1,385	$1,385
	2	Sub-Assembly	VARIAN951-5027	$1,000	$2,000
	1	Part	HPS_CCG	$1,463	$1,463
	1	Sub-Assembly	MDC_2-75_SHORT_NIPPLE	$75	$75
	1	Part	NEXTORR_D_200-5	$8,941	$8,941

Sub-Assembly 1530-00050 contains:					***$42,656***
	1	Sub-Assembly	1530-00121	$4,836	$4,836
	1	Sub-Assembly	TURNTABLE-10INCH		$0
	1	Part	MDC150041	$361	$361
	1	Part	MDC450006	$415	$415
	2	Part	MDC150008	$129	$258
	1	Sub-Assembly	TRANSLATOR_ASSEMBLY	$6,735	$6,735
	1	Sub-Assembly	233847	$4,940	$4,940
	1	Part	NEXTORR_D_500-5	$12,097	$12,097
	1	Sub-Assembly	MDC406002	$401	$401
	1	Part	HPS_CCG	$1,463	$1,463
	1	Sub-Assembly	RGA_INFICON_ADAPT	$150	$150
	1	Part	INFICON_RGA	$10,000	$10,000
	1	Sub-Assembly	VARIAN951-5027	$1,000	$1,000

Sub-Assembly 1530-00060 contains:					***$106,190***
	1	Sub-Assembly	1530-00101	$10,000	$10,000
	1	Part	RNN-400_FA_	$7,185	$7,185
	1	Sub-Assembly	1530-00090	$12,960	$12,960
	1	Sub-Assembly	LSM38-100-H	$2,567	$2,567
	1	Sub-Assembly	INFICON_MONITOR (Thickness)	$3,662	$3,662
	2	Sub-Assembly	VAT48236	$10,220	$20,440
	1	Sub-Assembly	VAT504936	$7,770	$7,770
	1	Part	NEXTORR_D_2000-10	$20,688	$20,688
	1	Sub-Assembly	VARIAN951-5027	$1,000	$1,000
	1	Sub-Assembly	CF_TEE_150-3	$125	$125
	1	Sub-Assembly	LESKER_L-0275	$90	$90
	1	Part	HPS_CCG	$1,463	$1,463
	1	Sub-Assembly	RGA_INFICON_ADAPT	$150	$150
	1	Part	INFICON_RGA	$17,865	$17,865
	1	Part	INFICON_ELECTRONICS	$0	$0
	1	Sub-Assembly	234_VIEWPORT	$225	$225

Sub-Assembly 1530-00070 contains:					***$105,725***
	1	Sub-Assembly	1530-00102	$5,000	$5,000
	5	Sub-Assembly	OME40_W_Z-SHIFT	$19,145	$95,725
	1	Sub-Assembly	laser with chopper and electronics	$5,000	$5,000

Sub-Assembly 1530-00080 contains:					***$19,359***
	1	Sub-Assembly	1530-00103	$4,000	$4,000
	2	Sub-Assembly	LESKER_SHUTTER	$1,060	$2,120
	2	Sub-Assembly	VIEWPORT	$695	$1,390
	2	Sub-Assembly	LSM38-100-H	$2,567	$5,134
	1	Sub-Assembly	CATHODE_HEATER	$5,000	$5,000
	1	Sub-Assembly	MASK_ASSEMBLY	$1,715	$1,715

Sub-Assembly 1530-00090 contains:					***$12,960***
	1	Sub-Assembly	GRIPPER_FLANGE	$600	$600
	1	Part	THERMOCOUPLE_FEEDTHROUGH_1_33CF	$290	$290
					$0
	2	Part	SBLM-133-1	$835	$1,670
	2	Part	THREADED_ACTUATOR	$200	$400
	1	Sub-Assembly	PUCK_HOLDER	$10,000	$10,000

Supporting Sub-Assemblies and Parts:					***$81,000***
	1	Sub-Assembly	ELECTRONICS RACK	$1,000	$1,000
	10	Part	POWER SUPPLY, EFFUSION CELL	$4,900	$49,000
					$0
	1	Part	CHILLER	$15,000	$15,000
	1	Part	WATER PLUMBING & VALVES	$5,000	$5,000
	1	Part	ELECTRICAL CONTROL CABLES	$3,000	$3,000
	1	Part	COMPUTER HARDWARE	$2,000	$2,000
	1	Part	COMPUTER SOFTWARE	$5,000	$5,000
	1	Part	VACUUM HARDWARE	$1,000	$1,000
	1	Part	HEATER BLANKETS/PARTS	$5,000	$5,000

Spare Parts:					***$28,435***
	1	Sub-Assembly	EFFUSION CELL	$16,950	$16,950
	1	Part	POWER SUPPLY, EFFUSION CELL	$4,900	$4,900
	3	Part	SUMO CRUCIBLES	$2,195	$6,585

Summary

The primary technical objective of the Phase I program was to identify all hardware and software required for a multi-alkali cathode factory. Then the costs were developed for the hardware and software and finally a layout of the factory within the AES facility was developed.

Cornell developed automated procedures and purchased control hardware and instrumentation to complete their automated growth system. This system minimizes operator influence during photocathode growth by implementing a series of software and hardware feedback loops on the process variables improving the reliability of the production cycle. Since AES is using industrial effusion cells with individual cooling jackets around each cell the hardware will have different thermal time constants than the hardware at Cornell. AES will develop the control software for the AES system and is planning to use Labview for the control software. The AES system is based on the hardware and instrumentation Cornell identified for their system.

Cornell has transferred all the necessary information to AES that is required for an automated multi-alkali cathode growth system. AES has developed a design and plan to implement this system at AES and test the results at BNL.

X. References

[1] P. Castro, Proceeding of LINAC 2000, (2000) 696
[2] R. Hajima, *Proceeding of APAC07*, (2007) 11
[3] J.L. Abelleira Fernandez and LHeC Study Group, *J. Phys. G: Nucl. Part. Phys*., **39** (2012) 075001.
[4] V.N. Litvinenko, Y.S. Derbenev, *Phys. Rev. Lett.*, **102**, (2009) 114801
[5] LEReC White Paper, Brookhaven National Lab, http://www.c-ad.bnl.gov/ardd/LEeC/LEReC_white_paper_080613.pdf
[6] C. Gulliford, A. Bartnik, I. Bazarov, L. Cultrera, J. Dobbins, B. Dunham, F. Gonzalez, S. Karkare, H. Lee, H. Li, Y. Li, X. Liu, J. Maxson, C. Nguyen, K. Smolenski, Z. Zhao, *Phys. Rev. ST Accel. Beams,* **16** (2013) 073401
[7] L. Cultrera, S. Karkare, B. Lillard, A. Bartnik, I. Bazarov, B. Dunham, W. Schaff, K. Smolenski, *Appl. Phys.Lett.,* **103** (2013) 103504
[8] L.Cultrera, Proceedings of the 2014 International Particle Accelerator Conference, Dresden, Germany, 48 (2014)
[9] D.H. Dowell et al. , *Nucl. Instr. Meth. Phys. Res. A*, **622**, (2010) 685
[10] W. E. Spicer, *Phys. Rev*., **112**, (1958) 114
[11] P. Musumeci et al., *Phys. Rev. Lett.*, **100**, (2008) 244801
[12] P. Davis et al., *Proceedings of PAC93*, (1993) 2976
[13] T. Nakajyo, et al., *Jpn. J. Appl. Phys.*, **42**, (2003) 1470
[14] E. Shefer et al., Nucl. Instr. and Meth. in Phys. Res. A, **411**, (1998) 383
[15] R. Mirzoyan et al., Nucl. Instr. and Meth. in Phys. Res. A, **567**, (2006) 230
[16] *RCA Electro-Optics Handbook,* 2nd ed., (RCA, Harrison, NJ, 1974), 153.
[17] *Hamamatsu PMT Handbook* ver. 2, Hamamatsu Corporation, Japan
[18] P. Michelato, A. Di Bona, C. Pagani, D. Sertore and S. Valeri, *Proceedings of the 1995 Particle Accelerator Conference,* Dallas, TX, 1049 (1996).
[19] L. Cultrera, I. V. Bazarov, J. V. Conway, B. Dunham, S. Karkare, Y, Li, X. Liu, J. M. Maxson, K. W. Smolenski, *Proceedings of the 2011 Particle Accelerator Conference,* New York, NY, 1942 (2012).
[20] R. E. Simon, A. H. Sommer and W. H. McCarroll, Radio Corporation of America, RCA Laboratories, *Research Study for Increasing the Sensitivity of Photoemitters,* U.S. Army Final Report **AD464792L** (1965).
[21] I.V. Bazarov, B.M. Dunham, Y. Li, X. Liu, D.G. Ouzounov, C.K. Sinclair, F. Hannon, T. Miyajima, *J. Appl. Phys.,* **103** (2008) 054901.

[22] I.V. Bazarov, B.M. Dunham, X. Liu, M. Virgo, A.M. Dabiran, F. Hannon, H. Sayed, *J. Appl. Phys,.* **105** (2009) 083715.
[23] I.V. Bazarov, D.G. Ouzounov, B.M. Dunham, S.A. Belomestnykh, Y. Li, X. Liu, R.E . Meller, J. Sikora, C.K. Sinclair, F.W. Wise, T. Miyajima, *Phys. Rev. ST Accel. Beams* **11** (2008) 040702.
[24] L. Cultrera, I. Bazarov, A. Bartnik, B. Dunham, S. Karkare, R. Merluzzi, M. Nichols, *Appl. Phys. Lett.* **99** (2011) 152110.
[25] I.V. Bazarov, L. Cultrera, A. Bartnik, B. Dunham, S. Karkare, Y. Li, X. Xianghong, J. Maxson, W. Roussel, *Appl. Phys. Lett.* **98** (2011) 224101.
[26] D.A. Orlov et al., *Appl. Phys. Lett.* **78** (2001) 2721
[27] L. Cultrera, private communications.
[28] L. Cultrera, M. Brown, S. Karkare, W. Schaff, I. Bazarov, B. Dunham, *J. Vacuum Sci. and Tech.* **32** (2014) 031211.
[29] N. Massegu, A. Konrath, J.M. Barois, P. Christol and E. Tournie, *Elect. Lett.* **44** (2008) 315.