Development of next generation rugged electron sources for low emittance, high quantum efficiency, and/or high average current applications

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Cathodes are essential components of present and future high energy physics (HEP) accelerator facilities such as the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) [1]. Likewise, photocathodes and electron guns are critical for radiation sources based on compact accelerators. They are widely used in medical imaging and national security applications, but the physics of the technology also figures prominently in detectors, communications, imaging, e-beam lithography / microscopy, and directed energy. A DOE HEP report [2] identifies near (1-5 years) and long (> 5 years) term needs for development of next generation cathodes/electron guns for compact accelerator applications in these areas.

Here, electron sources are core enabling technology for two state-of-the-art applications of electron accelerators: free electron lasers (FEL) and electron microscopes. A DOE report on the future of electron sources [3] identifies performance goals electron sources require to meet the needs for brighter X-ray sources with increased temporal resolution, higher energy, and electron microscopes with higher resolution. Advances in bright electron sources and research trends are reviewed by Musumeci *et al.* [4]. Emerging new material science, theory, and simulation methods to design photocathodes with specifically targeted emission properties are presented by Moody *et al.* [5]. All relate limitations to photocathode properties. The brightness of electron sources determines the peak photon energy of an FEL, the spatial resolution of an electron microscope and affects the endpoint luminosity of a collider. Other properties of electron sources - lifetime, operational vacuum requirement, peak and average current density and temporal response, are also critical for many applications.

Here, we discuss electron sources we have been developing at the Los Alamos National Laboratory (LANL) and the Brookhaven National Laboratory (BNL) with theoretical support from the Naval Research Laboratory (NRL) to address the current and future needs of HEP accelerator facilities. We also focus on important research problems that should advance the development of electron sources over the near and long term future to enable new HEP capabilities. LANL and BNL have extensive collaborations, especially in semiconductor photocathode technologies, and together possess a robust array of materials science capabilities, augmented by simulation models developed at NRL, all of which are required to enable progress.

In this LOI, we consider photocathodes and novel ideas apart from sources based on field emitters for dielectric wakefield, dielectric laser, and mm-wave accelerators. A separate LOI from members of the LANL electron source team focuses on these applications. Another LOI from LANL considers issues on modeling and simulations of electron sources and injectors. Furthermore, development of next generation cathodes is expected to benefit from applications of machine learning approaches. Members of the LANL team focus on ML methods in a separate LOI.

Positive electron affinity (PEA) semiconductor photocathodes in accelerators enable the production of the high brightness electron beams by combining high quantum efficiency (QE), low mean transverse energy (MTE), sub-ps response time, and relative longevity, but future needs require additional improvements and capabilities. The LANL/BNL collaboration focuses on alkali antimonide (AA) [6, 7] and cesium telluride (Cs_2Te) [8] cathodes, with the goal of surmounting performance limitations by using a theory-guided materials science approach. We have succeeded in growing large grain material (with macroscopic lateral grains) with well defined crystal orientation, thereby reducing performance robbing internal electron-electron scattering, and achieving QE in excess of 35% for AA and 50% for Cs_2Te. The spatial uniformity of these cathodes should significantly reduce MTE, especially at the high gradient operation required by FELs and many HEP applications. Necessary improvements, especially in regards to epitaxial growth, may result in better crystal structure and utilization of complex heterostructure growth (as in many III-V systems).

A separate BNL effort to optimize the surface structure of photocathodes succeeded in dramatically improving the uniformity (reducing the roughness by almost 2 orders of magnitude compared to traditional deposition), by creating AA films which are amorphous via sputtering. This is a potential pathway to creating photocathodes on complex structures, and therefore has application to many HEP detectors as well. In addition to optimizing the bulk structure of PEA photocathodes, LANL is involved in surface coatings of cathodes to improve their ruggedness, longevity and performance (MTE and QE), particularly by using hexagonal monolayers (BN, graphene) [9, 10, 11].

The temporal response of PEA cathodes is often adequate, but there are applications where sub-ps (xFEL's) and fs-scale beams (Ultrafast electron diffraction) are necessary. For this reason, the LANL/BNL collaboration is investigating methods of improving the QE of thin film cathodes using optical etalons - index matched substrates which produce optical standing waves within the cathode material. With these enhancements, it is expected that AA cathodes can reach sub 100 fs response time by brining photo-excitation nearer to the surface and shortening emission delay.

Some applications in HEP and elsewhere (for example radiography and electron cooling of hadrons) require high average currents - larger than the 100 mA that is typically achievable from a photocathode. One approach is to use Diamond as an electron amplifier [11, 12], but that relies on the formation of a stable negative electron affinity (NEA) surface with hydrogen termination. BNL and LANL are developing devices based on this approach to achieve A/cm2 average currents.

Many applications in HEP require polarized electrons (e.g., ILC and CLIC [1]). The traditional approach to generation of polarized electrons is the use of GaAs and its derivatives (strained superlattice, etc). While there has been progress on more robust surface coatings, no path for this technology to operate in a high gradient RF cavity is apparent. LANL and BNL are pursuing the demonstration of an emission spin filter, similar to the Ferromagnetic multilayers already used for spin polarized detectors, as such a device should be robust to high fields. While the transmission efficiency would likely be $\sim 1\%$, the coupling of this technology to the aforementioned diamond amplifier provides a technical pathway to robust polarized electron sources.

Finally, LANL/BNL/NRL are developing new and extended modeling and simulation methods and tools to investigate and design novel photocathode materials with engineered electron emission properties. The focus of the theoretical models and their implementation is on integration of different emission models and their utilization of computational results from more intensive methods [13] such as density functional theory, Monte Carlo and charged particle transport, quantum mechanical tunneling and electron emission physics methods [14]. Such hybridization is unavoidable to enable high fidelity modeling and simulations of complex material structures for electron source development and simulations of electron beams with complex structure in accelerator structures, where the needs of beam optics codes place a premium on rapidity of execution, but computational materials science methods are prohibitive to use there. Developing interrelated excitation / transport / emission components of the larger theory and simulation methods and tools has mainly been to understand and incorporate optical and scattering properties that govern emission probability of unpolarized electron beams, and to account for chemical and physical surface roughness that impact emission probability and intrinsic emittance [15]. The importance of generating polarized electron beams for future HEP facilities (e.g., ILC and CLIC), demands new codes for simulation of optical pumping of polarized electrons, charge and spin transport, and emission of spin-polarized electrons through heterostructure protective monolayer barriers that filter spin and energy distribution or enhance surface resistance to contamination or poisoning will become critically important over the near and mid term future. Such models will entail substantial modification and extension beyond traditional three-step models used in simulation, and will require a unification of quantum transport, thermal heating models, delayed emission models, emission barrier modeling for photo assisted field and field assisted photoemission, geometric modifications to emission site models and/or nanotube models, dark current models (typically thermal-field and secondary), and a quantification of their energy and velocity distributions that feed the launch models of beam optics codes.

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