Prospects for Future Electron Source Development (AF7: Targets and Sources)

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Photoemisison-based electron sources (photocathodes) play a key role in particle colliders, electron-based hadron coolers as well as ultrafast science instruments like X-ray Free Electron Lasers (XFELs) and Ultrafast Electron Scattering (UES) setups [1,2,3]. In general, low intrinsic emittance, high quantum efficiency (QE), quick response time and a long lifetime are important characteristics for photocathodes used for any application, however, depending on the application, some characteristics are more critical than others. For example, existing and planned particle colliders and electron based hardon coolers typically require large currents (in the range of a few to a few 100 mAs) to be extracted from the photocathode and hence have a very stringent requirement on the QE being greater than 1% in the visible range, but have only modest requirements in terms of the intrinsic emittance. A lower intrinsic emittance can still be beneficial as it enables novel, cheaper designs for future electron coolers and particle colliders. Ultrafast science instruments on the other hand will benefit enormously from the lowest possible intrinsic emittance, but do not necessarily require a very high QE. An order of magnitude improvement in intrinsic emittance is essential for development of compact XFELs and for extending the applicability of ultrafast electron diffraction techniques to large marco-molecular systems. All applications benefit from the cathode being robust to vacuum and operating conditions to enable continuous facility operations. A quick response time is essential to optimize the space charge dynamics during beam acceleration to minimize emittance degradation and to obtain the smallest possible temporal resolution in UES setups. Additionally, spin-polarized electron emission is another characteristic that is essential for colliders.

Very often these properties come at the cost of each other and hence optimizing for all of them simultaneously is impossible. For example, the intrinsic emittance can be minimized by reducing the incident photon wavelength close to the photoemission threshold, but that reduces the QE, often to unacceptably low values [1,4]. Another example is that of high QE cathodes (NEA-GaAs or alkali-antimonides) which are essential for colliders and electron coolers which required several mA of average beam current from the cathode. Even though these cathodes provide the necessary high QE in green light they are extremely sensitive to vacuum and operating conditions in the photoinjector and hence degrade rapidly when extracting large average currents [5]. Such negative correlations in the photocathode properties arise from the physics of photoemission and the chemistry of the surfaces of cathodes that are typically used as electron sources. Breaking these negative correlations may be possible via using engineered materials in which the electronic structure, optical properties and surface characteristics are designed to improve certain photoemission properties without sacrificing others.

With the goal of understanding the physical origins of the various photocathode properties and optimizing them, there has been an enormous ongoing effort within the accelerator community for more than a decade. The effort has resulted in two biennial workshop series: The Photocathode Physics for Photoinjectors (P3) [6] workshop series in the US and the European Workshop of Photocathodes for Particle Accelerator Applications (EWPAA) workshop series in Europe [7]. As a result of these efforts we now have a good understanding of the physical origins of the various photocathode properties and are in a good position to develop tailored photocathode materials specific to the required application [4].

One of the most prominent consequences of this photocathode effort is an increased collaboration between accelerator physicists and materials science experts, condensed matter physicists and chemists. In the recent years several such collaborations have emerged at various national labs and universities and have significantly aided cathode development. The most prominent of such collaborative efforts is the NSF funded Science and Technology Center for Bright Beams (CBB) [8].

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The photocathode related efforts within CBB have been mainly concentrated around investigating the various factors that result in increased intrinsic emittance and developing techniques to minimize it in realistic photoinjector conditions. Several factors like excess energy of the photon above the work function, temperature, physical and chemical roughness, electronic band structure, many-body scattering with phonons and other excitations and non-linear photoemission have been identified as factors that limit the intrinsic emittance. Upon minimizing the contributions of the various factors by an appropriate choice of a single crystal photocathode (the Cu(100) surface) with the right electronic band-structure and an atomically flat-ordered surface, CBB investigators recently demonstrated an order of magnitude reduced intrinsic emittance compared to that typically obtained in existing photoinjectors at 35 K temperature and near-threshold photon energy for single-electron-per-bunch pulses [9]. For higher charge densities the emittance is limited by non-linear photoemission effects of multi-photon emission and laser heating of electrons [10].

Efforts to extend these ultra-low emittance results to larger bunch charges are under way within CBB. These include developing single crystal, atomically flat, ordered surfaces of high QE alkali-antimonide materials, developing ordered work function reducing overlayers for III-V semiconductor cathodes and identifying single crystal materials with band-structures that confine the transverse momentum of emitted electrons to a small value.

In the last several decades enormous progress has been made in the field of materials science, condensed matter physics and photonics. Several of these advancements could be used to develop the next generation photocathodes. For example, topologically non-trivial materials like topological insulators, Dirac semi-metals etc have a very narrow dirac-cone like band structure which could be used to generate ultra-low-emittance electron beams [11]. Ordered thin films of complex oxides could be used as work function reducing layers to achieve negative electron affinity conditions resulting in high QE with a robust surface. Spin coupling in the band structure could be used effectively to generate polarized electrons [12]. Light guiding photonics-based structures could be used for on-chip laser-pulse-shaping and hence electron beam shaping [13]. Plasmonic structures on the surface could be used for effective light trapping and generating nano-patterns on the surface [14,15,16]. While there have been some isolated studies about using some of these advancements in photocathodes, most advancements remain largely untapped.

In summary, in this letter, we would like to emphasize the importance of continued collaborations between accelerator physicists and other materials related fields for effectively utilizing the advancements made in these fields for photocathode development and are critical for developing cathode technologies which optimize for multiple cathode metrics without significant trade-offs.

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