Dear Kwang-Je,

I have attached an annotated list of references having to do with the current state-of-the-art with various cathodes, primarily photocathodes, but also a bit on other types. As I indicated in my introduction, it is very important to specify the application and its requirements before selecting a cathode and gun type. There is no "one size fits all" solution, I'm afraid.

As for R&D, I think there are a great many questions that are presently unanswered. Perhaps the most fundamental is what is the maximum amount of charge one can put into a given 6-dimensional volume of phase space, given the limitations on the external fields that can be applied. I find it amusing that the various RF gun proponents now range from 700 MHz (Los Alamos/AES) to 17 GHz (MIT), all of them seeking the same answer! At least SLAC has abandoned the W-band work at ~ 90 GHz! A profitable area for progress in photoemission guns would be to develop reliable methods for generating the uniformly populated (transversely and longitudinally) optical pulses to generate uniform charge distributions from the cathode, for obtaining a minimum emittance.

I think that the business of measuring emittance needs some serious study, and perhaps the group could discuss this a bit, and arrive at consensus as to what is required to have a high quality measurement. I have alluded to this in what I wrote.

As for references to electron polarization, this is a pretty specialized community. Since 1983, there have been a number of polarized electron source workshops, held every other year in conjunction with the (now pretty large) Spin Physics Symposium. Since about 1997, these source workshops have been held in the "odd" years, in conjunction with the International Workshop on Polarized Beams and Polarized Targers. Actually, in my opinion, every year is much too often - there are simply so few people working in the field that there is not that much progress in any one year. But, these proceedings, which may be a little difficult to find, are far and away the best sources of information on polarized electron sources. The short answer is that at present, everyone uses GaAs and related semiconductor photocathodes in DC guns, so the technology is not very broad. Most of the current effort is dedicated to obtaining cathodes which deliver the highest polarization - which is now well above 80%, and rumored to be about 90% on the best cathodes out at SLAC. There has been one attempt to date at operating a GaAs photocathode in an RF gun, and it was disastrous. The cathode lasted less than an hour, and for only a very small number of RF pulses. So, there is lots of work to do in the area, but the present technology base is very small, and the number of people actually doing R&D in the area very few.

I'm sorry I will not be able to attend - I'm sure it will be a very interesting get together, that I would enjoy participating in. If there is any chance that there will be a written report, and/or a CD of the presentations and summaries, etc., I would very much appreciate receiving this.

I am away between tomorrow and the 15th of September, but will be in e-mail contact. If there are questions you have that I might help with, please let me know.

Best,

Charlie

Annotated List of References on Cathodes, Emission Processes, and Beam Measurements

Charles K. Sinclair – August 2003

There are relatively few questions to be asked regarding electron emitters. One needs to know what is required to achieve useful emission (e.g. temperature, illumination, field strength, etc.); how robust and practical the emitter is to fabricate and use; what the limitations on current, current density, and temporal response may be; what range of duty factors is practical; and possibly what the thermal emittance and/or electron polarization are. For accelerator applications, only thermionic emission and photoemission have been widely applied. It is difficult to generate useful, easily modulated, and reproducible currents by field emission, so that method has not yet seen significant application for the generation of accelerator beams. The realities of field emission are such that it is unlikely to form the basis for broadly useful electron sources for accelerators (see, for example V. V. Zhirnov et al., J. Vac. Sci. Technol. B 19, 87 (2001)). Similarly, ferroelectric emission, while able to generate relatively high charge, moderate duration current pulses, has not yet proven useful for many accelerator beam applications. Recently, hybrid emission modes, such as photoemission from a moderately heated thermionic emitter, are under study, and appear promising.

The references below provide information on photoemission and thermionic emission, as well as some information on various hybrid emission mechanisms. While all these mechanisms may be used to generate useful electron beams, their characteristics vary widely. It is essential to have a clearly stated set of requirements for any particular application before one can intelligently discuss the “best” choice for an electron emitter and the means to apply the required electric field to it. The electron source for a SASE FEL based on a room temperature linac will look very different from that for an ERL light source using a CW superconducting linac, for example. Proposed linear colliders and electron-ion colliders require polarized electron beams, which significantly restrict the choices for an electron source.

All high quantum efficiency photocathodes are direct bandgap, p-type, semiconductors, and to date all belong to one of three families – the alkali antimonides (e.g. Cs_3Sb, K_2CsSb, etc.), the alkali tellurides (e.g. Cs_2Te, KCsTe, etc.), and a number of bulk III-V semiconductors with a surface dipole layer formed by Cs and an oxidant like O or F. The first two families have positive electron affinity (PEA), in contrast to the bulk semiconductors, which show NEA. To date, the alkali antimonide and telluride cathodes have been applied only in RF guns, while the NEA cathodes have been operated only in DC guns.

The spectral responses of the three families are different. The alkali antimonide cathodes function primarily in the visible, the alkali tellurides in the UV and near

UV, and the bulk semiconductors in the visible through near IR. Quantum efficiencies of 20% or greater have been prepared on members of all three families at their optimum wavelengths. It should be noted that practical laser sources must generally be optical frequency doubled, tripled, or quadrupuled for use with the antimonide and telluride cathodes, though not for the bulk semiconductor cathodes.

The “standard” reference on photoemission cathodes is the book Photoemissive Materials by A. H. Sommer, Robert E. Krieger Publishing Company, Huntington, New York, 1980. This book is a reprint, with a new preface and updated references, of the original book published by John Wiley & Sons in 1968. The book has an inadequate treatment of negative electron affinity (NEA) photocathodes, which were initially developed in the late 1960s, but is otherwise a thorough discussion of photocathodes. More recent advances are covered in the review article by H. Timan, Advances in Electronics and Electron Devices, v. 63, Academic Press, 1985, p. 73.

High quantum efficiency alkali antimonide and alkali telluride photocathodes developed for accelerator applications are described in: A. di Bona et al, Nucl. Instr. Meth. A 385, 385 (1997); S. H. Kong et al., J. Appl. Phys. 77, 6031 (1995); D. Bisero et al., Appl. Phys. Lett. 69, 3641 (1996); and D. Bisero et al., Appl. Phys. Lett. 70, 1491 (1997). The performance of alkali telluride cathodes in an RF gun is presented in E. Chevallay et al. Proceedings of the XX Linac Conference, Monterey, CA., 2000, paper MOB08. Finally, large scale production of alkali antimonide and telluride photocathodes is described in A. Braem et al., Nucl. Instr. Meth. A 502, 205 (2003).

An excellent, though somewhat dated, review of NEA photocathodes is the article NEA Semiconductor Photoemitters, by John S. Escher, in Semiconductors and Semimetals, v. 15, Willardson and Beer, eds., Academic Press, New York, 1981, p. 195.

An early, but still widely used reference on NEA photocathodes is the book Negative Electron Affinity Devices, by R. L. Bell, Clarendon Press, Oxford, 1973. It should be noted that the temporal response calculated in Appendix A of this book is much slower than has been subsequently measured. Also, much of the information on materials technology is outdated. However, the underlying physics of NEA photocathodes is well covered in this book.

It is important to note that to date all practical sources of polarized electrons, such as required for linear colliders and research electron accelerators, are NEA semiconductors.

In PEA photoemittters, the conduction band minimum lies below the external vacuum level, making emission from the bottom of the conduction band energetically impossible. With NEA photoemitters, the conduction band minimum lies above the external vacuum level, and electrons that have thermalized at the conduction band minimum may be emitted. This leads to the potential for a very low thermal emittance from NEA photoemitters.

While in many applications the thermal emittance of the electron source is inconsequential, being dwarfed by the effects of space charge, time varying fields, etc., in some cases the thermal emittance may be a large contribution to the total. In these cases, the NEA photocathodes are particularly attractive. The thermal emittance may be characterized by an effective transverse energy. This has been measured for NEA GaAs at room temperature to be as low as 35 meV (B. M. Dunham et al., Proceedings of the 1995 Particle Accelerator Conference, Dallas, TX, IEEE, Piscataway, NJ, p. 1030). Note that room temperature is equivalent to ~ 25 meV.

In principle, by cooling a NEA GaAs cathode, the effective thermal energy and the emittance could be lowered further. This has been pursued by the Terekhov group at Novosibirsk, as part of an effort to generate a very cold electron beam for cooling ion beams. This group has measured the mean transverse energy from GaAs photocathodes at low temperature directly by a novel method (S. Pastuszka et al., Appl. Phys. Lett. 71, 2967 (1997); S. Pastuszka et al., J. Appl. Phys. 88, 6788 (2000); and D. A. Orlov et al., Appl. Phys. Lett. 78, 2721 (2001)). Very recently, this group has observed the emission of ballistic electrons with a mean transverse energy below 1 meV from a GaAs photocathode (V. V. Bakin et al., JETP Lett. 77, 167 (2003)). This result may provide a path for the production exceptionally bright electron beams.

All high quantum efficiency photocathodes are chemically reactive, and thus very sensitive to the vacuum conditions in which they operate. Very low partial pressures of chemically active gases, such as H_2O and CO_2, quickly poison these cathodes. Attempts to protect these cathodes from reactive gases with protective coatings have had limited success, and involve a significant penalty in quantum efficiency, as described in A. Breskin et al., Appl. Phys. Lett. 69, 1008 (1996).

Chemically harmless gases such as H_2 and CH_4 are ionized by the emitted electrons and may damage the cathode by ion back bombardment. Ultrahigh and extreme high vacuum technology is required to successfully utilize these cathodes. Since the PEA alkali antimonide and telluride cathodes are stoichiometric compounds, while the NEA III-V semiconductor cathodes are bulk materials activated to be photoemitters with a single atomic layer surface dipole, the nature of ion back bombardment damage may differ between PEA and NEA cathodes.

It is calculated that photocathodes in RF guns should not be susceptible to damage from ion backbombardment (J. Lewellen, Phys. Rev. ST-AB 5, 020101 (2002)). Photocathodes in DC electron guns show clear signs of ion back bombardment damage (C. K. Sinclair, in Proceedings of the 1999 Particle Accelerator Conference, New York, IEEE, Piscataway, NJ, 1999, p. 65). On the other hand, while secondary electrons cannot be a problem for cathodes in a DC gun, photocathodes in RF guns may be subject to damage from secondary electron bombardment.

The demanding vacuum requirements of high quantum efficiency photocathodes have led people to choose metal photocathodes in those cases where they can be used. Metal cathodes require illumination in the UV, and have low quantum efficiencies, typically no greater than 10^{-4}. For low duty factor operation, relatively low repetition rate UV optical pulses can be provided by frequency quadrupuled Nd lasers or frequency tripled Ti:sapphire lasers. Often, normal conducting RF guns simply use the copper wall of the RF structure as the photocathode. It has been observed that illumination by UV radiation can "clean" a metal surface, enhancing its quantum efficiency. A review of the cleaning and performance of metal photoemission cathodes is given in: T. Srinivasan-Rao et al., J. Appl. Phys. 69, 3291 (1991). To date, magnesium has shown the highest quantum efficiency, as reported in T. Srinivasan-Rao et al., Proceedings of the 1997 Particle Accelerator Conference, Vancouver, 1997, IEEE, Piscataway, NJ, p. 2790. It should be noted that magnesium is not suitable for RF cavity walls, so a magnesium cathode must be separately inserted into the RF cavity wall.

All simulations of photoemission electron sources show that the smallest final emittance is obtained when the bunch has a uniform charge density both transversely and longitudinally – a uniformly populated "beer can" of charge. Producing such a bunch requires a similar pulse of photons. The lasers used typically generate near-Gaussian (or worse) transverse and longitudinal profiles. These distributions are altered when optical harmonic generation is used. There is a substantial literature on the techniques to produce uniform transverse and longitudinal optical beam profiles. For example: Laser Beam Shaping: Theory and Techniques, by F. M. Dickey and S. C. Holswade, Marcel Dekker Inc., New York; F. M. Dickey and S. C. Holswade, Opt. Eng. 35, 3285 (1996); J. A. Hoffnagle and C. M. Jefferson, Appl. Opt. 39, 5488 (2000); M. A. Dugan et al., J. Opt. Soc. Am. B 14, 2348 (1997); and A. M. Weiner et al., J. Opt. Soc. Am. B 5, 1563 (1988). Unfortunately, the techniques for longitudinal pulse shaping are frequently directed toward making pulses shorter than desirable for photoemission electron sources. The generation of optical pulses or pulse trains with transverse and longitudinal profiles suited to the production of the lowest emittance electron beams is an important R&D topic.

Recent examples of the reductions in transverse emittance produced by improving the spatial or temporal laser beam profiles are given in: H. Tomizawa et al., Proceedings of the 2002 European Particle Accelerator Conference, p. 1819; and J. Yang et al., J. Appl. Phys. 92, 1608 (2002). The importance of uniform cathode emission (involving both a uniform laser profile and uniform quantum efficiency) to achieving minimum transverse emittance has been measured by F. Zhou et al., Phys. Rev. ST-AB 5, 094203 (2002).

The temporal response of photocathodes may be an important consideration. The alkali antimonide and telluride cathodes have an optical absorption roughly a factor of twenty higher than that of the III-V semiconductors. Thus, photoexcited electrons in the alkali cathodes have a much shorter distance to diffuse to reach the cathode surface, and the temporal response is correspondingly shorter. These cathodes can deliver pulses shorter than a few picoseconds. The III-V semiconductors, on the other hand, deliver longer pulses. The temporal response of GaAs photocathodes has been measured to be less than 40 psec by A. Aleksandrov et al., Phys. Rev. E 51, 1449 (1995), A. V. Aleksandrov et al., Proceedings of the 1996 European Particle Accelerator Conference, p. 1535. Shorter duration pulses have been produced from III-V semiconductors by using a thin active layer, although this reduces the quantum efficiency by reducing the optical absorption.

Thermionic emitters are a well-developed and well-understood technology. The thermal emittance of a beam from a thermionic emitter can be comparable to that of a beam from PEA photoemitters, since the latter have fairly large effective transverse energies. To obtain a high current density, it is necessary to operate a thermionic emitter at very high temperatures. If a grid is employed to control the emission, the emittance may be significantly enlarged. For this reason, several recent thermionic gun designs control the emission by pulsing the high voltage on the gun, eliminating the control grid. The best examples of these guns are the 550 kV gun developed by Haimson Research Corporation (J. Haimson et al., Proceedings of the 1997 Particle Accelerator Conference, Vancouver, 1997, IEEE, Piscataway, NJ, p. 2808), which uses a conventional dispenser cathode, and a 500 kV gun with a CeB_6 cathode under development for the Spring-8 Compact SASE Source (T. Shintake et al., Proceedings of the 24th ICFA Beam Dynamics Workshop on Future Light Sources, Hyogo, Japan, 2002). The Haimson gun, presently operational, is designed to deliver a 1 A beam with a normalized emittance below 3 mm-mrad, while the SCSS gun is planned to deliver a 3 A beam with a final normalized emittance, after chopping, acceleration, and several stages of bunch compression, of 2 mm-mrad. These two guns operate at low repetition rates, and likely represent very close to the ultimate performance that can be achieved with thermionic gun technology.

A number of attempts have been made to obtain improved beam quality by employing "hybrid" emission, where more than one emission mechanism is involved. Generally, these attempts have used photoemission from thermionic, field, or ferroelectric emitters, to gain the advantage of producing short pulses. The University of Maryland group has done considerable work to model these situations (K. Jensen et al., Appl. Phys. Lett. 81, 3867 (2002); K. L. Jensen et al., Nucl. Instr. Meth. A 507, 238 (2003)). Recently, they have observed enhanced photoemission from a heated thermionic emitter, with characteristics consistent with their model (K. L. Jensen et al., accepted for publication in Appl. Phys. Lett., and K. L. Jensen et al., accepted for publication in Phys. Rev. ST-AB). Results from photoelectric field emission do not appear quite so promising, as the laser intensities are both very high and close to the damage threshold of the cathodes to obtain even modest beam currents (C. Hernandez Garcia and C. A Brau, Nucl. Instr. Meth. A 475, 559 (2001)). Photoemission from ferroelectric cathodes has also been demonstrated (I. Boscolo et al., Proceedings of the 1999 Particle Accelerator Conference, New York, 1999, IEEE, Piscataway, NJ, p. 1985).

Considerable care must be taken to obtain high quality transverse emittance measurements from high brightness electron sources. For example, it was recently pointed out (S. G. Anderson et al., Phys. Rev. ST-AB 5, 014201 (2002)) that the commonly used quadrupole scan method of emittance measurement often gives a result in disagreement with both multislit-based emittance measurements and PARMELA simulations, due to the effects of space charge. This paper predicts that the quadrupole scan method consistently gives emittance results larger than those measured by the multislit method. However, emittance measurements made at the TTF Photoinjector, using both the multislit and quadrupole scan methods, find that the multislit emittance measurements are consistently larger than the quadrupole scan measurements (Ph. Piot et al., Proceedings of the 2001 Particle Accelerator Conference, Chicago, 2001; IEEE, Piscataway, NJ, p. 86), in direct contradiction to the above paper. Clearly work remains in this area.

Measurement of thermal emittance also needs to be done with care. Dunham at al. (op. cit.) measured the thermal emittance of a NEA GaAs photocathode from a 100 kV DC gun as a function of illuminated spot size on the cathode, illuminating wavelength, and beam current. From this they were able to determine the effective transverse energy as a function of wavelength. The effective transverse energy from NEA GaAs cathodes has been directly measured by D. A. Orlov et al. (op. cit.), using a dedicated low energy apparatus. Comparable measurements of the thermal emittance of alkali antimonide and telluride photocathodes has not been reported.