High current field emission electron sources for linear colliders and RF source applications

E.I. Simakov, H.L. Andrews, C.K. Huang, D. Kim, T.J.T. Kwan, J.W. Lewellen, K. Nichols, V. Pavlenko
Los Alamos National Laboratory, Los Alamos, NM
J. Shao, J. Power
Argonne National Laboratory, Lemont, IL
C. Jing, S. Antipov
Euclid Techlabs, Bolingbrook, IL
S.M. Lewis, E.A. Nanni
SLAC National Accelerator Laboratory, Menlo Park, CA

In this Letter-of-interest (LOI) we discuss technology needs for electron sources for various advance acceleration concepts and novel microwave sources for the future linear collider and solutions for these needs that we developed at Los Alamos National Laboratory (LANL).

The brightness of an electron source determines the eventual brightness of an electron beam at the output of an electron linear collider, an electron-hardron linear collider, at the wiggler of a X-ray free electron laser, and for other accelerator applications. A large program on development of high quantum efficiency (QE) in the visible range and low mean transverse energy (MTE) cathode is on-going at LANL, and a separate LOI is being submitted by members of the LANL photocathode team.

This LOI focuses on LANL's recently developed capabilities for fabrication and characterization of the diamond field emission array (DFEA) cathodes, and DFEA's applications relevant to HEP. Shown in Fig. 1, DFEAs represent arrays of micron-scale nano-diamond pyramids with sharp nanometer scale tips. They are formed using a mold-transfer process, in which nano-diamond is deposited into sharpened silicon molds using a microwave power-assisted chemical vapour deposition (MPCVD) process [1,2]. Because this technique uses standard silicon wafer processes to pattern the array, DFEAs can be formed with a very wide range of base lengths and pitches. DFEAs are robust to exposure to air, emit in both poor and good vacuum conditions, and can be conditioned to emit uniformly over the whole array. Because the tips are diamond, they are chemically inert and have excellent thermal properties; they can sustain high per-tip emission current without catastrophic failure modes.

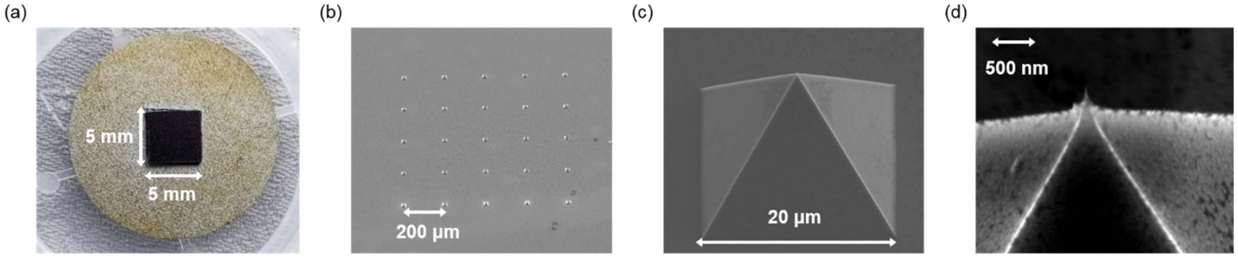

FIG. 1. (a) A polished molybdenum substrate with brazed diamond cathode. (b) Scanning electron microscope (SEM) images of a 5x5 array with a 200 µm spacing and (c) a single pyramid of a 20 µm base. (d) Exquisitely sharp tip on the top of the pyramid.

The first application for DFEAs that we envision are the nano-tip cathodes for dielectric laser accelerators (DLAs) [3]. DLAs accelerate particles in microstructures using energy from an ultra-fast infrared laser. This approach takes advantage of rapid developments in solid-state laser industry that now delivers high repetition rate high pulse energy infrared lasers producing GV/m intense electric fields at a very low cost. Field emission needle cathodes are sought after for DLAs due to their nanometer-size tips that provide high-current density high-brightness electron beams that are naturally suitable for the channels of DLAs with their sub-micrometer dimensions. Needle cathodes produce ultra-short electron beams through a process of the laser-induced field emission when excited by very short femtosecond laser pulses [4]. At Los Alamos we demonstrated generation of ultra-short electron beams produced from diamond tipped pyramids with femtosecond laser pulses at a wavelength of 1035 nm. To facilitate our understanding of the experiments we developed simulations that study beam transport (including quantum effects), and beam formation and emission at the nanoscale tip [5]. The details of our studies of the beam transport properties in nanotip cathodes are a subject of a separate LOI.

As a second application, we proposed to employ DFEAs as field-emission electron beam sources in radio-frequency (RF) guns, in particular for production of shaped electron beams to be used as drive bunches in dielectric-wakefield accelerators (DWAs) [6]. We fabricated triangular arrays of diamond pyramids and, with a team at Argonne Wakefield Accelerator, demonstrated production of a high current density triangular-shaped electron bunch through field emission in a high gradient 1.3 GHz electron gun [7]. We further demonstrated that the shaped electron beam could be transported along the beamline to the entrance of an emittance exchanger (EEX) that is designed to convert the transversely shaped electron beam into a longitudinally-shaped electron beam to achieve high transformer ratios in dielectric wakefield accelerators. In collaboration with SLAC National Accelerator Laboratory we also proposed to employ single diamond tips in a field-emission W-band electron gun that is designed to operate with up to 1 GV/m accelerating gradients [8]. The development of a high-gradient high-brightness THz electron gun is motivated by the need to reduce footprint and increase brightness of the future electron colliders and other HEP applications.

Finally, we have demonstrated current densities in excess of 1 A/mm^2 in dense arrays of diamond pyramids. These high current density cathodes may be employed in high power microwave sources for the future linear collider. The high power microwave sources (klystrons) that produce MWs of power require cathodes capable of delivering electron beam currents in hundreds of Amperes range. At LANL we put together a design of a novel 50 MW C-band multi-beam klystron with 8 cathodes producing the total current of 400 A at 50 A per cathode. Beam dynamics simulations show that the current density of 5 A/cm^2 is required for operation of such klystron [9]. That can be easily achieved in a DFEA cathode operating in a field emission regime instead of using a tungsten cathode that operates in a thermal emission regime at a very high temperature. If current density at the cathode could be increased to 20 A/cm^2, subsequently reducing the area of each cathode, the mode separation in the klystron would be reduced significantly, thus resulting in less mode competition, and higher power generation in a klystron.

[1] J.D. Jarvis, H.L. Andrews, C. a. Brau, B.K. Choi, J. Davidson, W.-P. Kang, Y.-M. Wong, J. Vac. Sci. Technol. B Microelectron. Nanom. Struct. 27, 2264 (2009).

[2] D. Kim, H.L. Andrews, B.K. Choi, and E.I. Simakov, in Proceedings of the 18th Advanced Accelerator Concepts Workshop AAC2018, Breckenridge, CO, USA, 2018.

[3] E.I. Simakov, H.L. Andrews, M.J. Herman, K.M. Hubbard, and E. Weis, AIP Conf. Proc. 1812, 060010 (2017).

[4] E.I. Simakov, H.L. Andrews, R. L. Fleming, D. Kim, V. Pavlenko, D. S. Black, K. J. Leedle, Proceedings of the 10th International Particle Accelerator Conference (IPAC19), 19-24 May, 2019, p. TUPTS089.

[5] C.-K. Huang, H.L. Andrews, R.C. Baker, R.L. Fleming, D. Kim, T.J.T. Kwan, A. Piryatinski, V. Pavlenko, and E.I. Simakov, Journal of Applied Physics 125, 164501 (2019).

[6] K. E. Nichols, H. L. Andrews, D. Kim, E. I. Simakov, M. Conde, D. S. Doran, G. Ha, W. Liu, J. F. Power, J. Shao, C. Whiteford, E. E. Wisniewski, S. P. Antipov, and G. Chen, Applied Physics Letters 116,023502 (2020).

[7] Heather Andrews, Kimberley Nichols, Dongsung Kim, Evgenya Simakov, Sergey Antipov, Gongxiaohui Chen, Manoel Conde, Darrel Doran, Gwanghui Ha, Wanming Liu, John Power, Jiahang Shao, Eric Wisniewski, IEEE Transactions on Plasma Science 48(7), 2671 (2020).

[8] S. M. Lewis, V. Dolgashev, A. Haase, E. A. Nanni, M. Othman, A. Sy, S. Tantawi, D. Kim, E. Simakov, Proceedings of the 10th International Particle Accelerator Conference (IPAC19), 19-24 May, 2019, p. TUPTS077.

[9] Song, H., Le, A., Kirshner, M., “50 MW C-Band Multiple Beam Klystron (MBK) for High Gradient Accelerators”, Los Alamos National Laboratory Report LA-UR-19-2771, 2019-08-02.