OPERATION OF A DIAMOND FIELD-EMISSION-ARRAY CATHODE IN A L-BAND RF GUN

P. Piot[1,2], B. Blomberg[1], C.A. Brau[3], B. K. Choi[4], W. Gabella[3], B. Ivanov[3], J. D. Jarvis[5], M. Mendenhall[3], D. Mihalcea[1], H. Panuganti[1]
[1] Department of Physics and Northern Illinois Center for Accelerator & Detector Development, Northern Illinois University DeKalb, IL 60115, USA
[2] Accelerator Physics Center, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[3] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, USA
[4] Department of Electrical Engineering and Computer Science, Vanderbilt University, and Vanderbilt Institute of Nanoscale Science and Engineering, Vanderbilt University,
[5] Advanced Energy Systems Inc., Medford, NY 11763, USA.

Abstract

We report on the operation of a field-emission diamond cathode in a L-band RF-gun (1.3 GHz) at Fermilab's HBESL facility. The diamond cathode consists of an array of a million sub-micrometric pyramidal diamond tips.Beam currents in excess of 10 mA were observed and the cathode did not show appreciable signs of degradation after days of operation. Measured Fowler-Nordheim characteristics and transverse beam densities are also reported.

INTRODUCTION

Over the past years, field-emission (FE) electron sources have been the subject of intense researches due to several advantages they offer over photoemission and thermionic sources. The main advantages of FE sources stem from their ability to produce very low-emittance bunched beams, their capability to generate high-average current beams, and the absence of requirement for an auxiliary laser system. A single-tip FE emits electrons from a very small transverse area and can therefore produce beams with extremely small, quantum-degenerate, transverse emittances [1, 2]. When arranged as large arrays, field-emission-array (FEA) cathodes can provide substantial average currents [3] to the detriment of emittance which then scales linearly with the FEA macroscopic radius [4, 5].

Pulsed field-emission occurs when a FE cathode experiences a time-dependent field, e.g., when located in a resonant radiofrequency (RF) cavity and the root-mean-square (rms) duration of the bunch is $\sigma_t \simeq \omega^{-1}[\beta_e E_0/B(\phi)]^{-1/2}$ where $\omega \equiv 2\pi f$ where E_0 and f refer to the field amplitude and frequency. The latter pulse duration is obtained by taking the current density, $B(\phi)$ is a function of the workfunction ϕ associated to the cathode material and β_e is a field-enhancement factor [6, 7]. Nominally, the bunch rms duration is a significant fraction of the RF field period typically resulting in beams with large energy spread. This limitation can however be circumvented by exposing the FE cathode to superimposed electromagnetic fields [8].

In this paper we report on the first operation of a diamond FEA (DFEA) cathode in a conventional L-band RF gun nominally operated with a Cesium Telluride (Cs_2Te) photocathode. The DFEA is composed of ungated diamond pyramids which have proven to be rugged. Depending on the size and pitch of the pyramids, tests under DC voltages have showed field emission to begin at macroscopic fields $E_0 \simeq 5$ MV/m, and current density as high as 30 A.m^{-2} has been obtained [9].

EXPERIMENTAL SETUP

The geometry of the DFEA cathode used for the experiment reported below appears in Fig. 1(a,b). It consists of an array of $\sim 1000 \times 1000$ pyramidal diamond tips with their extremities separated by ~ 10 μm. The typical pyramid base is ~ 4 μm and the radius of curvature of the tip is on the order of 10 nm. Electrostatic simulations performed with the finite-difference element program POISSON [10], indicate that local fields in excess of ~ 0.9 GV/m are achieved at the tip when subjected to a macroscopic field $E_0 = 30$ MV/m (corresponding to $\beta_e \sim 30$).

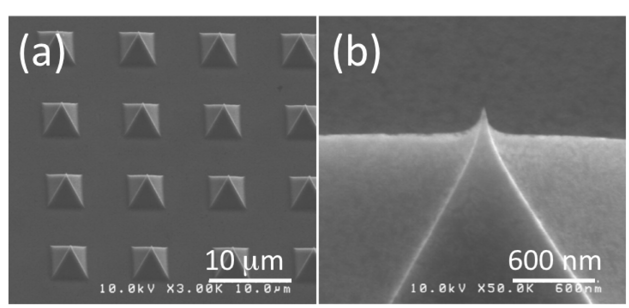

Figure 1: Electron-microscope photographs of the DFEA pattern (a) and close up of one pyramidal tip (b).

The cathode pattern was formed using a mold-transfer process whereby chemical vapor deposited (CVD) diamond is grown in sharpened silicon molds [11]. Using various techniques, DFEAs can be produced with single, double, or quadtip emitters. A variety of growth recipes

ISBN 978-3-95450-138-0

are used to achieve a desired combination of sp^2 and sp^3 carbon, dopant concentration, and nitrogen content. The DFEA are brazed on a Molybdenum substrate.

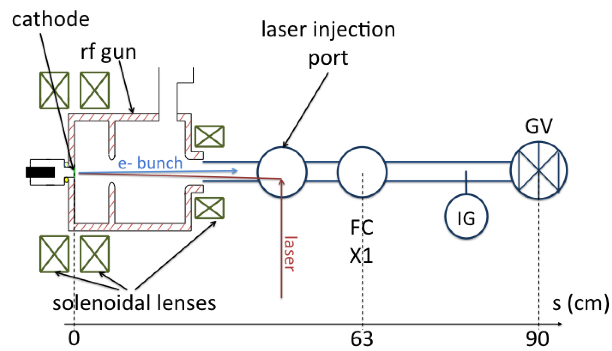

Figure 2: Experimental setup used to carry field-emission studies (a) . The legend is as follows: "FC": Faraday cup, "IG" ion gauge, "X1": scintillating screen for transverse beam density measurement.The insets are photograph of the DFEA cathode in its final position in the RF gun (b), and of the cathode holder with diamond coating on its font surface before insertion in the RF gun (c).

The DFEA cathode was located on the back plate of a 1.625-cell RF gun operating on the TM_{010} π mode at f = 1.3-GHz. The RF gun is powered by a $\leq$ 3-MW peak-power klystron pulsed at 1 Hz [12].

For the measurement presented below the RF macropulse width was set to 35 μs. The RF gun is surrounded by three solenoidal lenses that control the beam's transverse size. The charge and transverse distribution of the emitted electron beam can be measured with respectively a Faraday cup (FC) and scintillating screen (X1); see Fig. 2. Both diagnostics are located at $z = 0.63$ m from the cathode and are remotely insertable. The X1 screen is imaged on a charged-coupled-device (CCD) optical camera. A variable iris and neutral-density filters are used to attenuate the emitted optical radiation and mitigate saturation of the CCD. The optical resolution of the imaging system is $\sim$ 100 μm. A ion gauge (IG) located 0.5 m from the gun monitors the vacuum level in the section composed of the gun and diagnostics. Typical vacuum pressure levels in this beamline section are $\sim 1 \times 10^{-9}$ Torr. The forward RF power, P, injected in the RF gun cavity is measured using a calibrated RF diode detecting the low power from -30-dB directional coupler installed on the RF waveguide. The measured forward power can be used to infer the peak electric field at the cathode surface via $E_0[\text{MV/m}] \simeq 2.234 \times 10^2 \sqrt{P[\text{MW}]}$ where the RF-gun quality factor is taken to be $Q \simeq 2.3 \times 10^4$ and the cathode is assumed to be flushed with the RF-gun back plate.

The DFEA's substrate was brazed on a Molybdenum cathode holder compatible with the load-lock insertion mechanism used in the RF gun; see Fig. 3. The cathode holder was inserted in the RF gun and its position was adjusted to insure the gun resonant frequency remains at 1.3 GHz (as monitored with a spectrum analyzer). To insure electrical contact between the cathode holder and RF-gun-cavity walls, a Cu-Be spring is used. This spring is also found to be a source of spurious negligible field-emission current.

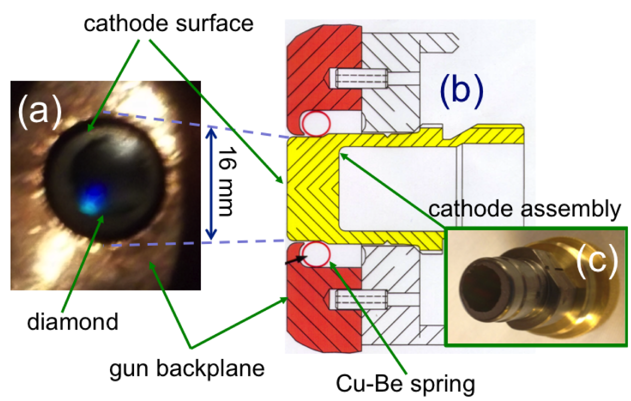

Figure 3: Photograph of the DFEA cathode (dark-blue area) inserted in the RF gun (copper back plate shown) (a). Cross-section sketch of the cathode insertion mechanism showing the RF gun back-plate (red) with cathode holder (yellow) (b). Photograph of the cathode holder (c).

MEASUREMENTS

A sample of F-N characteristics recorded over several days of operations appear in Fig. 4. The curves all have similar slopes at high fields [$\nu \equiv B(\phi)/\beta_e = 129.5 \pm 6.2$] for the cathode in its nominal position (with its emitting surface flushed with the RF gun backplate). A somewhat different slope is observed ($\nu' = 213.2 \pm 0.5$) when the cathode is retracted by a $\sim$ 2 mm. For these measurement the solenoids were turned off.

During the running period, the vacuum level was monitored and did not appreciably deteriorate ($\leq 1.2 \times 10^{-9}$ Torr). The current was also recorded for long period of time (typically up to one to two hours). An apparent current drift was observed by tracked back to klystron power drift over the time. Accounting for the E-field drift by computing an "instantaneous" F-N slope as $\mu \equiv E_0 \times \ln(I/E_0^2)$ indicates that the emission is stable with typical relative rms variation $\langle[(\delta\mu)/\mu]^2\rangle^{1/2} \simeq 0.37\%$. In practice correlated changes due to klystron-power drifts can easily be mitigated using a slow feedback loop.

The beam densities at X1 measured for a sample of operating conditions appear in Fig. 5. The beam sizes increase with field strength (due to larger emitting area) but can be

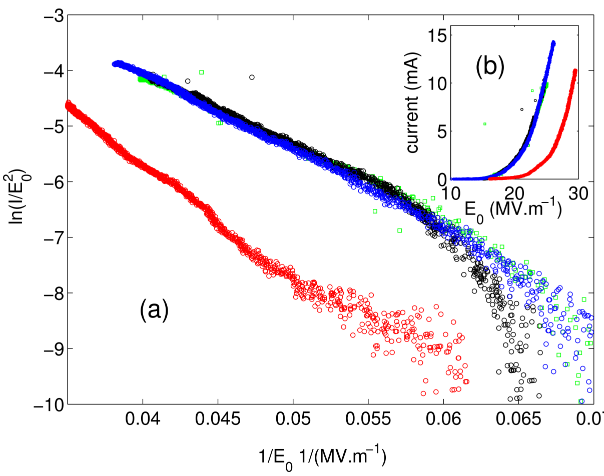

Figure 4: F-N plots (a) for the nominal (green, blue, black traces) and retracted (red) cathode position. For the nominal cases, the black and blue traces were respectively taken 10 and 59 days later than the black trace). The inset (b) displays the current evolution versus macroscopic field amplitude.

focused to a 1-mm (rms) spot size with the solenoids; see Fig. 5(d).

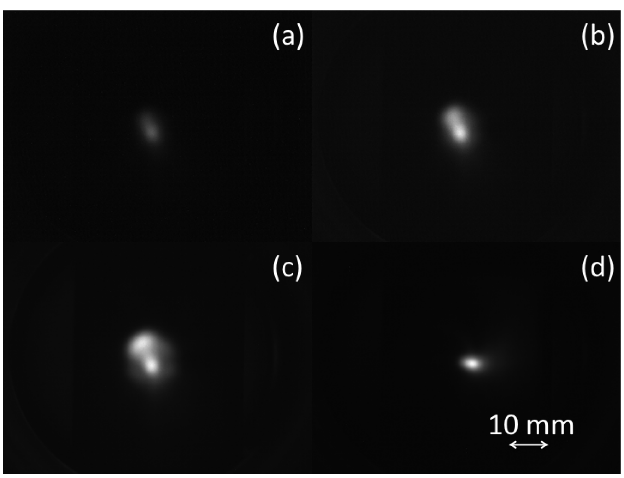

Figure 5: Transverse beam density measured at X1 for three cases of forward power $\hat{E}_0 \simeq 23.5$ (a), 25.5 (b) and 31 MV/m (c) with solenoids off and for a focused beam and $\hat{E}_0 = 31$ MV/m (d).

CONCLUSION

In summary we successfully demonstrated the operation of a DFEA cathode in a conventional L-band RF gun nominally design to operate using photocathodes. These results represent a significant step toward the realization of robust laser-free compact light sources for industrial, medical, and defense applications. Further tests will focus on characterizing the emittance of the beams generated from smaller-area FEA cathodes along with producing short bunch using gated DFEA cathodes currently under development [13].

We are indebted to M. Church, E. Harms , E. Lopez, J. Santucci, and V. Shiltsev for their support. This work is supported by the DARPA Axis contract AXIS N66001-11-1-4196 with Vanderbilt University, DOE Contracts No. DE-AC02-07CH11359 with the Fermi Research Alliance, LLC. and No. DE-FG02-08ER41532 with the Northern Illinois University.

REFERENCES

[1] K.L. Jensen, J. App. Phys 102 024911 (2007).

[2] J. D. Jarvis, H. L. Andrews, B. Ivanov, C. L. Stewar, N. de Jonge, E. C. Heeres, W.-P. Kang, Y.-M. Wong, J. L. Davidson, and C. A. Brau, J. Appl. Phys. **108**, 094322 (2010).

[3] K. B. K Teo, et al., Nature 437, p. 968 (2005).

[4] S. C. Leemann, A. Streun, A. F. Wrulich , Phys. Rev. ST Accel. Beams 10, 071302 (2007).

[5] J. D. Jarvis, B. K. Choi, A. B. Hmelo, B. Ivanov, C. A. Brau, J. Vac. Sci. Technol. B **30**, 042201 (2012)

[6] J. W. Wang and G. A. Loew, "Field Emission and RF breakdown in high-gradient room-temperature linac structure", report SLAC-PUB-7684 (unpublished, 1997).

[7] D.Y. Zhong, G.Y. Zhang, S. Liu, T. Sakurai, E.G. Wang, Appl. Phys. Lett. **80** 506 (2002).

[8] J. W. Lewellen and J. Noonan, Phys. Rev. ST Accel. Beams, **8**, 033502 (2005).

[9] 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 **27**, 2264 (2009).

[10] J.H. Billen and L.M. Young, in Proceedings of the 1993 Particle Accelerator Conference, Washington, DC (IEEE, Piscataway, NJ, 1993), p. 790.

[11] W. P. Kang, J. L. Davidson, M. Howell, B. Bhuva, D. L. Kinser, D. V. Kerns, Q. Li, and J. F. Xu, J. Vac. Sci. Technol. B **14**, 2068 (1996).

[12] J.-P. Carneiro, et al., Phys. Rev. ST Accel. Beams **8**, 040101 (2005).

[13] J. D. Jarvis, H. L. Andrews, C. A. Brau, B. K. Choi, J. Davidson, W.-P. Kang, and Y.-M. Wong, in Proceedings of the 2009 free-electron-laser conference (FEL09), p. 376 (2009).