Eur. Phys. J. D **15**, 345–348 (2001)

THE EUROPEAN PHYSICAL JOURNAL D

EDP Sciences

Intense electron emission from carbon fiber cathodes

Ya.E. Krasik[a], A. Dunaevsky, and J. Felsteiner

Physics Department, Technion, 32000 Haifa, Israel

Received 12 March 2001

Abstract. We studied the emission properties of carbon fiber cathodes. These cathodes were made either of a single carbon fiber or of carbon fabric, or of an array of carbon fiber bundles. It was found that an intense emission of electrons occurs from a plasma which is formed on the carbon fiber surface as a result of a flashover process. In addition, the time delay in the appearance of the electron emission with respect to the start of the accelerating voltage pulse was found to depend strongly on the voltage growth rate. A simple model of the plasma formation is suggested.

PACS. 52.50.Dg Plasma sources – 29.25.Bx Electron sources – 52.25.Tx Emission, absorption, and scattering of particles

It is well-known that explosive emission plasma [1] serves as an almost infinite source of electrons. However, the generation of high-current electron beams at accelerating electric fields $E \leq 10^5$ V/cm is a rather serious problem because explosive emission cathodes have failed to obtain significant electron emission at these moderate accelerating fields [1]. The most promising materials which show a "low-voltage" threshold ($E \leq 10^4$ V/cm) and small (several ns) delay time in the appearance of electron emission are carbon fibers [2–8]. Generation of electron beams with cross-sectional areas in the range of 10–100 cm^2, currents of several kA with current densities of tens of A/cm^2, and pulse durations of several μs was demonstrated at $E = 10{-}30$ kV/cm [2–8]. We believe that the crucial point in the operation of these cathodes is the understanding of the physical mechanism of the plasma formation. However, in most of this research only waveforms of the diode voltage and current were measured which is not adequate for characterizing the nature of the fast ignition of these cathodes. Nevertheless, it was suggested that the intense electron emission occurs either due to a field emission mechanism [2,3] or due to an explosive emission plasma formation [5–8]. In this paper we report experimental data which showed that the plasma formation occurs as a result of a flashover process along the surface of the carbon fiber cathode. These cathodes were made either of a single carbon fiber or of carbon fabric, or of an array of carbon fiber bundles.

We performed experiments with a cathode made of a single carbon fiber (fiber resistivity $\eta = 1\,375$ $\mu\Omega$ m) [9] having diameter of 8 μm and length of 5 mm. The carbon fiber was glued by silver-contained epoxy to a cathode holder made of a medical needle. It was placed at a distance of $d_{AC} = 1{-}10$ mm from an anode made of a stainless steel mesh. At a distance of 3 mm behind the mesh we placed a Faraday cup. The diode was powered by two types of high-voltage (HV) generators with different accelerating voltage amplitude φ_c, internal impedance ρ, and pulse duration τ ($\varphi_c = 2{-}6$ kV, $\rho = 50$ Ω, $\tau = 100$ ns, and $\varphi_c = 15{-}20$ kV, $\rho = 25$ Ω, $\tau = 20$ ns). The carbon fabric cathode and the cathode made of bundles of carbon fibers had an emitting area of 100 cm^2. The latter cathode consisted of ∼120 carbon fiber bundles placed at a distance of 5 mm between one another. In the case of carbon fabric or carbon fiber bundles the diode was powered by a HV generator ($\varphi_c \leq 300$ kV, $\rho = 84$ Ω, $\tau = 250$ ns). The diode voltage and current were measured by a voltage divider and a Rogovsky coil, respectively. A fast framing camera 4Quik05A was used to observe the light emission from the cathode surface. The uniformity of the beam was checked by X-ray imaging of the anode and by an array of collimated Faraday cups (CFC). We believe that the observed light emission is associated with the plasma. Micro-divergence of the beam was measured with a pinhole camera by analyzing the patterns of the micro-beams on a dielectric film. The lifetime of the cathodes was checked in the repetition mode of the HV generator operation $f = 1{-}5$ Hz. In order to measure the time resolved evolution of the vacuum deterioration we used a pair of specially designed Penning probes. To produce a dc Penning discharge we used a positive bias voltage of 0.8–1.2 kV applied to the anode and a pair of Sm–Co magnets. The Penning probes were calibrated in stationary conditions according to the data obtained from the Edwards AIM-X-NW25 gauge by varying the vacuum in the chamber. The Penning probes were enclosed inside a screening box and were placed at a distance of 10 cm aside from the AC gap. In the latter experiment the anode was made either of a stainless steel disk or a 50% transparent

[a] e-mail: fnkrasik@physics.technion.ac.il

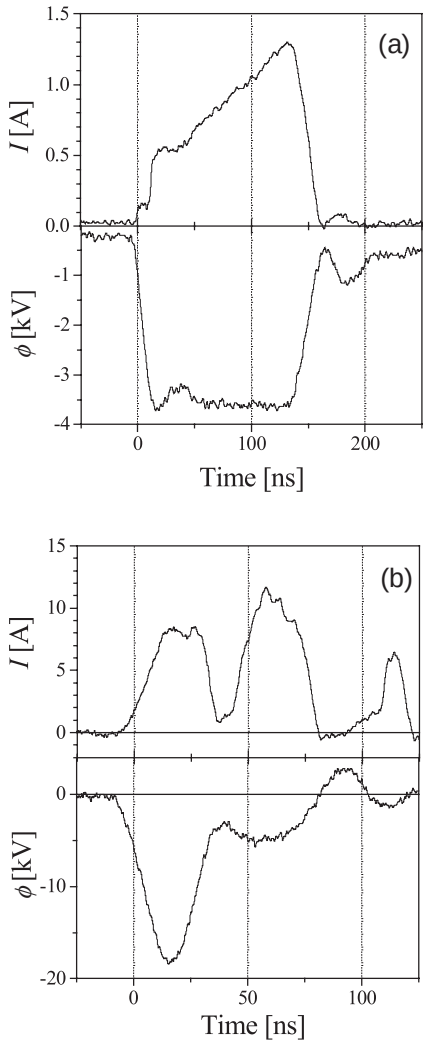

Fig. 1. Typical waveforms of the voltage and the current for a diode with a single carbon fiber emitter for an accelerating pulse of: (a) long duration and low amplitude, and (b) short duration and high amplitude. Anode-cathode gap $d_{\mathrm{AC}} = 3$ mm.

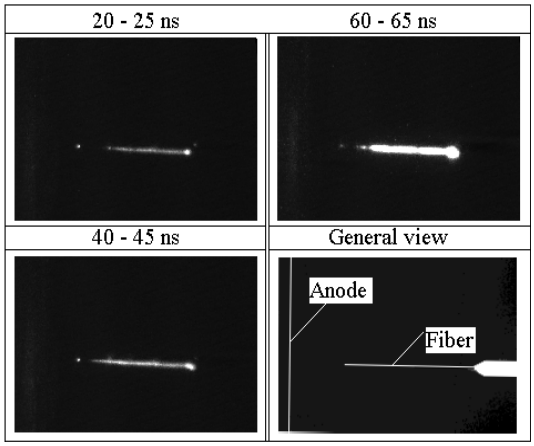

Fig. 2. Framing photographs (5 ns frame duration) of an individual carbon fiber emitter obtained at different times with respect to the beginning of the accelerating pulse. $d_{\mathrm{AC}} = 3$ mm, accelerating voltage $\varphi_{\mathrm{c}} = 7$ kV, diode current $I = 3$ A, pulse duration $\tau = 100$ ns.

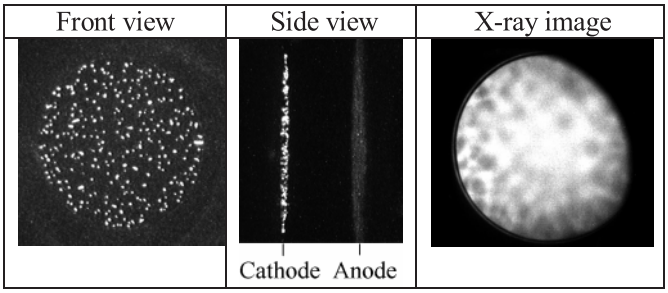

Fig. 3. Front-view and side-view framing photographs (10 ns frame duration) and an X-ray image of the anode obtained with a delay time of 60 ns with respect to the beginning of the accelerating pulse. Cathode is made of carbon fabric. $d_{\mathrm{AC}} = 35$ mm, $\varphi_{\mathrm{c}} = 190$ kV, $I = 1.1$ kA.

stainless steel mesh in order to study the role of the anode material in the vacuum deterioration. Experiments were performed in a vacuum of $(2-4) \times 10^{-5}$ torr which was kept by a 700 l/s diffusion pump.

Typical voltage and current waveforms with a single carbon fiber emitter are presented in Figure 1. In these experiments we determined the threshold for the appearance of electron emission to be $E = 8 \pm 1$ kV/cm at $\mathrm{d}E/\mathrm{d}t \approx 3$ kV/(cm ns). We note the increase of the observed electron current amplitude during the accelerating pulse (see Fig. 1a). In addition, in Figure 1b, we depict three pulses of the emitted current observed with a short duration accelerating pulse. It is seen that the amplitude of the current reaches 7–8 A at $\varphi_{\mathrm{c}} = 8$ kV. The increase of the current amplitude during the "plateau" of the accelerating pulse (Fig. 1a) as well as the observed larger amplitude of the current pulse at its second jump despite the smaller amplitude of the voltage (Fig. 1b) strongly indicate a fast expansion of the cathode plasma towards the anode. This expansion leads to the decrease of the anode-cathode gap and, in turn, to the increase of the current density of the emitted electrons. We also took fast framing photographs of the single fiber emitter (see Fig. 2). The appearance of the light coincides with the beginning of the electron emission. A distinguished feature of the obtained photographs is that the light appears not only from the top of the carbon fiber as it should be expected in the case of explosive emission plasma, but also from its side surface. These data strongly indicate that the origin of the plasma is a flashover process along the surface of the fiber.

In general we observed similar emission properties for the cathodes made of carbon fabric and of carbon fiber bundles at accelerating voltage amplitudes $\varphi_{\mathrm{c}} = 150-300$ kV, current amplitudes $I = 0.5-2$ kA and $d_{\mathrm{AC}} = 25-60$ mm. A typical image of the front surface of the carbon fabric cathode obtained at 60–70 ns from the start of the accelerating pulse is presented in Figure 3. It was found that the light emission starts within 10 ns after the start of the accelerating pulse. We note two the most important features of these observations. First,

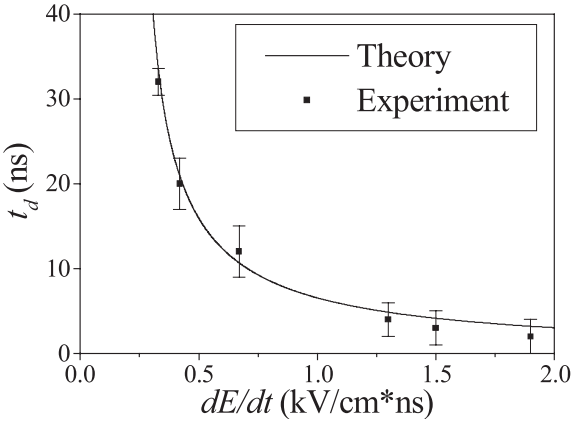

Fig. 4. The predicted time delay in the appearance of the electron emission *versus* the electric field derivative. Experimental data relate to the carbon fabric cathode. $d_{\rm AC} = 35$ mm, $\varphi_{\rm c} = 190$ kV, $I = 1.1$ kA.

it was observed that light emission appears from individual bright spots rather than from the total cathode surface and these bright spots do not change their size during the accelerating pulse. The second important feature is that the larger $\varphi_{\rm c}$ and $\mathrm{d}E/\mathrm{d}t$, a larger number of bright spots was observed. In addition, side-view observations showed the absence of the expansion of the cathode light-emitting region which is consistent with quasi-constant diode impedance behavior. The calculated ratios of the diode current I to its space-charge limited value, $I/I_{\rm sc}$, showed that the cathodes provide $I/I_{\rm sc} \cong 1{-}1.5$ in the range of $E = 35{-}65$ kV/cm within ~40 ns after the start of the accelerating pulse. These data also indicate the existence of a quasi-stationary plasma boundary which is consistent with the results reported in references [2–8].

We studied the time delay $\tau_{\rm d}$ in the appearance of electron emission for different values of $\mathrm{d}E/\mathrm{d}t$ while keeping the maximum amplitude of the accelerating electric field $E = \varphi_{\rm c}/d_{\rm AC}$ approximately constant ($E = 50 \pm 3$ kV/cm) (see Fig. 4). It is seen that the time delay depends strongly on $\mathrm{d}E/\mathrm{d}t$ especially at $\mathrm{d}E/\mathrm{d}t < 0.5$ kV/(cm ns). We believe that the observed dependence strongly indicates that some additional mechanism should be involved in the plasma formation because the explosive emission model [1] does not take into account the influence of $\mathrm{d}E/\mathrm{d}t$.

The uniformity of the electron beam can be seen in Figure 3 where we present an X-ray image of the anode. It is seen that the image consists of patterns having the form of circles with different intensities and dimensions. The observed data show spatial non-uniformity of the electron beam generated at $E < 60$ kV/cm. Using the array of CFCs it was found that the non-uniformity of the electron beam was $\pm 12\%$ at $\varphi_{\rm c} = 240$ kV. At smaller accelerating voltages the observed non-uniformity was much worse. By the use of the pinhole camera we found the micro-divergence to be $\alpha/2 \approx 2.2^\circ$ and $\alpha/2 \approx 2.6^\circ$ for carbon fabric and carbon fiber bundles cathodes, respectively.

The obtained dependence of the diode current on the number of generator shots showed only a ~9% reduction in the diode current ($I_{N=100} = 2.4$ kA and $I_{N=10\,000} = 2.2$ kA). Thus one can conclude that the degradation of the emission properties of carbon fiber cathodes is insignificant. Using the Penning probes we found out that the larger is the emitted electron current density the larger is the increase of the pressure in the vacuum chamber. It was observed that in the case of the stainless steel mesh anode the increase of the pressure was almost twice as large as that in the case of the stainless steel disk anode for the same electron current density. We estimated the density of desorbed neutrals per unit cathode area for the case of the stainless steel disk anode assuming that the main input to the process of vacuum degradation is neutral desorption from the cathode surface. These estimates give 0.4×10^{16} cm^{-2} and 0.7×10^{16} cm^{-2} neutral densities at current densities of 12 A/cm^2 and 25 A/cm^2, respectively. With our experimental setup (vacuum chamber volume of 41 l and diffusion pump rate of 750 l/s) the maximum achievable repetition rate of the HV generator operation was 5 Hz.

We believe that in our experiments explosive plasma is not realized as it was suggested in previous publications [5–8]. Indeed, the explosive emission mechanism assumes the current to flow through the emitter. Thus one can estimate the potential difference between the beginning and the end of the carbon fiber while the observed current of ~1 A flows through it. The fiber cross-sectional area is $S = 5 \times 10^{-7}$ cm^2. The fiber length is $L = 5$ mm which yields the resistance of one fiber to be $R = \eta L/S = 1.38{\times}10^5\ \Omega$. One can see that the 1 A current causes a potential difference of 138 kV which is impossible when one takes into account the accelerating voltages used. Also, another simple estimate showed that the fiber should explode in one shot because of Joule heating by the current flowing through it. This is in contradiction with the experimental observation where a single fiber hold a more than 10^3 generator shots.

We carried out additional experiments on single carbon fibers of 8 mm length which have a significantly smaller resistivity (Thornel Pitch Fibers, type P-100, $\eta = 2.5\ \mu\Omega\,$m and Thornel Pan Based Fibers, type T-40R, $\eta = 13\ \mu\Omega\,$m). We observed the same results for both types of fibers and these results were similar to those obtained with the high resistivity fiber. In these experiments a 20 kV-amplitude and 20 ns-duration negative HV pulse was applied to the needle. At an anode-cathode gap of 3 mm we observed electron current with the amplitude of 35 A. Such high current can not flow through the fiber. Indeed, a potential drop between the top of the fiber and the place where it was glued to the needle gives 60 kV or 75 kV/cm for fiber type T-40R. This voltage is three times larger than the applied HV pulse amplitude. In the case of P-100 type fiber the voltage difference was 5 time less. Nevertheless, we observed the same process of the surface flashover as in the cases of high resistive fibers.

The obtained voltage and current waveforms and framing photographs strongly indicate that the electron

emission occurs from the plasma which covers the side and top surfaces of the fiber and expands towards the anode. An indirect proof of the formation of the flashover plasma is the neutral flow formation and the insignificant deterioration in the cathode emission properties. At present we do not know the composition of the flashover plasma. We can only speculate that this plasma consists of ions of adsorbed atoms of surface monolayers and of carbon ions because of possible carbon fiber surface erosion. This erosion could happen due to interaction of the plasma charged particles with the carbon fiber surface. Additional spectroscopic investigations are required in order to clarify the composition of the surface flashover plasma.

We suggest the following model for the surface flashover plasma formation. Let us consider a fiber as an individual capacitor $C_\mathrm{f} = \varepsilon_0 \pi r^2/L$ connected in parallel with a resistor R_f which represents the resistance of the fiber $R_\mathrm{f} = \eta L/\pi r^2$. There is also a resistor R_d which represents the resistance related to the field emission current [1] I_FN towards the anode, $R_\mathrm{d} = \varphi/I_\mathrm{FN}$ where φ is the potential of the top of the fiber. Application of the acceleration voltage causes the appearance of a negative charge Q at the top of the fiber which is induced by a displacement current $j_\mathrm{ds}\pi r^2$ (charging of C_f), by a field emission current $j_\mathrm{fe}\pi r^2$ (discharging C_f by a current flowing to the anode), and by a leakage current $j_\mathrm{R}\pi r^2$ (discharging C_f by a current flowing through the fiber resistance to the cathode plate). The expression for the change in the potential at the top of the fiber is:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \frac{\varphi_\mathrm{c}}{\tau_\mathrm{f}}\frac{L}{d_\mathrm{AC}} - \frac{L}{\varepsilon_0} j_\mathrm{fe}(\varphi) - \frac{1}{\eta\varepsilon_0}\varphi.$$

Here we assumed a linear growth rate of the accelerating electric field $\mathrm{d}E/\mathrm{d}t \approx \varphi_\mathrm{c}/(d_\mathrm{AC}\tau_\mathrm{f})$ where τ_f is the rise time of the accelerating voltage. The field emission current density j_fe is governed by the Fowler-Nordheim law [1] where the electric field at the top of the cylindrical fiber is estimated as $E \sim \varphi/r$. Assuming that the surface flashover along the fiber occurs when the potential difference between the top of the fiber and the fiber holder reaches the breakdown voltage ($\Delta\varphi \approx 10$ kV corresponds to a breakdown threshold of $\sim$20 kV/cm), we calculated the time delay in the appearance of the flashover plasma. The resulting curve was fitted to the measured time delay with the resistivity $\eta = 1\,017\ \mu\Omega\,\mathrm{m}$ (see Fig. 4). One can see the good agreement of the calculation with the measured time delay.

Concerning the observed beam divergence which corresponds to a transverse electron energy of several hundred eV we believe that the reason is the discrete nature of the plasma sources. A 2D computer simulation of the trajectories of electrons emitted from different locations on the side surface of the fiber (assuming that plasma covers its side surface) showed that electrons acquire a large transverse velocity because of a tangential electric field at the vicinity of the surface. The measured micro-beam divergence and the observed X-ray image of the anode are in good agreement with the calculated results.

Thus, the present experimental results and simulations allow us to draw the following conclusions:

(1) the formation of the plasma occurs as a result of surface flashover;
(2) the time delay in the plasma formation as well as the plasma uniformity depends strongly on $\mathrm{d}E/\mathrm{d}t$;
(3) the extracted electron beam has a transverse velocity because of the discrete nature of the plasma sources.

This research was supported in part by the Fund for the Promotion of Research at the Technion.

References

1. G.A. Mesyats, *Explosive electron emission* (URO Press, Ekaterinburg, 1998).
2. J.G. Eden, D. Epp, Rev. Sci. Instrum. **51**, 781 (1980).
3. R. Prohaska, A. Fisher, Rev. Sci. Instrum. **53**, 1092 (1982).
4. H. Kosai, A. Fisher, Rev. Sci. Instrum. **61**, 1880 (1990).
5. E. Garate, D. McWilliams, D.E. Voss, A.L. Lovesee, K.J. Hendricks, T.A. Spencer, M. Collins Clark, A. Fisher, Rev. Sci. Instrum. **66**, 2528 (1995).
6. A. Fisher, E. Garate, *Proc. 12th Int. Conf. on High-Power Particle Beams*, Haifa, Israel, 1998, p. 133.
7. Yu.A. Vasilevskaya, M.A. Vasilevskii, I.M. Roife, V.I. Engel'ko, S.P. Yakovlev, E.G. Yankin, Sov. Phys. Tech. Phys. **29**, 58 (1984), and references therein.
8. M.A. Vasilevskii, I.M. Roife, V.I. Engel'ko, E.G. Yankin, Sov. Phys. Tech. Phys. **31**, 284 (1986).
9. Catalog of Alfa AESAR, a Johnson Matthey Company, *Research Chemicals, Metals and Materials*, 1998.