Passive and Active Plasma Emission Sources for High-current Electron Beam Generation

Yakov E. Krasik  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Joseph Z. Gleizer  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Dmitry Yarmolich  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Vladislav Vekselman  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Yoav Hadas  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Alexander Krokhmal  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Konstantin Chirko  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Or Peleg  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
Joshua Felsteiner  Non-member  (Department of Physics, Technion - Israel Institute of Technology)
I. Schnitzer  Non-member  (Rafael)

Keywords: passive and active plasma sources, electron beam generation

In this review we present main results of experimental research of passive and active plasma sources for high-current electron beam generation obtained during the last few years in our Plasma & Pulsed Power Laboratory. We describe passive plasma sources (ceramic-metal, velvet and carbon fiber cathodes) based on flashover plasma and active plasma sources based on a ferroelectric plasma source (FPS) as well as on an FPS-assisted hollow anode (HA) plasma source. The main data concerning the plasma parameters (plasma density and temperature, plasma uniformity and plasma potential) and the main features of these plasma sources (plasma formation, life-time, vacuum compatibility) are discussed. Also we investigated a Metal-Ceramic Plasma Source (MCPS) in a form of a disk made of TiO2 ceramic with stainless steel spherical particles having diameter of ∼9µm and density ∼4000 particles/cm². All these cathodes were studied using various electrical, optical, spectroscopic and x-ray diagnostics in the diode powered by the high-voltage 250ns pulse duration generator and. Experiments with passive plasma cathodes showed that the amplitude and uniformity of the electron beam depend on the amplitude and rise time of the accelerating voltage (see Fig. 1). The shorter the rise time of the voltage the larger is the current amplitude and the better is the uniformity of the beam in spite that the light emission from the cathode surface occurs from individual bright spots.

In the case of FPS it was shown that the plasma is formed on the ferroelectric surface ferroelectrics as a result of incomplete discharges. These discharges are initiated in triple points by the application of a driving pulse between the rear solid and front strip electrodes. It was found that the plasma electron density and temperature are in the range of $10^{12}$–$10^{13}$cm$^{-3}$ and ∼3eV, respectively, and the neutral density in the vicinity of the ferroelectric surface is ∼$10^{13}$cm$^{-3}$.

It was shown that that incomplete surface discharges are accompanied by the formation of intense micro-particles flow. These micro-particles were observed at different distances from the FPS by fast camera coupled with microscope when micro-particles were lightened by pulsed laser beam. It was found, that the dust micro-particles have dimensions in the range of 1–10µm (but few particles size of >20 µm was found too) and mean particle size is of ∼5µm. Assuming the same composition of micro-particles and the ferroelectric sample one can estimate an average mass of micro-particle as $m = 7.5 \times 10^{-13}$ kg.

The parameters of the FPS-assisted HA electron source operated at background gas pressure ≥ 10$^{-6}$ Torr were investigated. In Table 1 we show that one can control the plasma density and temperature by changing the HA discharge current amplitude.

The application of the accelerating pulse leads to extraction of electrons from the HA plasma and generation of an electron beam with current amplitude up to 1.4kA. Using a de-coupling resistor and a capacitor between the HA output grid and the HA, a negative auto-bias potential up to ∼−300V was obtained. This auto-bias potential prevents the plasma from penetrating into the AC gap, allowing the diode operation in a space-charge limited mode. It was also found that extraction of electrons from the HA plasma leads to a drastic increase in the plasma potential (up to several kV) with respect to the HA walls and output grid.

<table>
<thead>
<tr>
<th>Discharge current [A]</th>
<th>Electron temperature [eV]</th>
<th>Plasma density [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>2±1</td>
<td>$(2\pm1)\times10^{12}$</td>
</tr>
<tr>
<td>800</td>
<td>3±1</td>
<td>$(2\pm1)\times10^{12}$</td>
</tr>
<tr>
<td>1000</td>
<td>5±25</td>
<td>$(4\pm1)\times10^{12}$</td>
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Fig. 1. Typical waveforms of the voltage and current in the diode with velvet cathode
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1. Introduction

High-current electron beams with a current amplitude of $10^3$–$10^4$A, electron energy of $\leq 500$keV and cross-sectional area of $10^2$–$10^4$cm$^2$ play a major role in efficient operation of relativistic microwave tubes, pumping of gaseous lasers, and other applications. Electron sources based on field emission failed to operate in high-current diodes because of a necessity of extremely high electric field and pure vacuum conditions. Thermionic emission cathodes can supply the required electron current density. However, this type of sources is inertial, it requires additional heating supplies, and high vacuum conditions are necessary to avoid emission degradation. Explosive emission plasma which is produced by an accelerating pulse, also have serious drawbacks: there is a relatively large time delay in plasma appearance and plasma non-uniformity at an accelerating electric field $<10^5$V/cm. In addition, fast plasma expansion leads to shorting of the anode-cathode (AC) gap, which limits the duration of the accelerating pulse. Thus, research of alternative electron sources for generation of large area, uniform electron beams at moderate accelerating electric fields with current density of several tens of A/cm$^2$ is still an actual problem.

2. Metal-Ceramic Plasma Source (MCPS)

We investigated an MCPS in a form of a disk made of TiO$_2$ ceramic with stainless steel spherical particles uniformly inserted inside$^{11}$. These particles had an average diameter of 9µm and their average surface density was determined as 4000 particles/cm$^2$. The ceramic disk had a diameter of 10mm and a thickness of 2mm. The disk was placed at different distances (20–60mm) from the anode. The electron diode was powered by a high-voltage (HV) generator producing a HV pulse up to 300kV in amplitude, 350ns in duration and variable rise time in the range of $dE/dt = (0.5–2.5) \times 10^{12}$V/(cm⋅s).

The diode voltage and current were measured by a voltage divider and Rogowsky coils (see Fig. 1). A fast framing camera 4Quik-05A was used to observe the light emission from the cathode and anode surfaces (Fig. 1). The uniformity of an electron beam was checked by x-ray imaging of the anode and using an array of collimated Faraday cups. The micro-divergence of the electron beam was measured with a multi-pinhole camera.

The obtained experimental results showed that there is a ns time scale delay in the appearance of electron emission with respect to the beginning of the accelerating pulse. Also, it was found that the amplitude of the diode current exceeded significantly the space-charge limited value. The latter indicates a significant decrease in the AC gap and the increase in the cathode plasma emitting area during the HV pulse due to a fast transverse and
longitudinal expansion of the cathode plasma. Framing images of the plasma formation on the surface of the MCPS (front and side views) showed that the plasma formation occurs already at the pre-pulse of the accelerating voltage [average electric field in the AC gap of 5kV/cm, electric field growth rate of \( \approx 1.5 \times 10^{12} \text{V}/(\text{cm} \cdot \text{s}) \)].

The plasma formation was found to occur at the place of connection between the metal-ceramic disk and the cathode holder (see Fig. 2), i.e. in the triple points location. This plasma expands in the form of a narrow surface discharge along the surface of the disk and reaches its edge with a further expansion into the AC gap. Thus, the source of emitted electrons is the plasma which is formed on the metal-ceramic surface as a result of a flashover process. The temporal behaviour of the diode impedance showed a significant decrease of the impedance during the accelerating process. The expansion velocity was found to be \( 1.4 \times 10^{7} \text{cm/s} \) for \( 6.4 \times 10^{12} \text{V/s} \). It was found that the cross-sectional distribution of the electron current density on the anode is non-uniform and could be approximated by a Gaussian. Typical x-ray images of the anode irradiated by the electron beam showed that the most intense x-ray radiation occurred at the center of the anode. In addition, it was shown that the generated electron beam had a large micro-divergence, within the range of \( 6^\circ - 10^\circ \).

The obtained fast plasma formation at a relatively small electric field and its growth rate can be explained by the specific composition of the tested MCPS. During the process of the cathode preparation a large amount of micro-pores has been formed due to the different thermal expansion coefficients of the ceramic and the metal. These micro-pores can be considered as triple points where significant electric field enhancement occurs\(^{(2)}\).

Thus, the surface flashover initiated in the triple points at the cathode holder propagates along the surface of the metal-ceramic cathode as a result of consequent micro-discharges of these micro-pores. The further obtained anomalous fast plasma expansion inside the AC gap can be explained by the same physics which is involved in the acceleration of plasma flows in erosion type plasma guns. The present results concerning the non-uniform current density distribution, fast plasma expansion and large electron beam divergence, rule this cathode out for applications which require good beam quality and constant diode impedance. However, for technological applications (for instance, the generation of x-ray bursts for sterilization) this type of cathode can be used successfully because it shows extremely long life-time (\( > 10^7 \) accelerator shots) and good reproducibility of the electron beam parameters.

Another type of multi-MCPS was made of 14 ceramic (alumina, \( \varepsilon = 10 \)) plates with a thickness of 1mm and brass spring electrodes clasped to them. These structures were fixed in slots made in a brass base. The base was placed into a stainless steel screening ring having a diameter of 130mm (Fig. 3). This type of multi-MCPS showed similar as ceramic disk, i.e., a fast flashover plasma formation initiated in triple points. The difference was only in the less intense plasma formation from the individual source and a stronger dependence of the time delay in the plasma appearance on the growth rate of the accelerating field\(^{(3)}\).

### 3. Carbon Fiber and Velvet Plasma Sources

We investigated several types of velvet, corduroy, carbon fabric and carbon fibers cathodes\(^{(3)}\) using the same diagnostics and HV generator as in the experiments with MCPS. In additional we used spectroscopic measurements\(^{(4)}\). All cathodes had the same cross-section of the emitting surface, 100cm\(^2\).

Experiments carried out at an accelerating electric field of 30–60 kV/cm and an electric field rate of 0.5–2.5 kV/(cm ns) showed the following main results. The time delay of the electron emission appearance, the current amplitude and the uniformity of the electron beam, depend on the amplitude and rise time of the accelerating voltage and on the rise time of the voltage (Fig. 4). The shorter the rise time of the voltage the larger is the current amplitude and the better is the uniformity of the beam.

The light emission from the cathode surface occurs from individual bright spots. These bright spots represent individual plasma sources that produce separate electron beamlets. The amount, dimensions and the time delay of these spots appearance depend on the type of the cathode and the rise time of the accelerating voltage. The shorter the voltage rise time the larger amount of the spots and the smaller time delay of these spots appearance were observed. Also, a fast change in the intensity of the spots occurs during the accelerating pulse. At the beginning of the accelerating pulse these sources have similar sizes and brightness and are distributed with satisfactory uniformity on the...
velvet surface. Further into the pulse, the peripheral spots increase their brightness and size and the brightness of the spots located in the central part decreases (Fig. 5).

In spite of the individual character of the cathode plasma sources, the distribution of the extracted electron beam is satisfactorily uniform. The beam uniformity cannot be explained by electron divergence in the accelerating gap, which does not exceed a few degrees in the case of a cathode with a screening ring. Electron divergence (∼30°) appears when the cathode is made in the form of a ring with a central non-emitting area. Lifetime test of the cathodes showed that the smallest decrease (∼10%) of the beam current amplitude after 4×10^5 generator shots was observed with cathodes made of carbon fabric and carbon fibers. The vacuum compatibility of the tested cathodes and, consequently, the repetition rate of the electron beam generation depend on the type of the cathode. The smallest outgassing properties were shown by cathodes made of carbon fibers. This type of cathode allows generation of electron beams with repetition rate up to 5 Hz.

Time and space resolved spectroscopic measurements showed that the source of electrons is surface cathode plasma. The plasma forms as a result of the discharge on the fiber surface. The density and expansion velocity of this plasma depend on the density of the emitted electrons, i.e., the larger the density of the emitted electrons, the faster is the expansion velocity and the larger is the plasma density. The density and temperature of the plasma electrons do not exceed 4×10^13 cm⁻³ and 8 eV, respectively; in the vicinity of the velvet surface for j_k≈45 A/cm² (Fig. 6). Plasma expansion with velocity of 1±0.2 cm/μs stops at a distance where the plasma electron saturation current density becomes equal to j_k.

In general, if there are no specific requirements on the uniformity of the electron beam and on the beam divergence, the tested cathodes can be successfully used for the generation of electron beams having a cross-sectional area of 100 cm², with current density of tens of A/cm² and pulse duration of several hundreds of ns.

4. Ferroelectric Plasma Sources (FPS)

A review on intense electron emission from ferroelectrics (Fig. 7) can be found in (20). It has become accepted that the source of this emission is the plasma formed on the surface of the ferroelectric as a result of incomplete discharges. The latter are initiated in triple points by the application of a driving pulse between the rear solid and front strip/grid electrodes (Fig. 8). Due to electric field enhancement in triple points electron emission begins at these locations. These electrons produce avalanching along the FPS surface in tangential electric field. For instance, electron and ion flows generated during surface discharge were studied using collimated Faraday cups (CFC) (see Fig. 9). In some of experiments, to ignite surface discharges a positive driving pulse with a slow rise and fast fall time was applied to the FPS rear electrode (see Fig. 10(a)). The application of the driving pulse causes low-density plasma formation and charging of the FPS capacitance. The switching of the FPS capacitor using the spark gap switch (Fig. 9) causes fast discharge of the ferroelectric capacitor. The latter leads to the appearance of tangential and normal components of the electric field at the vicinity of the FPS surface. The tangential electric field causes intense surface flashover, i.e., dense plasma formation, and normal component of the electric field leads to intense charge particle emission outwards the FPS.

Typical waveforms of driving current, the plasma electron and ion current density, emitted from the front surface of the FPS are shown in Fig. 10 (b), (c), (d). One can see that during the rise in the driving pulse charged particles flow outwards of the ferroelectric is negligible small. The generation of intense electron and ion flows occur during the fall in the positive and negative falls in the driving pulse ringing, respectively. These data are explained by expulsion of electrons/ions which were bounded to the ferroelectric surface by the ferroelectric polarization surface charge during the charging process.

Electrical measurements showed that the plasma electron density n_e and temperature T_e are in the range of 10^{12}–10^{13} cm⁻³ and ∼3 eV, respectively, and the neutral density in the vicinity of the ferroelectric surface is ∼10^{15} cm⁻³. Also, it was shown that the increase in the driving pulse amplitude leads to the increase in the density and propagation velocity of the plasma.

Spectroscopic measurements of the plasma produced at the front surface of a BaTiO₃ sample of 8 mm thickness and 80 mm diameter by a driving pulse of 15 kV amplitude and 400 ns showed
that in the vicinity of the ferroelectric surface the plasma electron density is $5 \times 10^{12}$ cm$^{-3}$, the electron temperature is 3 eV and the ion temperature is $\leq 0.5$ eV. In Ref. (7), (8) driving pulses with the variable pulse duration and different slopes of the driving pulses were used. Using driving pulses with either fast falling voltage or delayed second driving pulse, the plasma density up to $10^{15}$ cm$^{-3}$ was generated. The latter was explained by the plasma formation due to ionization of a cloud of heavy neutrals desorbed from the ferroelectric surface by the first current pulse. It should be noted that the plasma density obtained with $E_{\text{max}} \approx 15$-20 kV/cm of a short duration ($\leq 300$ ns) driving pulse is in the range of $10^{12}$--$10^{13}$ cm$^{-3}$. The density of the plasma produced due to ionization of the cloud of neutrals by a relatively long driving pulse (1--10 µs) is significantly higher and it lies in the range of $3 \times 10^{13}$--$8 \times 10^{14}$ cm$^{-3}$. This allows one to consider this dense plasma as a practically unlimited electron source in the electron diode for generation electron beam with current density of several hundreds of A/cm$^2$.

The FPS has already been used as an electron source for the generation of electron beams with a cross-sectional area of 100 cm$^2$ and satisfactory cross-sectional uniform current density of $j_{e} \leq 5$ A/cm$^2$ under the application of an accelerating pulse of 250 kV in amplitude and 250 ns in duration (9). These experiments also showed that the diode operation is characterized by plasma pre-filling of the accelerating gap. In order to prevent plasma pre-filling, a biased control grid was used, but in this case the current density of the extracted electron beam was $\leq 5$ A/cm$^2$ because of a limited plasma density of $5 \times 10^{12}$ cm$^{-3}$. Using the enhanced density of the FPS surface plasma, an electron diode controlled by optic fibers was operated at a repetition rate of 0.5 Hz during 1 hour, when an accelerating pulse of $\sim 250$ kV in amplitude and $\sim 250$ ns in duration was applied (Fig. 11) (10).

Carried out experiments showed that the use of the FPS with fast fall time of the driving pulse (see Figs. 9, 10) allows reproducible generation of electron beams of $\sim 1$ kA in amplitude, current density of 10--15 A/cm$^2$ and uniform cross-sectional current density distribution (Figs. 12 and 13).

It was shown in Ref. (11) that surface discharges are accompanied by the formation of micro-particles flow. These micro-particles were observed at different distances from the FPS by 4Quick05A camera coupled with microscope when micro-particles were lightened by pulsed laser beam. After applying $\sim 10^3$ driving pulses it was found that walls and windows of the vacuum chamber and the surface of the FPS are covered by a macroscopic amount of a microscopic dust. It was found, that the dust micro-particles have dimensions in the range of 1-10 µm (a few particles size of $>20$ µm was found too) and mean particle size is $\sim 5$ µm.

Assuming the same composition of micro-particles and the ferroelectric sample one can estimate an average micro-particle mass as $m = 7.5 \times 10^{-13}$ kg.

Typical dust micro-particle images at the vicinity of the FPS surface for different $\tau_{d}$ are shown in Fig. 14. One can see that the dust micro-particles have dimensions in the range of 1-10 µm (a few particles size of $>20$ µm was found too) and mean particle size is $\sim 5$ µm. Assuming the same composition of micro-particles and the ferroelectric sample one can estimate an average micro-particle mass as $m = 7.5 \times 10^{-13}$ kg.

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obtains average micro-particle charge \( q \) taking into account that at \( V > 6 \cdot 10^{-15} \text{ C} \), \( l = 0.5 \text{ mm}, h = 1.2 \text{ mm} \) at \( d = 1 \text{ mm} \) (Fig. 14) and theirs distribution functions \( F(V) \) are presented in Fig. 15(a) and Fig. 15(b) respectively. It was found that the front of micro-particle cloud propagates with a velocity of \( \sim 160 \text{ m/s} \). For instance, at \( d = 1 \text{ mm} \) micro-particles appear in the counting window at \( \tau = 6 \mu \text{s} \). However, an average velocity of micro-particles was found to be significantly less, \( \langle V \rangle \sim 60 \text{ m/s} \), because of an angular velocities distribution of the particles.

In the experiment with biased grid placed at \( d = 10 \text{ mm} \), a comparison of \( F(V) \) with and without external electric field was performed. A pulsed electric field (pulse duration of \( 1.5 \text{ ms} \)) was applied to the grid with \( \tau = 10 \mu \text{s} \). It was found that in the case of negative bias the total number of micro-particles is almost the same as in the case of un-biased grid. However, the mean velocity \( \langle V \rangle \) increases on \( \sim 8 \text{ m/sec} \) in comparison with the mean velocity in the case of grounded grid case. Assuming that the increase in \( \langle V \rangle \) is due to micro-particles acceleration by electric field and taking into account that at \( d = 6 \text{ mm} \) the potential is \( \sim 3.8 \text{ kV} \), one obtains average micro-particle charge \( \langle q \rangle \approx 6 \cdot 10^{-15} \text{ C} \). In the case of positive bias the number of micro-particles decreases \( \sim 8 \) times. Thus, one can state that micro-particles obtained a positive charge. However, a small amount of negatively charged micro-particles can not be excluded, as well.

It is understood, that an additional research is required in order to understand the processes involved in emission of charged micro-particles. However, one can suppose that intense non-complete discharges are accompanied by large surface temperature gradients which cause local mechanical stresses and, respectively, formation of micro-particles. The above suggestion explains qualitatively also the obtained positive charge which appears due to electron emission by mechanically stressed micro-particles due to piezo-electric effect.

5. Hollow Anode Plasma Source (HA)

In Ref. (11)-(13) the parameters of the FPS-assisted HA source operated at background gas pressure \( \geq 10^{-6} \text{ Torr} \) were described (Fig. 16). This HA was used as an electron source in a diode powered by an HV generator for generation of high-current electron beams with cross-sectional area \( \geq 10^2 \text{ cm}^2 \). It was shown that the FPS-assisted HA is a powerful and the most compact pulsed electron source among other investigated sources. Indeed, it was found that the plasma formed on the surface of ferroelectric samples as a result of incomplete surface discharges under the application of a driving pulse serves as an effective source of electrons which ignite the main HA discharge. The density of this surface plasma increases significantly up to \( 10^{15} \text{ cm}^{-3} \) (Fig. 17) that allows one to consider this plasma as a practically unlimited source of electrons up to a current density of several tens of kA/cm². Thus it was shown that the FPS requires only a driving pulse to be ignited and further it generates the dense plasma in a self-consistent mode due to continuous bombardment of its surface by the plasma particles. In the experiments different ferroelectric samples were used. The example of the light emission from the multi-FPS during the HA discharge is shown in Fig. 18. One can see uniform light emission from 7 FPSs each supplying current of 150 A from an area of 0.5 cm². Using an FPS electron source, reliable and reproducible HA discharge with current up to 1.4 kA at vacuum of \( 5 \times 10^{-6} \text{ Torr} \) was demonstrated (Fig. 19). It was shown that the increase in the discharge voltage leads to a linear increase in the HA discharge current.

The HA plasma studied by different electrical probes and visible light spectroscopy (Table 1) showed that one can control the plasma density and temperature by changing the HA discharge current amplitude.

\[ F(V) = N(V)/\Delta V = N(V)d \langle V \rangle. \]

The particles number in the window size of \( l = 0.5 \text{ mm}, h = 1.2 \text{ mm} \) at \( d = 1 \text{ mm} \) (Fig. 14) and theirs distribution functions \( F(V) \) were described

![Fig. 12. Typical waveform of the voltage and current in a diode with an FPS cathode](image)

![Fig. 13. X-ray image of the electron beam generated in the diode with FPS cathode](image)

![Fig. 14. High spatial resolution microscope photography of micro-particles](image)

![Fig. 15. Micro-particles number, velocity distribution functions \( F(V) \) at vicinity of the FPS surface](image)
The application of the accelerating pulse leads to extraction of electrons from the HA plasma and generation of an electron beam with $I_b \leq 1.4 \text{kA}$ (Fig. 20). Using a de-coupling resistor and a capacitor between the HA output grid and the HA, a negative auto-bias potential up to $-300 \text{V}$ was achieved. The latter prevents the plasma from penetrating into the AC gap, allowing the diode operation in a space-charge limited mode. It was also found that extraction of electrons from the HA plasma leads to a drastic increase in the plasma potential (up to several kV) with respect to the HA walls and output grid (Fig. 20). However, extraction of electrons from the positively charged plasma is possible due to the screening of the grid potential by randomly moving plasma ions.

It was shown that in the case of a uniform plasma density distribution in the vicinity of the HA output grid the distribution of the electron beam density is also uniform (Figs. 21 and 22). Here in the main part of the accelerating pulse the diode operates in a space-charge limited mode.

6. **Summary**

In this review we presented the experimental data concerning parameters of MCPS, carbon fiber, velvet cathodes, FPS and FPS-assisted HA electron sources. These sources were used for generation of electron beams with current up to 2kA, electron energy of 300keV and pulse duration of 250ns.

**Acknowledgements**

We are grateful to Dr. A. Dunaevsky for his active participation in some of these experiments. This research was supported by the
Absorption, State of Israel.

Center for Absorption in Science, Ministry of Immigrant Absorption, State of Israel.

(Manuscript received Jan. 9, 2007, revised July 2, 2007)

References


Yaakov E. Krasik (Non-member) received the M.Sc. (1976) and Ph.D. (1980) in physics from the Tomsk Polytechnical Institute, Russia. From 1980 to 1991, he was with the Nuclear Research Institute, Tomsk and from 1991 to 1996 with the Weizmann Institute of Science, Rehovot, Israel. Since 1997 to he has been with the Physics Department, Technion, Haifa, Israel, where he is currently a Associated Professor. His main research interests are related to pulsed current-carrying plasmas.

Joseph Z. Gleizer (Non-member) received the M.Sc. degree in electrical engineering physics and Ph.D. in Particle Accelerators from Tomsk Polytechnics University, Tomsk, Russia in 1977 and 1970, respectively. He is currently the Senior Scientist in the Department of Physics, Technion, Israel. His research is related to the non-stationary current-carrying plasma including active plasma cathodes and explosive emission plasma.

Yakov E. Krasik

Dmitry Yarmolich (Non-member) received the B.Sc. degree in physics from the Belarus State University, Minsk, M.Sc. degree in physics from the Technion, Israel in 1996 and 2005, respectively. Currently he is a Ph. D. student at the Plasma and Pulsed Power Lab., Physics Department, Technion, Israel. The subject of his research is related to active plasma cathodes for high-current electron beam generation.

Vladislav Vekselman (Non-member) received the M. Sc. Degree in physics from the Kazan University, Russia, in 2000. Currently he is a M.Sc. student at the Plasma and Pulsed Power Lab. in the Physics Department, Technion, Israel conducting of plasma cathodes.

Yoav Hadas (Non-member) received the B.Sc. degree in physics from the Technion, Haifa, Israel in 2005. Currently he is a Ph.D. student at the Plasma and Pulsed Power Lab. in the Physics Department, Technion, Israel conducting of plasma cathodes.

Alexander Krokhmal (Non-member) received the M.Sc. degree and Ph. D. degree in physics from the Charkov Physics Institute, Russia and Technion, Haifa, Israel in 1995 and 2005, respectively. Since 2005 he is with Jordan Valley Semiconductor, Israel. His main research interests include plasma carrying plasma and x-ray diagnostics.

Konstantin Chirko (Non-member) received the M.Sc. degree and Ph. D. degree in physics from the Tomsk Polytechnical Institute, Tomsk, Russia and Technion, Haifa, Israel in 1992 and 2004, respectively. Since 2005 he has been with Applied Materials, Israel. His main research interests include plasma carrying plasma and plasma processing.

Or Peleg (Non-member) received the B.Sc. degree and M. Sc. Degrees in physics from the Technion, Israel in 2002 and 2005, respectively. Currently he is a Ph. D. student at the Physics Department, Technion, Israel. The subject of his research is related to active plasma cathodes and non-linear optics.

Joshua Felsteiner (Non-member) received the B.Sc. degree in physics and mathematics from the Hebrew University of Jerusalem, Israel, and the Ph.D. degree in physics from the University of Toronto, Canada, in 1962 and 1967, respectively. Since 1967, he has been with the Physics Department, Technion, Haifa, Israel, where he is currently a Professor. His main research interests include solid state and plasma physics.