Space- and time-resolved characterization of nanosecond time scale discharge at pressurized gas

S. Yatom, V. Vekselman, J. Z. Gleizer, and Ya. E. Krasik

Physics Department, Technion, 32000 Haifa, Israel

Nanosecond discharge in dense gases has been the focus of intense research since the 1960’s due to the interesting physical phenomena involved and its important practical applications. Plasma produced in such a discharge is used widely for pulsed laser pumping, effective release of energy from microwave compressors, and switching of low-inductance gas spark gaps, and has potential applications in biomedical treatments, fast combustion of gas mixtures, and aerodynamics. It is also known that nanosecond time-scale high-current gas discharge is accompanied by short-duration X-ray emission,[1 - 5] the latter being explained by the generation of high-energy non-thermal runaway electrons (RAE). In spite of intense experimental and theoretical research studies, the role of the different phenomena that govern the high-current pressurized discharge and the generation of the RAE beams remains unclear.

In the experiment, the gas-filled diode was driven by an all-solid state nanosecond high-voltage (HV) generator. The electrical scheme of the generator is similar to that described in Ref. 6. The generator has two outputs with pulse durations of 1 ns and 5 ns, where the pulse duration is defined at full width at half maximum (FWHM) with amplitudes of $V \approx 100$ kV and $V \approx 200$ kV respectively. The design of the gas-filled diode used in the current research is presented in Fig. 1. A stainless steel 10 mm width blade served as a cathode. For time-resolved X-ray and visible light diagnostics, two photo-multiplier tubes (PMT), were used. Time- and space-resolved imaging of the lightemission from the anode-cathode (AC) gap was carried out using a fast framing 4QuikE camera (Fig. 2b). Observation of different stages of discharge allowed us to calculate the velocity of the plasma light emission front propagation for different gas pressures and AC gap lengths. In addition, to verify the RAE beam energy distribution

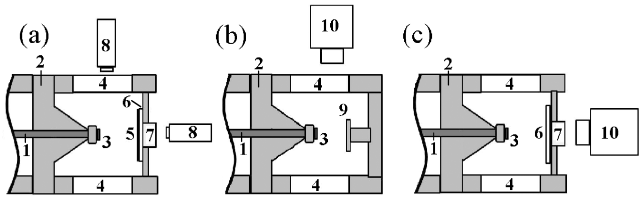

Fig. 1. (a) Diode configuration for light and x-ray diagnostics, (b) diode configuration for optical imaging diagnostics, (c) diode configuration for RAE beam diagnostics. 1- transmission line, 2- insulator, 3- cathode, 4- windows, 5- *Ta* foil, 6- *Al* foil, 7- plastic scintillator, 8- PMT, 9- anode , 10- fast-framing camera.

obtained from the X-ray analysis and to find the maximum RAE energy, the experiments were carried out. A scintillator was placed behind the *Al* foil, which served as an anode, and a camera was placed behind it (see Fig. 1c). Varying the thickness of *Al* foils (10-60 μm), the images of different light intensities due to electrons having sufficient energy to penetrate the given aluminum foils were obtained.

Typical side view framing images of the discharge light emission for a 1.5 cm AC gap supplied by a 1 ns duration HV pulse for different time delays with respect to the beginning of the light emission at the cathode edge at air gas pressure 3×10^5 Pa are shown in Fig. 2. One can see that the discharge occurs in the form of several plasma channels, originating from the cathode edge. The most intense light emission occurs from the upper and lower cathode edges where one expects the largest values of the electrical field enhancement to be. The framing images demonstrate that the light emission from the discharge channels is diffusive in form at atmospheric pressure and AC gaps in the range 1–3 cm. In the case of elevated pressure ($\geq 2\times10^5$ Pa), discharge plasma channels

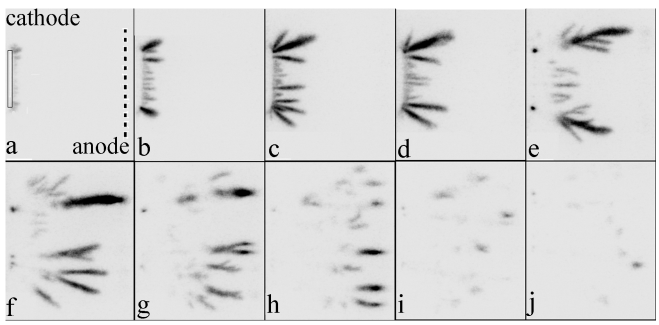

Fig. 2. Light emission evolution across 1.5 cm AK gap at air pressure of 3×10^5 Pa, 1 ns duration HV pulse. Frame duration - 1.5 ns. The time delay of the frame beginning with respect to the appearance of light at the cathode in nanoseconds: (a) 0, (b) 0.3, (c) 1.5, (d) 1.7, (e) 3.1, (f) 4, (g) 6.4, (h) 6.7, (i) 6.9, and (j) 7.8.

have a "contracted" form (Fig. 2), for AC gaps > 1 cm. In addition, one can see in Fig. 2 that the process of plasma recombination in pressurized discharges occurs in the nanosecond time scale after the HV termination. The plasma light emission front propagation velocity was found to be dependent on the air pressure and AC gap length. Namely, this velocity steadily decreases with the increase in gas pressure and gap length, as can be expected. Summarized data on the plasma light emission front propagation velocity versus the pressure *P* and AC gap length *d* are presented in Fig. 3. Let us note that the velocities (~10^9 cm/s) that were obtained greatly exceed the plasma thermal electron velocity (for reasonable electron temperature <20 eV).

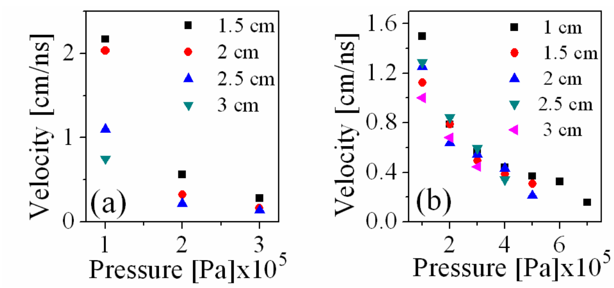

Fig. 3. Dependence of light emission front propagation velocity on air pressure and AK gap length for (a) 1 ns and (b) 5 ns HV generator pulse durations.

In order to obtain the energy distribution of the RAE beam, a set of *Al* foils whose thickness was in the range (10 – 60) µm were placed in front of the scintillator (see Fig. 1a), and ~100 images were recorded by the framing camera for each foil thickness. The dependence of the light intensity versus the *Al* foil thickness is shown in the insert to Fig. 7. We used NIST data for electron stopping power in aluminum for an energy range 1 - 200 keV to recover the electron energy spectrum. Computer simulation recreated the intensity decay curve for electrons that penetrate the *Al* foils of the thicknesses used in the experiment. This simulated curve was compared to the experimental one, to yield the best-fitting electron energy spectrum. The result of this analysis for a 1 ns HV pulse is presented in Fig. 4. According to the best fitted simulated RAE energy spectrum, the maximum electron energy is ~110 keV, which is smaller than $e\varphi_{ac}$~122 keV.[7] Here let us note that in the experiment the use of 64-µm thick *Al* foil (cutoff electron energy of ~94 keV) already led to a decrease in the light intensity to noise level. The latter indicates the small amount of electrons with E_e > 94 keV. To check this result, the electron maximum energy in the same diode with pressure reduced down to ~1 Pa was measured (see Fig. 2c). In this case, one can consider gas-filled diode operation as a vacuum diode where electrons acquire energy equal to $e\varphi_{ac}$. These experiments showed a high light intensity with 64-μm thick *Al* foil and only with 110-μm thick *Al* foil (cutoff electron energy of ~120 keV) does the light intensity decrease to noise level. Thus, as could be expected, one can state that the decrease in the pressure leads to an increase in the amount of high-energy electrons with $E_e \approx e\varphi_{ac}$.

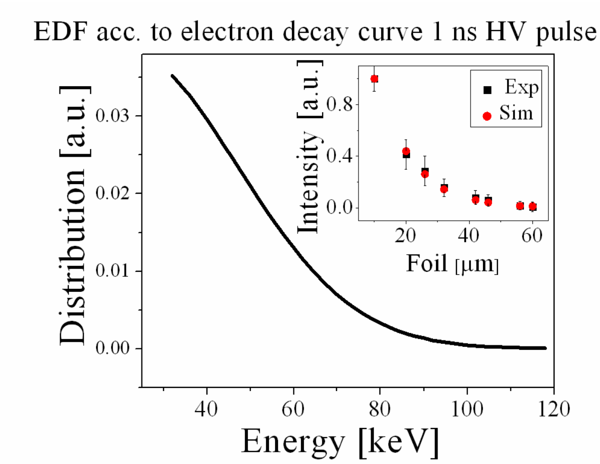

Fig. 4. RAE energy distribution function for 1ns HV pulse. AK gap is 1 cm, air pressure is 10^5 Pa. Intensity of the recorded images vs. Al foil thickness is shown in the insert.

References

1. J. C. Martin, *On Pulsed Power* (Plenum Press, New York, 1996).
2. L. P. Babich, T. V. Loiko, V. A. Tsukerman, Soviet Phys. Usp. **33**, 521 (1990).
3. L. V. Tarasova, L. N. Khudyakova, T. V. Loiko, and V. A. Tsukerman, Zh. Tekh. Fiz. **44**, 564-568, (1974).
4. G. A. Mesyats and M. I. Yalandin, IEEE Trans. Plasma Sci. **37**, 785 (2009).
5. V. F. Tarasenko and I. D. Kostyrya, Russian Physics Journal **48**, 1257 (2005).
6. S. N. Rukin, Instruments and experimental techniques **42**, 439 (1999).
7. S. Yatom, V. Vekselman, J. Z. Gleizer, and Ya. Krasik, Space-and time-resolved characterization of nanosecond time scale discharge at pressurized gas, J. Appl. Phys., **109**, 073312, (2011).