Combined dc electric–ultraviolet to near infrared optical breakdown of Ar in a wide range of impact parameters

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Abstract. A combined dc electric–optical breakdown ($\lambda = 213, 266, 355, 532$ and $1064$ nm; $\tau_{\text{FWHM}} = 68$ ps, 18 ns; $I_0 = 10^9–10^{13}$ W/cm$^2$; $E_{\text{dc}} = 0–13.2$ kV/cm) and discharge dynamics in argon has been experimentally investigated at pressures ($p = 1.0 \times 10^1–5.57 \times 10^5$ Pa). Breakdown thresholds were evaluated at different gas pressures and irradiation wavelengths for 0.5 breakdown probability in terms of laser and electric components. It has been discovered that such a combined breakdown could take place at laser and electric components values significantly less than those for “pure” optical or electric impact.

1. Introduction
Ignition of pulsed breakdown in gases has been studied for a long time and has a number of applications. Various combinations of dc, gas, rf [1], microwave electric and optical fields [2–4] have been studied by the moment, including injection of seed electrons (thermal [5], photoemission [6], chemical reactions or pre-ionization of the gas gap [7]). In most cases, both fields’ vectors are collinear at combined impact (or radiation propagates along the electric field). For combined impacts, three regimes are considered in [8], two of those correspond to one of the components predominance, and a region of truly combined impact.

Characteristic electric and optical breakdown threshold minima in gases are in the regions of $10^2–10^3$ Pa and $10^6–10^7$ Pa, respectively [9]. For each breakdown ignition method, besides minimum threshold regions, there are regions where combined impact has the highest energy efficiency. Analysis of electric and optical breakdown mechanisms suggest the presence of synergistic effects at combined impact, being associated with seed electrons origin and their acceleration in different regimes and under different conditions [10].

2. Experimental setup
Setup is based on a vacuum chamber pumped by a dry vacuum station (Pfeiffer vacuum TSH071e), the pressure is recorded by a diaphragm vacuum gauge (Ceravac CTR100), which is insensitive to the gas type [11]. Argon (99.998%, Linde Gas) pressure in the experimental chamber initially pumped down to $10^{-2}$ Pa was varied from $5.5 \times 10^5$ Pa to $10^4$ Pa. Nd:YAG pico-($\tau_{\text{FWHM}} = 68$ ps) and nanosecond ($\tau_{\text{FWHM}} = 11–18$ ns) lasers (Lotis TII LS-2147, LS-2151...
Figure 1. Thresholds of Ar combined breakdown at 18 ns, 213 nm laser impact: 1—
$p = 1 \times 10^5$ Pa; 2—$p = 1.8 \times 10^4$ Pa; 3—$p = 2.3 \times 10^4$ Pa; 4—$p = 1.1 \times 10^4$ Pa; 5—$p = 5.5 \times 10^3$ Pa; 6—$p = 2.8 \times 10^3$ Pa.

and Solar LS LQ929) provided five harmonics ($\lambda = 1064, 532, 355, 266,$ and 213 nm) in pulsed-
periodic mode (10 Hz). The radiation was focused by a quartz lens $F = 150$ mm in a spot of
0.1 mm diameter. Inter-electrode gap was fixed at 3.8 mm and 10 mm. A positive potential
up to $U = +5$ kV was supplied (Stanford Research Systems PS350/5000V-25W) through a
high-voltage feedthrough to the lower flat copper electrodes; the upper one was grounded, and
the electric field strength reached $E = 13.2$ kV/cm (current limited to 5.25 mA) was achieved.
Breakdown was detected by the presence of plasma broadband emission for optical breakdown
and by circuit shortening during combined and electric breakdown. Nomarski interferometer
with a 20 ns gated ICCD camera (Nanoscan Nanogate-2) was used to record the discharge
dynamics.

The optical and electric breakdown thresholds were first evaluated at different Ar pressures;
the results of these reference experiments correspond well to [12, 13]. To measure the combined
breakdown thresholds, we varied radiation power density at fixed voltage until threshold
was reached. Optical breakdown of a medium is probabilistic by nature [14]; we used the
values corresponding to 50% breakdown probability as threshold ones. Between the series of
measurements, voltage was turned off to neutralize the gas, since accumulation of charged
particles leads to distortion of measurement results (this was most obvious during the reference
experiments in the air).
Figure 2. Synergistic factor maximum and relative electric field strength for it for combined Ar breakdown at 68 ps, 355 nm laser impact.

3. Results and discussion

Breakdown phenomena in argon are studied well enough [15–17], but we still obtained some new data on the thresholds for optical breakdown in the ultraviolet (uv) range and combined electro–optical breakdown (figure 1). For analysis of the results, it is reasonable to use relative quantities characterizing the change in the combined breakdown threshold components (optical and electric ones): $i = I_0/I_{opt}$ and $u = E/E_{el}$. Direct current electric field influence on the combined breakdown threshold optical component increases as the pressure and radiation wavelength decrease. This trend can be explained by the fact that the probability of multiphoton ionization increases proportionally to the photon energy, while decrease in gas number density reduces the probability of seed electrons recombination during their number doubling time (20 ps) and increases electron energy as a result of acceleration in the electric field between. Comparison of our results with the data in [18] shows that the energy density for the fundamental frequency radiation (i.e. number of photons [19]) required for optical breakdown of Ar is not very different for exposure to 2.5 ps and 12 ps pulses (the electric field strength in the light wave differs by a factor of 70).

To characterize combined thresholds deviation of pure values, we suggest to use a synergistic factor $S = (u - 1) \ln i$—more pronounced combined impact effect is, greater value this parameter has ($S < 0$ at negative effect [11]). Synergistic effect becomes more pronounced with pressure and wavelength decrease and its maximum moves towards less $u$ (figure 2).

Multiphoton ionization and electron tunneling in the field of a strong electromagnetic wave are possible during exposure to short radiation pulses [20]. Presence of natural seed electrons in a small focal region is unlikely during action of a short laser pulse. Multiphoton ionization of Ar was studied in [21, 22], where a slight dependence of its probability on wavelength was demonstrated for visible–near infrared (nir) radiation, those were higher than calculated values (ionization potential is $I_{Ar} = 15.76$ eV, and for 1064 nm the required number of photons is $n = 14$). In [23], a small difference was observed in the optical breakdown thresholds for
Figure 3. Discharge in Ar (5.5 bar) 1 s after optical breakdown ignition at potentials applied to 3.8 mm gap: a—0 kV; b—1 kV; c—2 kV; d—3 kV; e—4 kV; f—5 kV.

Resonant and non-resonant impact, i.e., electrons are formed due to the tunneling effect or processes involving interaction between radiation and a condensed phase (dust, aerosol particles) rather than due to photoionization. In [18], it was shown experimentally that during exposure to ultrashort (1 ps) pulses, when radiation power density reaches $10^{15}$ W/cm$^2$, ionization of noble gases atoms, including Ar, is described well by semi-classical tunneling theories (i.e., ionization occurs due to Coulomb processes in the electric field of a light wave), but multiphoton ionization dominates even for pulse durations of 50 ps for visible (586 nm) radiation.

The decrease in the electric component of the breakdown threshold may be caused by electrons photoemission from the cathode surface under scattered laser or optical breakdown plasma uv radiation. A rarefied region is formed behind laser-induced shock wave front, so decrease may also happen according to Paschen’s law. The ionization front behind this shock wave could also increase the effective conductance of the inter-electrode gap. The substantial decrease of the combination breakdown threshold optical component during exposure to uv laser radiation indicates partial ionization of the gas even without optical breakdown. Such a phenomenon is well known for a train of picosecond uv pulses [24] directed along the electric field. In our experiment, the radiation was directed perpendicularly. The role of a specific mechanism for the breakdown thresholds decrease obviously changes depending on radiation spectral and power characteristics, the electric field strength, the gas pressure and the gas type [25].

Discharge dynamics has been recorded to discover combined breakdown mechanisms and features. Electric arc and laser induced shock wave energies ratio resulted in different interaction patterns (figure 3). Main feature of those was dense radiating filament formation due to arc induced annular compression of optical discharge plasma. This phenomenon became more pronounced at high u since electric circuit was shortened earlier ($10^{-7}$ s order) after optical
breakdown. Laser induced shock wave dynamics analysis in terms of Sedov’s theory for point explosion [26] shows that, being interpolated with allometric function \( y = a + b^{-c}, (R^2 > 0.996) \), front movement dimensionality with beam waste source size correspond to flat one in axial direction and is nearly cylindrical for radial. For combined breakdown arc induced shock wave is also well described with flat front approximation ca. 250 ns delayed after laser impact (at 5 kV). Laser induced shock wave radial dimensions become influenced by the electric arc: contact surfaces of radiation and Joule heated gas regions become obvious near optical axis, multiple internal shock waves can be seen further.

4. Conclusions

Thresholds for electro–optic combined breakdown of Ar exposed to uv–nir radiation in a dc electric field have been experimentally evaluated. Combined breakdown threshold’s electric and optical components substantial decrease has been demonstrated, most pronounced at reduced pressures and at exposure to uv radiation. Radiation energy not power density rates shown to be critical for breakdown. Combined discharge dynamics has been recorded, that revealed lateral compression of laser-induced plasma by the electric discharge, leading to formation of \( 10^{-6} \) s order lifetime dense emitting region extended along the optical axis.

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