Optical Breakdown

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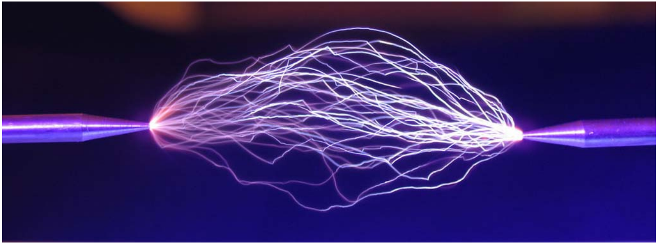
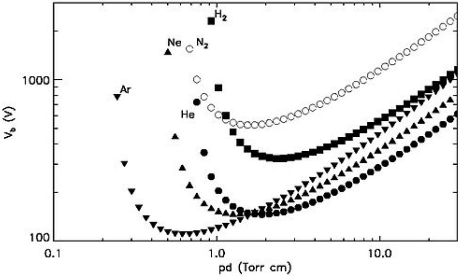
Abstract

Article studies optical breakdown effect in focused laser radiation. Theoretical description of breakdown formation in gases provided. Threshold fields are estimated. Spectra and oscillograms of breakdown spark measured in different substances.

Introduction

Static electrical breakdown

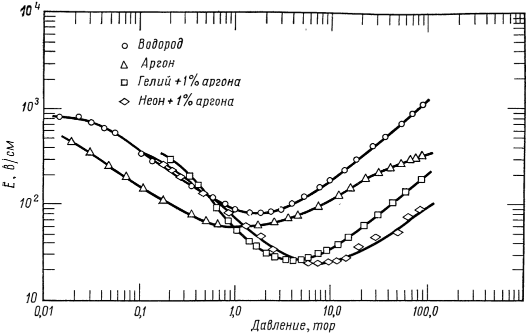




Paschen's law describes static electrical breakdown.

Alternating-field electrical breakdown

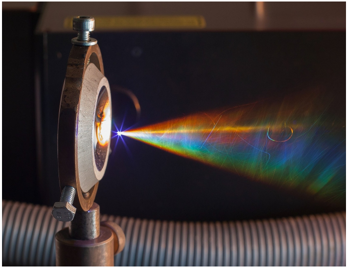
Mercury lamp



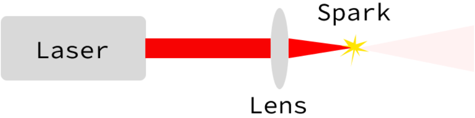
Threshold field on pressure
(f = 992 MHz, diffusion length 0.631 cm)

Alternating field also induces breakdown.

Optical breakdown



Femtosecond laser air breakdown



Basic scheme

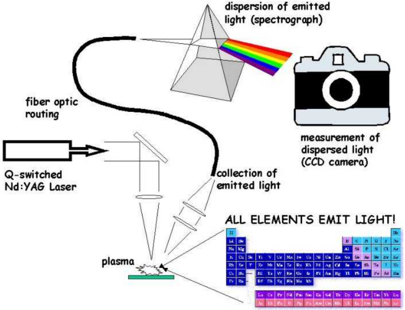
- Optical breakdown – $E \approx 10^6 \div 10^7$ V/cm.
- Static and alternating field – $E \approx 3 \cdot 10^4$ V/cm.

Charachteristic parameters:

$$P \approx 30 \text{ MW}, \quad d = 0.2 \text{ mm}$$

$$S \approx 10^5 \text{ MW/cm}^2, \quad E \approx 6 \cdot 10^6 \text{ V/cm}$$

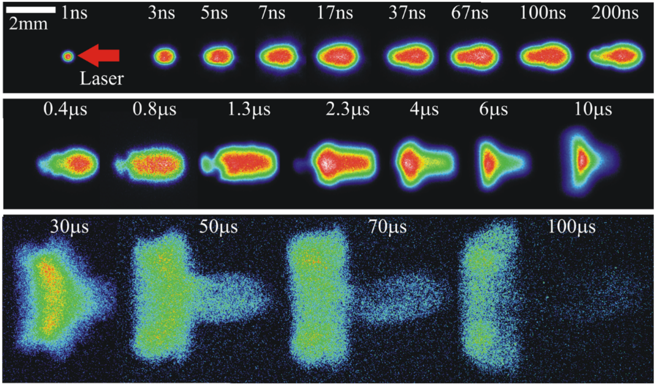
Optical breakdown applications



Laser-Induced Breakdown Spectroscopy (LIBS)

- Laser-Induced Breakdown Spectroscopy.
- Connected with nuclear fusion.
- Development of quantum theory.

Spark stages



Spark evolution in time

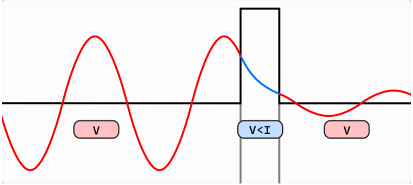
Three stages of laser spark:

- Breakdown: ionization and initial plasma formation.
- Plasma-photon interaction, plasma front movement.
- Shock wave spreading, glowing.

Theory

Breakdown initiation – Tunneling vs Photoeffect

Two mechanisms of electron ejection by radiation:

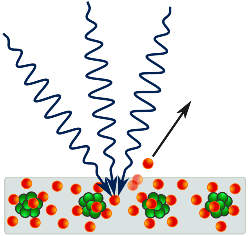


Quantum tunneling

- E – lightwave field.
- ω – ligthwave frequency.
- I – ionization energy.

$\Delta \sim \frac{I}{eE}$ – potential barrier width.
$v \sim \sqrt{I/m}$ – electron velocity.
$\tau \sim \Delta/v \sim \frac{\sqrt{Im}}{eE}$ – electron time-of-flight of barrier.

$\omega\tau \ll 1$ – 'static' field condition.



Multiquantum photoelectric effect

$\omega\tau \gg 1$ – condition of many quanta absorption on oscillation.

Estimation on optical frequencies gives $\omega\tau \gg 1$.

Multiquantum photoeffect probability

- w – multiquantum photoeffect probability
- n – number of absorbed photons
- S – light intensity

$w \sim S \sim E^2$ – proportional to intensity.
$w \sim \frac{1}{I}$ – higher ionization energy implies lower probability.
$w \sim \frac{1}{\omega}$ – lower frequency implies more time to absorb photons.
$w \sim (...)^n$ – n-fold absorption.

$$w \sim \left(\frac{E^2}{\omega I}\right)^n$$

According to quantum mechanics L.V.Keldysh obtained:

$$w = B\omega n^{3/2}\left(\frac{\bar{e}e^2E^2}{8m\omega^2 I}\right)^n \tag{1}$$

Threshold field estimation

Within $t_1 \approx 40$ ns in spot of $r \approx 0.2$ mm $N = 10^{13}$ electrons should appear:

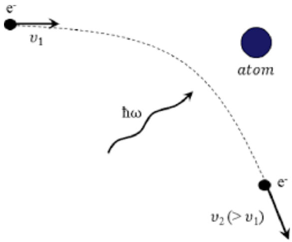
$$N = \frac{4}{3}\pi r^3 N_a t_1 w$$

$$\boxed{E = \sqrt{\frac{8m\omega^2 I}{\overline{e}e^2}}\left[\frac{w}{\omega n^{3/2}}\right]^{1/2n}}$$

	Xenon	Argon	Air
Experiment[1], V/cm	$(1.5 \div 2.3) \cdot 10^6$	$(2.7 \div 3.1) \cdot 10^6$	$(5 \div 13) \cdot 10^6$
Estimation, V/cm	$110 \cdot 10^6$	$150 \cdot 10^6$	$130 \cdot 10^6$

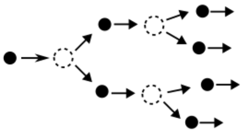
[1] According to: [1], [4], [5], [3], [6]

Breakdown development – electron avalanche



Inverse bremsstrahlung

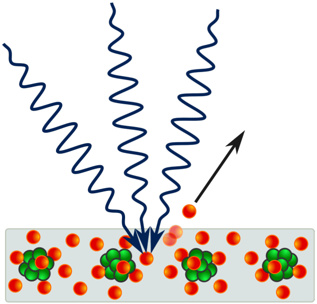
- Classic: in alternating field oscillation energy converts to heat in collisions.
- Quantum: electron absorbs photons on collisions.



Electron avalanche

Electron avalanche develops.

Breakdown development – Photoeffect vs Avalanche



Multiquantum photoeffect

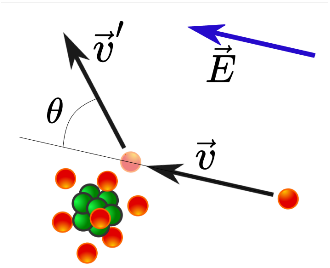
Electron absorbs few atoms simultaneously:

$n \cdot h\nu \sim n \cdot 2\ \mathrm{eV} > I \sim 10 \div 20\ \mathrm{eV}$

Breakdown development:

- $p \geqslant 1$ atm – electron avalanche.
- $p \ll 1$ atm – multiquantum photoeffect.

Energy growth – classic theory



Electron-atom collision

Isolated electron cannot take away field energy. Collision is essential condition.

$$\varepsilon_{\rm osc} = e^2 E_0^2 / 4m\omega^2 \sim 0.01 \text{ eV}$$

$$\varepsilon \sim 10 \text{ eV} \text{ – electron energy}$$

$$\boxed{\varepsilon \gg \varepsilon_{\rm osc} \gg h\nu}$$

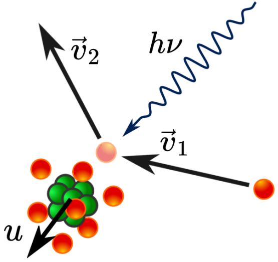
Motion equation with 'friction':

$$m\dot{v} = -mv\nu_m - eE \qquad E = E_0 \exp(-i\omega t)$$

$\nu_m = \nu_c(\overline{1 - \cos\theta})$ – effective collision frequency.
Work done by field on electron:

$$\boxed{d\varepsilon/dt = \frac{e^2 E^2 \nu_m}{m(\omega^2 + \nu_m^2)}} \qquad (2)$$

Energy growth – quantum theory



Photon absorption

Photon energy is much higher than oscillation energy:

$$h\nu = 1.8 \text{ eV} \gg \varepsilon_{\text{osc}} \approx 2.3{\cdot}10^{-2} \text{ eV}$$

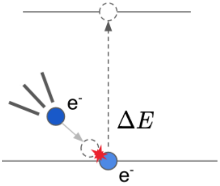
(ruby laser,
$\omega = 2.7 \cdot 10^{15}$ *Hz,* $E \approx 10^{7}$ *V/cm)*

Quantum mechanics shows that classic formula conditions can be enhanced:

$$\boxed{\varepsilon \gg h\nu \gg \varepsilon_{\text{osc}}}$$

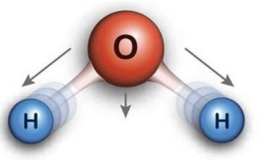
Electron energy $\varepsilon \approx 10$ *eV meet conditions.*

Electron energy loss



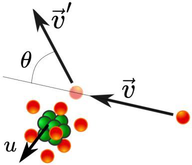
Excitation by collision

Non-elastic
$\varepsilon \sim 2/3I \div 3/4I$
(inert gases)



Molecular vibrations

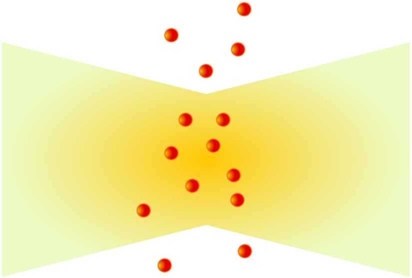
Non-elastic
Whole range of ε
(molecular gases)



Collision recoil

Elastic
All collisions

Electron losses



Electron diffusion

Main loss mechanism – diffusion from focus spot.

Breakdown criterion

- Pressure $p \ll 100$ atm $\Rightarrow$ energy losses $\ll$ diffusion.
- Laser impulse time t_1 is very short $\Rightarrow$ diffusion is negligible.

Electron amount:

$$N_e = N_0 e^{\nu_i t} \qquad \nu_i = \frac{1}{I}\frac{d\varepsilon}{dt}$$

ν_i – electron-atom ionization frequency,
Within impulse time $t_1 \approx 30 \div 50$ ns $N_1 \approx 10^{13}$ electrons should appear:

$$\boxed{\nu_i > \frac{\ln(N_1/N_0)}{t_1}}$$

Threshold field estimation

Combining ionization frequency ν_i with energy growth $d\varepsilon/dt$:

$$\boxed{E = \left[\frac{m\omega^2 I}{e^2\nu_m t_1}\ln\frac{N_1}{N_0}\right]^{1/2}}$$

	Xenon	Argon	Air
Experiment[2], V/cm	$(1.5 \div 2.3)\cdot 10^6$	$(2.7 \div 3.1)\cdot 10^6$	$(5 \div 13)\cdot 10^6$
Estimation 1, V/cm	$110\cdot 10^6$	$150\cdot 10^6$	$130\cdot 10^6$
Estimation 2, V/cm	$1.5\cdot 10^6$	$2.7\cdot 10^6$	$2.4\cdot 10^6$

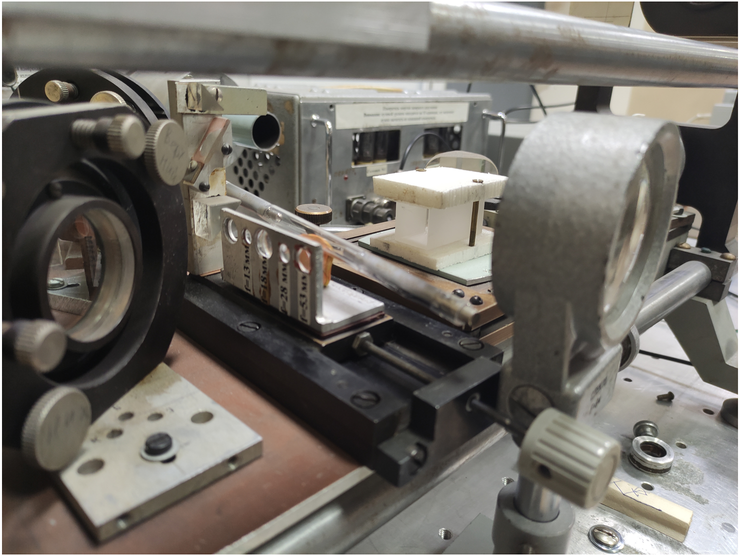
[2] According to: [1], [4], [5], [3], [6]

Измерения и Результаты

Экспериментальная установка

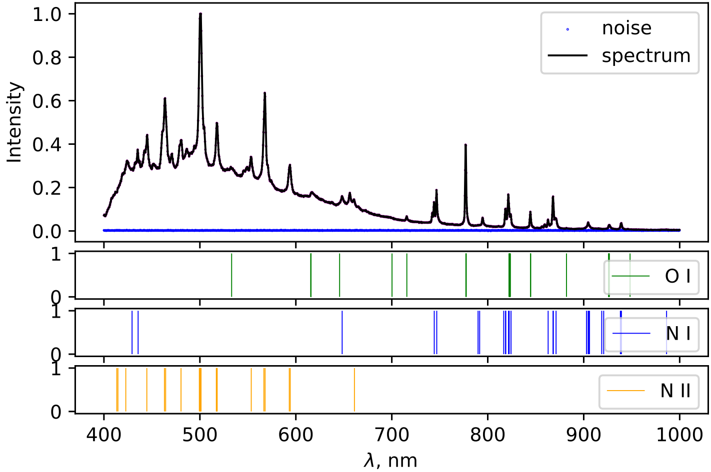
Общий вид установки
(на переднем фоне система линз для фокусировки вспышки)

Экспериментальная установка



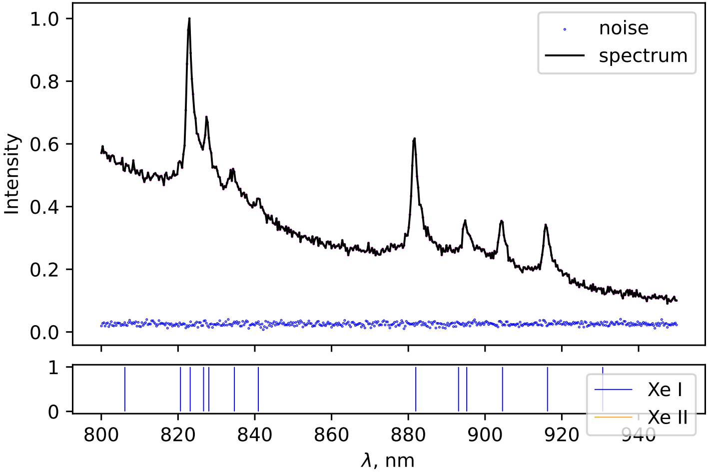
Площадка с набором линз для фокусировки пучка

Спектр воздушного пробоя



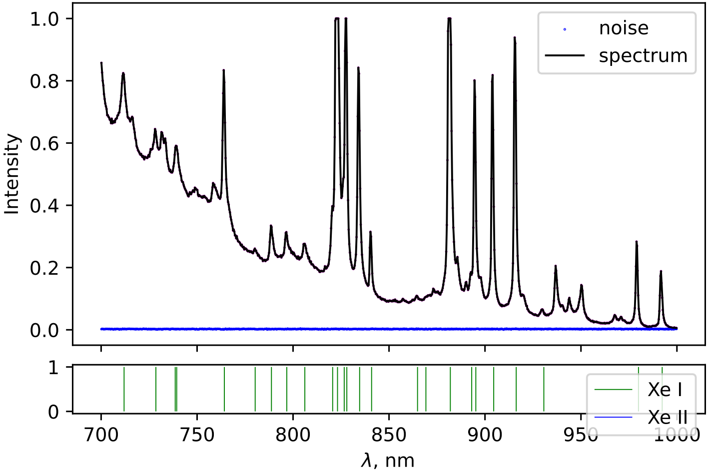
Спектр пробоя в воздухе

Спектр пробоя ксенона



Спектр пробоя ксенона в шаровой лампе

Спектр пробоя ксенона



Спектр пробоя ксенона в длинной лампе

Спектры

in progress...

Осциллограммы

in progress...

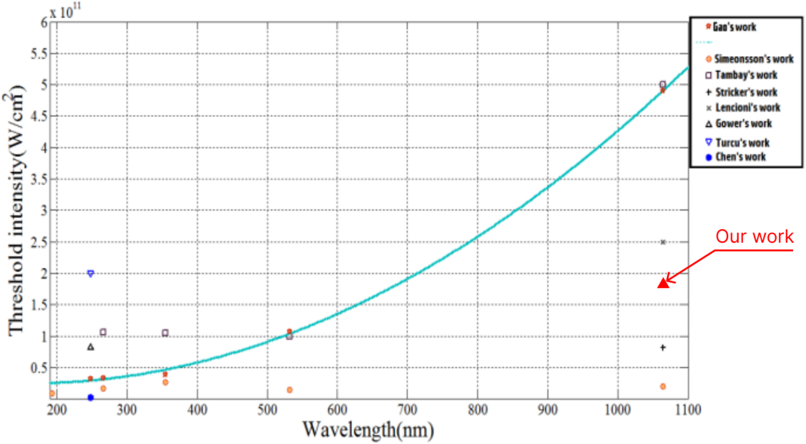
Conclusion

Conclusion

in progress...

Thank you for your attention!

Appendix: Air breakdown threshold



Variety of threshold fields

- Y. P. Raizer, 'Laser Spark and Propagation of Discharges'.
- S. S. Harilal, B. E. Brumfield, M. C. Phillips, 'Lifecycle of laser-produced air sparks'.
- Kai-Ting Yen, Chih-Hung Wu, Pin-Hsun Wang, Pi-Hui Tuan, Kuan-Wei Su, 'Investigating the Threshold Conditions of Air Breakdown with Mode-Locked Q-Switched Laser Pulses, and the Temporal Dynamics of Induced Plasma with Self-Scattering Phenomenon'
- F. Morgan, 'Laser beam induced breakdown in helium and argon'.
- Yosr E. E-D. Gamal, M. A. Mahmoud, Nagia Dawood, 'Numerical investigation of the threshold intensity dependence on gas pressure in the breakdown of xenon by different laser wavelengths'.
- Zhixing Gao, Lixuan Hana, Jing Lia, 'Investigation of laser induced air breakdown thresholds at 1064, 532, 355, 266 and 248nm'.
- H. Nishimura, T. Matsuda, A. Danjo, 'Elastic Scattering of Electrons from Xenon'.
- K. P. Subramanian, V. Kumar, 'Total electron scattering cross sections for argon, krypton and xenon at low electron energies'.
- A. Roldan, J.M. Perez, 'Energy deposition model for low-energy electrons (10–10 000 eV) in air'.