Optical Breakdown

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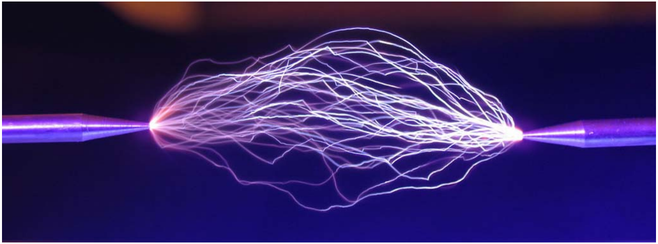
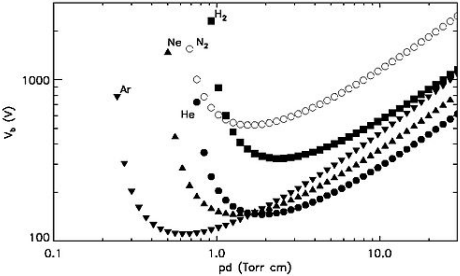
Abstract

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

Introduction

Static electrical breakdown

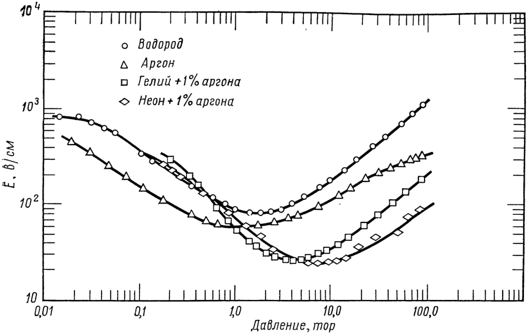




Paschen's law describes static electrical breakdown.

Alternating-field electrical breakdown

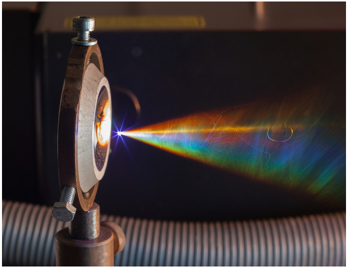
Mercury lamp



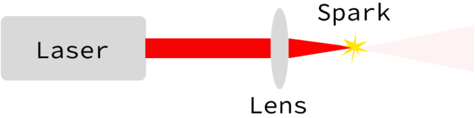
Threshold field on pressure
(f = 992 MHz, diffusion length 0.631 cm)

Alternating field also induces breakdown.

Optical breakdown



Femtosecond laser air breakdown



Basic scheme

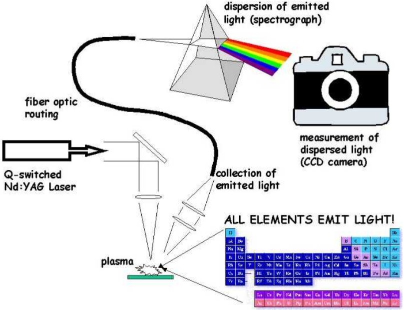
- Optical breakdown – $E \approx 10^6 \div 10^7$ V/cm.
- Static and alternating field – $E \approx 3 \cdot 10^4$ V/cm.

Charachteristic parameters:

$$P \approx 30 \text{ MW}, \quad d = 2 \cdot 10^{-2} \text{ cm}$$

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

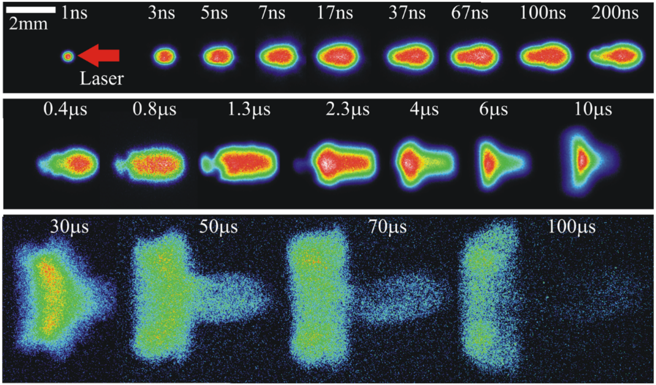
Optical breakdown applications



Laser-Induced Breakdown Spectroscopy (LIBS)

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

Spark stages



Spark evolution in time

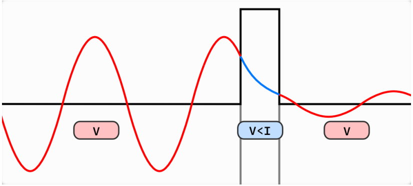
Three stages of laser spark:

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

Theory

Breakdown initiation – ionization by radiation

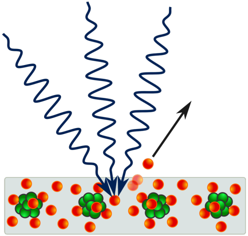
Two mechanisms of electron ejection by radiation:



Quantum tunneling

- E – lightwave field.
- 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 $r \approx 2 \cdot 10^{-2}$ cm $N = 10^{13}$ electrons should appear:

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

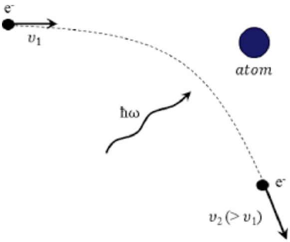
$$\boxed{E = \sqrt{\frac{8m\omega^2 I}{\bar{e}e^2}} \left[\frac{w}{\omega n^{3/2}}\right]^{1/2n}}$$

For argon:

$$E = 1.12 \cdot 10^8 \text{ V/cm – estimation}$$

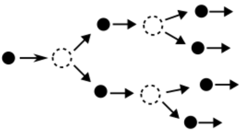
$$E = 2.69 \cdot 10^6 \text{ V/cm – experiment}$$

Breakdown development – electron avalanche



Inverse bremsstrahlung

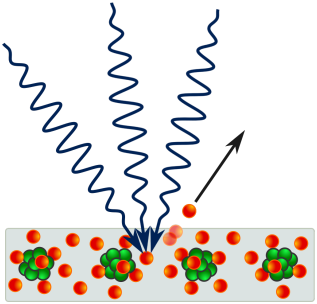
- Classic: in alternating field oscillation energy converts to heat in collisions.
- Quantum: electron absorbs photons on collisions.



Electron avalanche

Electron avalanche develops.

Breakdown development – multiquantum photoeffect



Multiquantum photoeffect

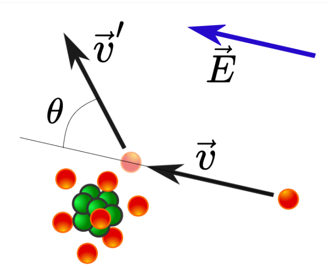
Electron absorbs few atoms simultaneously:

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

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.

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

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

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

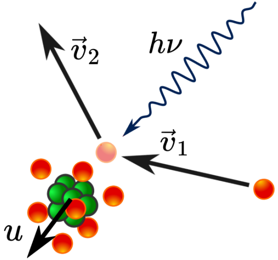
Motion equation with 'friction':

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

$\nu_m = \nu_c \overline{(1 - \cos\theta)}$ – 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)*

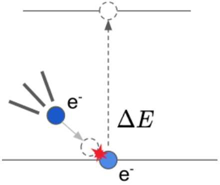
Quantum mechanics shows that classic formula conditions can be enhanced:

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

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

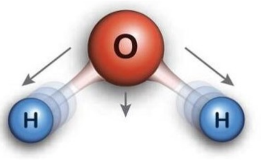
Electron energy loss

There are two types of energy losses: elastic and non-elastic.



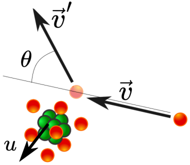
Excitation by collision

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



Molecular vibrations

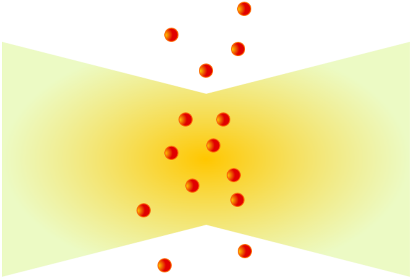
Non-elastic
Whole range of ε
(molecular gases)



Collision recoil

Elastic
All collisions

Electron losses



Electron diffusion

Main loss mechanism – diffusion from focus spot.

Breakdown criterion

Electron amount:

$$N_e = N_0 e^{[(\nu_i - \nu_d)t]} = N_0 e^{(t/\theta)},$$

$\theta = (\nu_i - \nu_d)^{-1}$ – avalanche time constant,
ν_i – electron-atom ionization frequency,
ν_d – diffusion loss frequency.
Within impulse time $t_1 \approx 30 \div 50$ ns $N_1 \approx 10^{13}$ electrons should appear:

$$\theta < \frac{t_1}{\ln(N_1/N_0)}.$$

Combining this condition with energy growth $d\varepsilon/dt$:

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

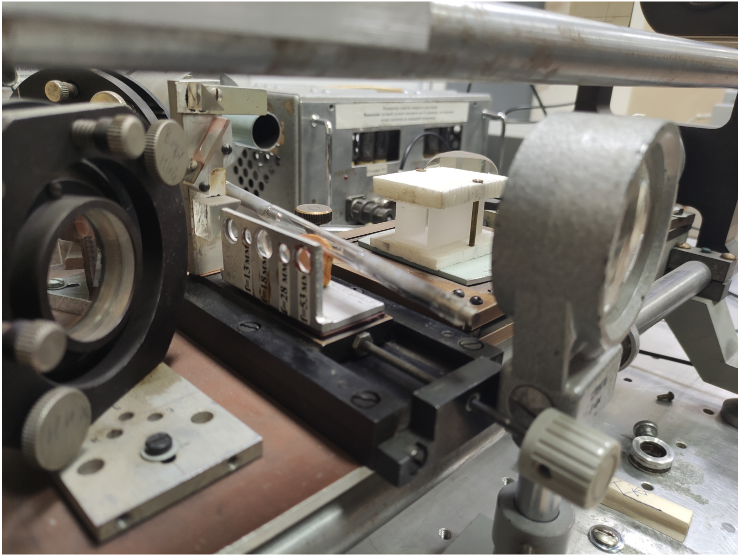
$\nu_m = \nu_c(1 - \overline{\cos\theta})$ θ – угол рассеяния.
$(1 - \overline{\cos\theta})$ обычно близка к 1 $\Rightarrow$ можно просто брать
$\nu_m = \nu_c$?.
$\nu_c = N_a v \sigma_c$, N_a – число атомов в 1 см^3, v – скорость электрона, σ_c – сечение упругого рассеяния.
Райзер, с53: У гелия частота столкновений почти не зависит от и энергии электронов $v_m \approx 2,4 \cdot 10^9 P$ (в торр). Полезно знать, что у водорода зависимость $\nu_m(v)$ также слабая и $\nu_m \approx 5.9 \cdot 10^9 P$ (в торр) Аргон: $\nu_m \approx 7 \cdot 10^9 P$ (в торр)

Измерения и Результаты

Экспериментальная установка

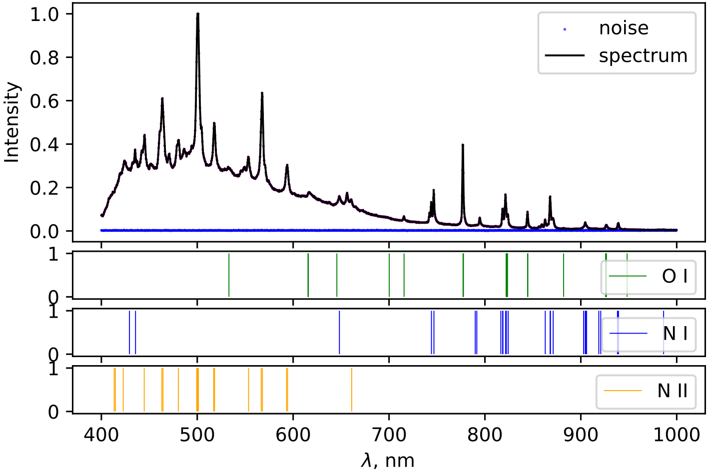
Общий вид установки
(на переднем фоне система линз для фокусировки вспышки)

Экспериментальная установка



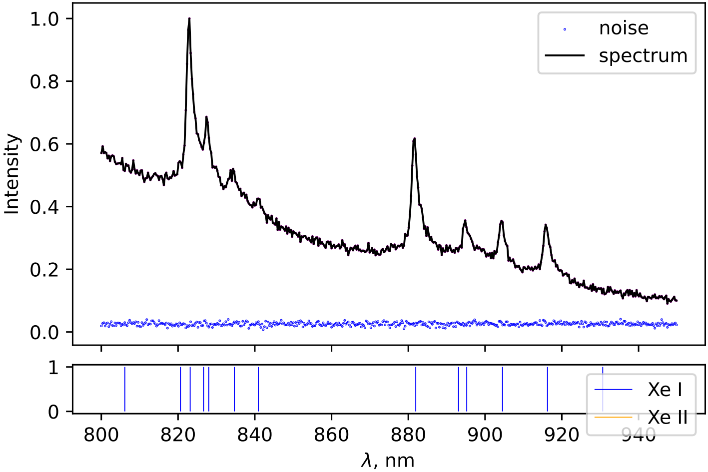
Площадка с набором линз для фокусировки пучка

Спектр воздушного пробоя



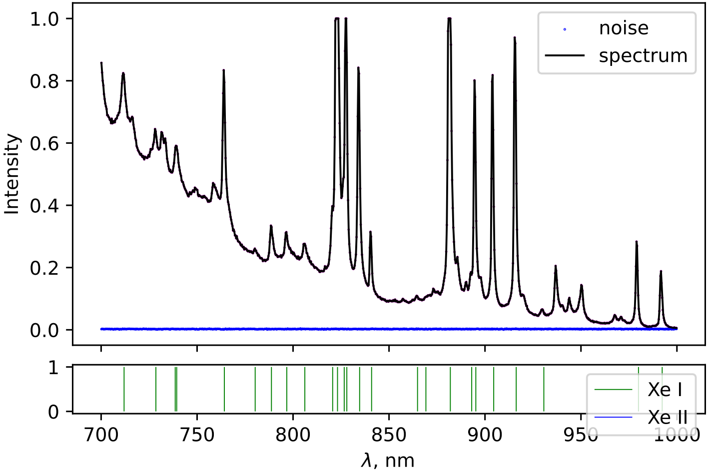
Спектр пробоя в воздухе

Спектр пробоя ксенона



Спектр пробоя ксенона в шаровой лампе

Спектр пробоя ксенона



Спектр пробоя ксенона в длинной лампе

Спектры

in progress...

Осциллограммы

in progress...

Выводы и Заключение

Выводы и Заключение

in progress...

Спасибо за внимание!