Plasma channels in air produced by UV laser beam: Mechanisms of photoionization and possible applications

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Charged and Neutral Particles Channeling Phenomena
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## Contents

- Applications of ionized channels produced by UV laser in gases:
  - guiding of HV electric and lightning discharges;
  - guiding of MW and THz radiation;
  - e-beam transport and acceleration;
- Experiments on HV discharges guiding at KrF GARPUN laser.
- Ionization of gases by UV laser light.
- Further investigations.
- Conclusions.

Laser sparks produced by pulsed Nd и CO₂ lasers is not continues and consists of separate plasma droplets; strong absorption restricts forward propagation of the laser beam.

These can be partially overcome by using axicon focusing but it requires rather high energy per unit length ~ 200 J/m for CO₂ laser: Appolonov et al, “Guiding of electrical discharge by continues laser spark under focusing of CO₂ laser beam by conical mirror”, Quantum Electronics, 32, 115 (2002).

UV laser light (λ=0.266μm) with pulse duration 35 ps make possible guiding a discharge of L= 40 cm at significantly lower energy ~10 mJ: Antipov et al, “Propagation of ionization wave (streamer) in along the laser-produced-channel”, Journal of Tech. Phys, 61, 200 (1991).
**Benefits of UV laser radiation for long-distance channels production**

- Diffraction divergence of KrF laser beam is 40 times less than that of CO₂ laser.
- UV laser beam produces uniform air ionization along the propagation due to 3- and 4-photon ionization of O₂ (ionization potential 12.2 eV) and N₂ (15.6 eV) without avalanche ionization.
- Critical electron density \( N_{ecr} = \frac{\pi c^2 m_e e^2}{\lambda^2} = 1.6 \times 10^{22} \text{ cm}^{-3} \) for KrF laser radiation (\( \lambda = 248 \text{ nm} \)) is two orders of magnitude higher than in fully ionized air plasma \( N_e = 2.7 \times 10^{19} \text{ cm}^{-3} \). As a result, plasma is transparent for UV radiation which can propagate up to \( \sim 2 \text{ km} \).
- For comparison, in CO₂–laser-produced plasma, electron density exceeds the critical value \( N_{ecr} = 10^{19} \text{ cm}^{-3} \) and about 50% of radiation (\( \lambda = 10.6 \mu \text{m} \)) is reflected by plasma.
**Polarization of the conducting channel – the main mechanism of lightning triggering**

*Distribution of charges in the thunderstone cloud and equivalent dipole*

The scales: $H \approx D \approx 3$ km; $Q_c \approx 10$ C. Potential relative to the ground in the middle of negative region $U \approx -290$ MB, near the lower boarder – 180MB. Average field strength $\sim 1$ kV/cm (Bazel’an & Raizer, *UPhN*, 170, 753 (2000)).

Lightning leader might be formed if in the 20-m channel electron density $N_e \sim 10^{12}$ см$^{-3}$ will be kept for $\sim 10$ µs, time of charge redistribution.

Charge flow along the channel leads to potential redistribution and field sharpening near the ends.
Virtual waveguides for microwaves

Idea of L. Losev: In virtual plasma waveguide the total reflection angle of microwave radiation at the plasma-air boundary has to exceed the diffraction angle:

$$\Theta = \left( \frac{\omega_p^2}{\omega^2 + \nu^2} \right)^{1/2} > \Theta_{MW} \approx \frac{\lambda}{d}$$

Simulations of I. Smetanin
Formation of hollow Bessel beams for guiding of THz
Electron balance in UV-ionized air plasma

Well-known processes:

(1) Multiphoton ionization (3-photon for $O_2$ and 4-photon for $N_2$)

(2) Attachment to $O_2$, is suppressed at $I > 2.5 \times 10^7$ W/cm$^2$

(3) Electron-ion recombination, predominate at $N_e > 10^{16}$ cm$^{-3}$

(4) Diffusion losses

(5) Photodetachment of $O_2^-$

(6) Recombination of $O_2^-$ and $O_2^+$ with $O_2^-$ and $N_2^+$

Less-known processes:

- Stepwise resonance photoionization ($2h\nu + h\nu$)
- Photoionization and photoeffect at airosol impurities
• After switch off an ionization source (UV light) electrons fully disappear in ~10 ns because of an attachment to $\text{O}_2$, while ion concentration falls down to $N_i \sim 10^{10}$ cm$^{-3}$ in ~100 µs due to recombination of $\text{O}_2^-$ with $\text{O}_2^+$, $\text{O}_4^+$ and $\text{N}_2^+$, being independent on the initial ionization,
For $O_2^-$ the bound energy $\sim 0.5$ eV and photodetachment process is available for $\lambda \leq 2500$ nm. For short wavelengths probability increases manifold (Burch et al., Phys. Rev., 112, 171 (1958) and UV light provides both initial photoionization and the following photodetachment of electrons.
Injection-controlled operation of GARPUN KrF laser

Far field

Input pulse
Output pulse

20 ns/div

0.1 mrad

Output
100J, 100 ns

Near field

Large-aperture GARPUN module

Master oscillator
EMG 150 TMSC

0.01J, 20 ns
Hybrid Ti:Sa/KrF laser facility GARPUN-MTW for amplification of short & long pulses

Berdysh e-beam-pumped preamplifier: 10*10*100 cm, 25J, 100 ns, ~0.1 mrad

Target chamber

Ti:S front-end “Start 248M”: 10 Hz; 60 fs; 8 mJ (λ = 744 nm) or 0.5 mJ (λ = 248 nm)

GARPUN e-beam-pumped amplifier: 16*18*100 cm, 100J, 100 ns, ~0.1 mrad
Experiments on laser triggering of HV discharge

KrF laser beam

τ=100 ns
E=40-0.1 J
λ=248 nm

$I=10^8 \div 5 \times 10^{10} \text{ W/cm}^2$

C=0.03 \text{ \mu F}
U=300-500 \text{ kV}
HV discharge gap
HV discharge without laser guiding
HV discharge with laser guiding
HV discharge at various conditions

$L=60 \text{ cm}$
$E=0.17 \text{ J}$
$U=+390 \text{ kV}$

$L=60 \text{ cm}$
$E=0.044 \text{ J}$
$U=+390 \text{ kV}$

$L=60 \text{ cm}$
$E=0.030 \text{ J}$
$U=+390 \text{ kV}$

$L=60 \text{ cm}$
$E=0.29 \text{ J}$
$U=-390 \text{ kV}$
**Electrical parameters of HV discharge**

1 – laser pulse  
2 – discharge current  
3 – HV pulse at the gap

\[ T = 4 \, \mu s \]  \[ C = 38 \, \text{nF} \]  \[ L = 10 \, \mu \text{H} \]

\[ R = 1.6 \, \Omega \] (short circuit)  
\[ R = 2.2-2.3 \, \Omega \] (nonguided discharge)  
\[ R = 1.8-2.2 \, \Omega \] (guided discharge)

\[ i(t) = A_0 \exp\left(-\frac{R_c}{2L_c}t\right) \left[ \frac{R_c}{2L_c} \sin(\omega t + \alpha_0) - \omega \cos(\omega t + \alpha_0) \right] \]

\[ T = \frac{2\pi}{\sqrt{\frac{1}{L_c C} - \frac{R_c^2}{4L_c^2}}} \]  
\[ A_0 = \frac{CU_0}{\sqrt{1 - \frac{R_c^2 C}{4L_c}}} \]
• At $U \sim 390$ kV maximal length of nonguided discharge was less than $l=50$ cm.
• Laser guided discharge length reached $l=80$ cm.
• At $l=60$ cm discharge guiding was kept for decreased laser energy down to $\sim 50$ mJ.
KrF laser: $E_{\text{las}} = 5 \div 100$ mJ, $\tau_{\text{las}} = 22$ ns, $F = 0.5, 2, 8$ m; $d_{\text{las}} = 25 \, \mu\text{m} \div 1 \text{mm}$, $I = 3 \times 10^6 \div 10^{11}$ W/cm$^2$, $l = 2 \div 10$ cm.

Distribution of radiation at the focal plane of the lens with $F=2$ m. Focal spot diameter is $\sim 100 \, \mu\text{m}$.
Oscilloscope traces

\[ R_{\text{load}} = 50\Omega, \ 10 \ \text{ns/div} \]

\[ R_{\text{load}} = 1 \ \text{M}\Omega, \ 0.5 \ \mu\text{s/div} \]

\[ R_{\text{load}} = 1 \ \text{M}\Omega, \ 50 \ \mu\text{s/div} \]

\[ R_{n} = 1 \ \text{M}\Omega, \ 500 \ \mu\text{s/div} \]
Current vs voltage dependences of photoionization discharge

\[ i_e = \nu_e S_{las} N_e e, \quad \nu_e = \mu_e E = \mu_e \frac{U}{l} \]

\[ N_e = \frac{i_e l}{\mu_e U S_{las} e}, \quad \mu_e \approx 1 \pi 2 A^{-1} \tilde{n}^{-1} \]

\[ \sigma_e = e \mu_e N_e \]
σ and $N_e$ dependences on laser intensity and probable ionization processes

$I = 5 \times 10^6 \div 5 \times 10^8 \text{ W/cm}^2$
linear dependence: $N_e \sim I$ – photoionization or photoemission of the impurities.

$I = 5 \times 10^8 \div 10^{11} \text{ W/cm}^2$ square power law: $N_e \sim I^2$ – two-step resonance ionization ($2h\nu + h\nu$).

$I > 10^{11} \text{ W/cm}^2$ – air breakdown.
High peak intensities required for multiphoton ionization are achieved at low energies of few mJ.

Negative phase modulation provides temporal compression of laser pulses along their propagation in atmosphere.

For peak power of KrF laser more than $P_{cr} = \frac{3.8\lambda^2}{8\pi n_0 n_2} \approx 100$ MW ($\lambda=248$; $n_0$ и $n_2$ – linear and nonlinear parts of the refraction index) Kerr self-focusing produces beam filaments with $\approx 100$ µm diameter and $N_e = 10^{15}-10^{16}$ cm$^{-3}$ propagating at multi-km distance.

$P_{cr}$ for $\lambda=248$ nm is 30 times lower, than for $\lambda=800$ nm (Ti:Sa laser).

Filaments are stable in adverse atmospheric conditions.

Filamentation of fs laser pulse along propagating length in dry air (left) and during the rain (right) (Mechain et al., Appl. Phys. B, 80, 785 (2005)).
Simulation of long & short pulses amplification

Start 248M Ti:Sa, 3ω

Prism stretcher with negative dispersion

0.1 mJ

Berdysh

GARPUN

Plane plate with positive dispersion

Nonlinear absorber

100 mJ

25 J

100 J

KrF master oscillator

V=7x7x100 cm³
W₀=0.6 MBr/cm³

V=16x16x100 cm³
W₀=0.6 MBr/cm³

Ar/Kr/F (59.85/40/0.15) P=1.2 atm
Photogalvanic measurements
Photoacoustic measurements

Laser pulse:
$E < 0.5 \text{ mJ}, \tau \sim 60 \text{ fs}$
$I = 10^{11} - 5 \times 10^{12} \text{ W/cm}^2$
Intensity dependence of electric signal $V$ and acoustic pressure $P$ in the range $10^{11} - 10^{12}$ W/cm$^2$ with a slope coefficient $3 \pm 0.1$ - two-step resonance ionization ($3h\nu + h\nu$).

Intensity dependence of electric signal $V$ and acoustic pressure in the range $3 \times 10^{12} - 5 \times 10^{13}$ W/cm$^2$ with a slope coefficient $3.7 \pm 0.1$ - direct four-photon ionization
Three-photon excitation of high-lying Rydberg states $b \ ^1\Sigma_u^+, \ c\ ^1\Sigma_u^+, \ c\ ^1\Pi_u, \ b\ ^1\Pi_u, \ o\ ^1\Pi_u,$ and $H^3\Phi_u$ and ionization by the external electric field with the strength $E \sim 1 \text{ MV/m}$

Dynamic polarizability is sufficient for a fs laser pulse with $I > 1 \text{ TW/cm}^2$ ($E \approx 30 \text{ MV/cm}$) to shift up the Rydberg states of nitrogen molecules by $\sim 1 \text{ eV}.$
CONCLUSIONS

- UV radiation of KrF laser ($\lambda=248$ nm, $\tau=20-100$ ns) with intensities $I=3*10^6 \div 10^{11}$ W/cm$^2$ produces in air long ionized channels with electron densities $N_e=3*10^8 \div 10^{15}$ cm$^{-3}$.
- Guiding of 1-m-long HV discharges was demonstrated with UV laser pulses of $\sim 100$-mJ energy.
- Two different regions were found for air ionization where electron density $N_e(I)$ depends on laser intensity as linear ($I=5*10^6 \div 5*10^8$ W/cm$^2$) or square power law ($I=5*10^8 \div 10^{11}$ W/cm$^2$) corresponding to impurity ionization and two-step resonance ionization ($2h\nu + h\nu$).
- For ionization of N$_2$ by short UV laser pulse ($\lambda=248$ nm, $\tau \sim 60$ fs) the power law with an index $3 \pm 0.1$ was observed in the range $I=10^{11} - 10^{12}$ W/cm$^2$ corresponding to two-step resonance ionization ($3h\nu + h\nu$) while for higher $I=3*10^{12} - 5*10^{13}$ W/cm$^2$ four-photon ionization occurred.
- Combination of short & long UV laser pulses is expected to form long-distance ionized channels which are of great interest for guiding of the lightning and transportation of MW and THz radiation as well as electron beams.