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

Presented by V.D. Zvorykin

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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.**

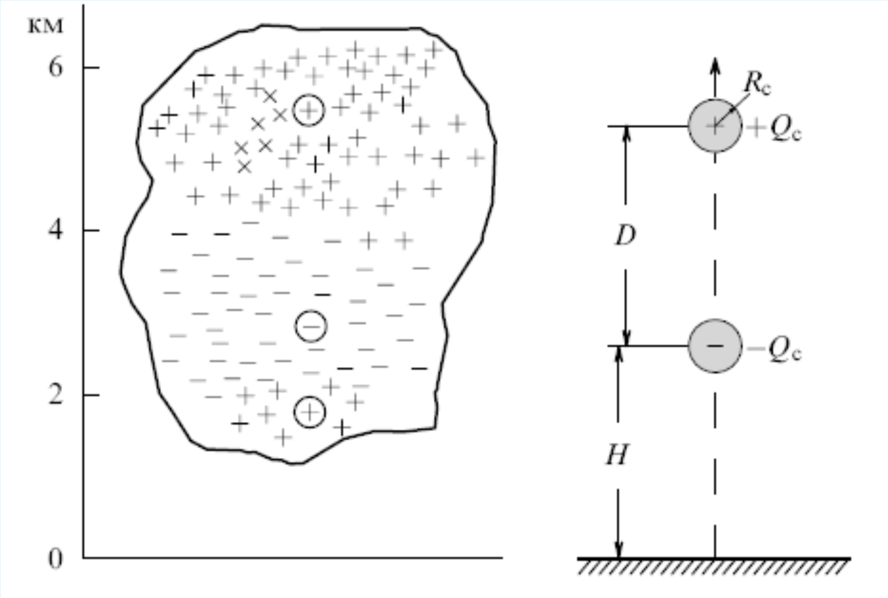
History of HV discharges triggering and guiding by the laser

- Triggering of long-distance discharges in atmospheric air was started with long laser sparks since 70-s: Koopman *et al*, "Channeling of ionizing electrical streamer by laser beam", J. Appl. Phys., 42, 1883 (1971); Zvorykin *et al*, "Initiation of long electrical discharges by the laser spark", Physika Plazmy, 5, 1140 (1979).
- Laser sparks produced by pulsed Nd и CO_2 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 CO_2 laser: Appolonov *et al*, "Guiding of electrical discharge by continues laser spark under focusing of CO_2 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

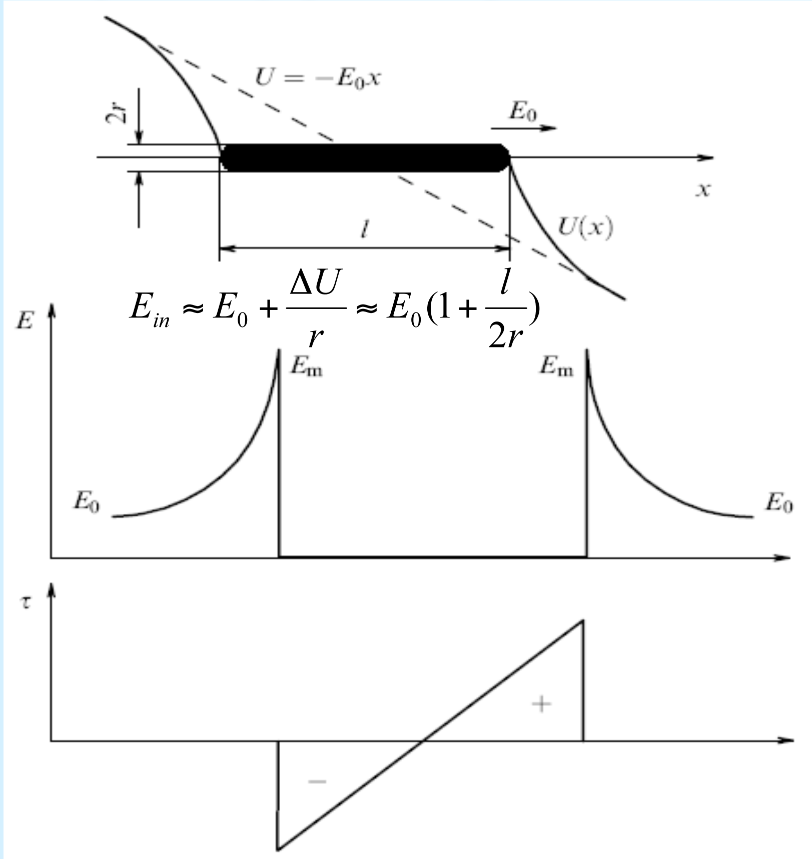
- Diffraction divergence of KrF laser beam is 40 times less then of CO_2 laser.
- UV laser beam produces uniform air ionization along the propagation due to 3-and 4-photon ionization of O_2 (ionization potential 12.2 eV) and N_2 (15.6 eV) without avalanche ionization.
- Critical electron density $N_{ecr} = \pi c^2 m_e / e^2 \lambda^2 = 1.6 \cdot 10^{22}$ cm^{-3} for KrF laser radiation (λ=248 nm) is two orders of magnitude higher then in fully ionized air plasma $N_e = 2.7 \cdot 10^{19}$ cm^{-3}. As a result plasma is transparent for UV radiation which can propagate up to ~ 2 км.
- For comparison, in CO_2–laser-produced plasma electron density exceeds the critical value $N_{ecr} = 10^{19}$ cm^{-3} and about 50% of radiation (λ=10.6 μm) 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 ~1 кV/cm (Bazel'an & Raizer, *UPhN*, 170, 753 (2000)).



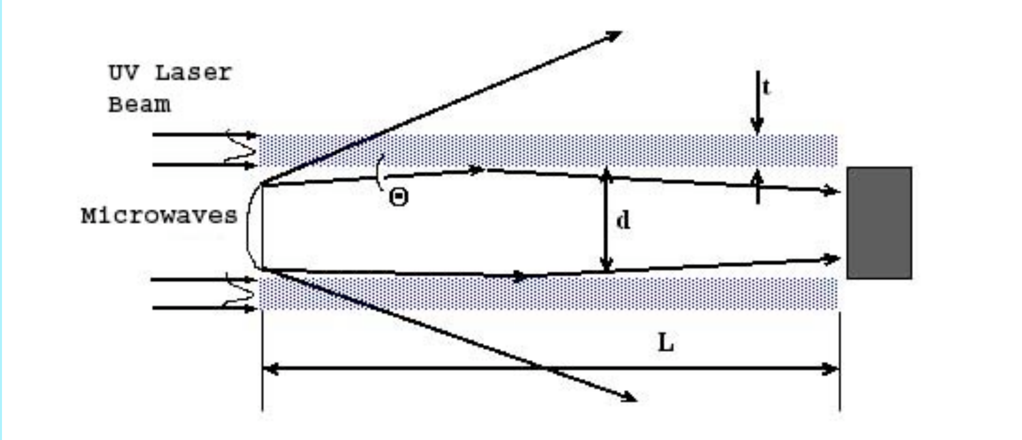
Charge flow along the channel leads to potential redistribution and field sharpening near the ends.

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

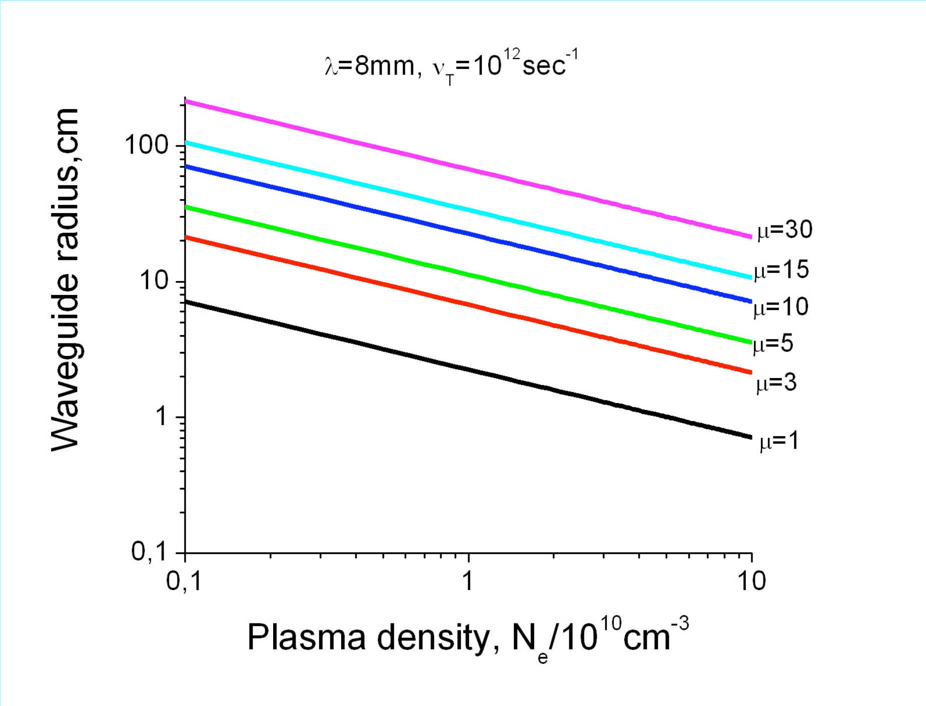
Virtual waveguides for microwaves

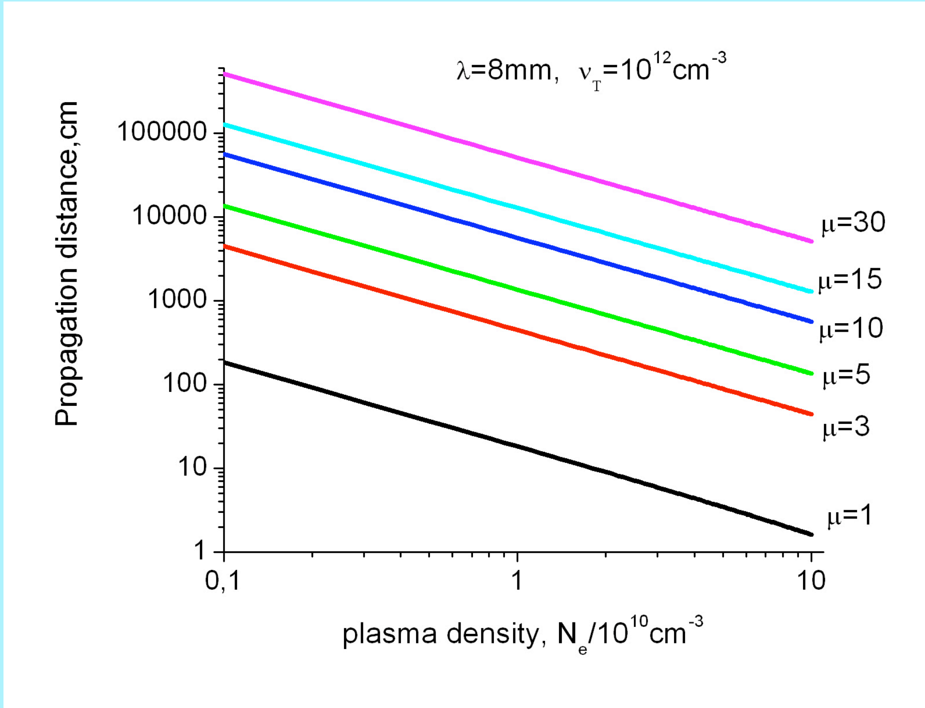
Idea of L. Losev: In virtual plasma waveguide the total reflection angle of microwave radiation at the plasma-air boundary has to exceed the diffraction angle:

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

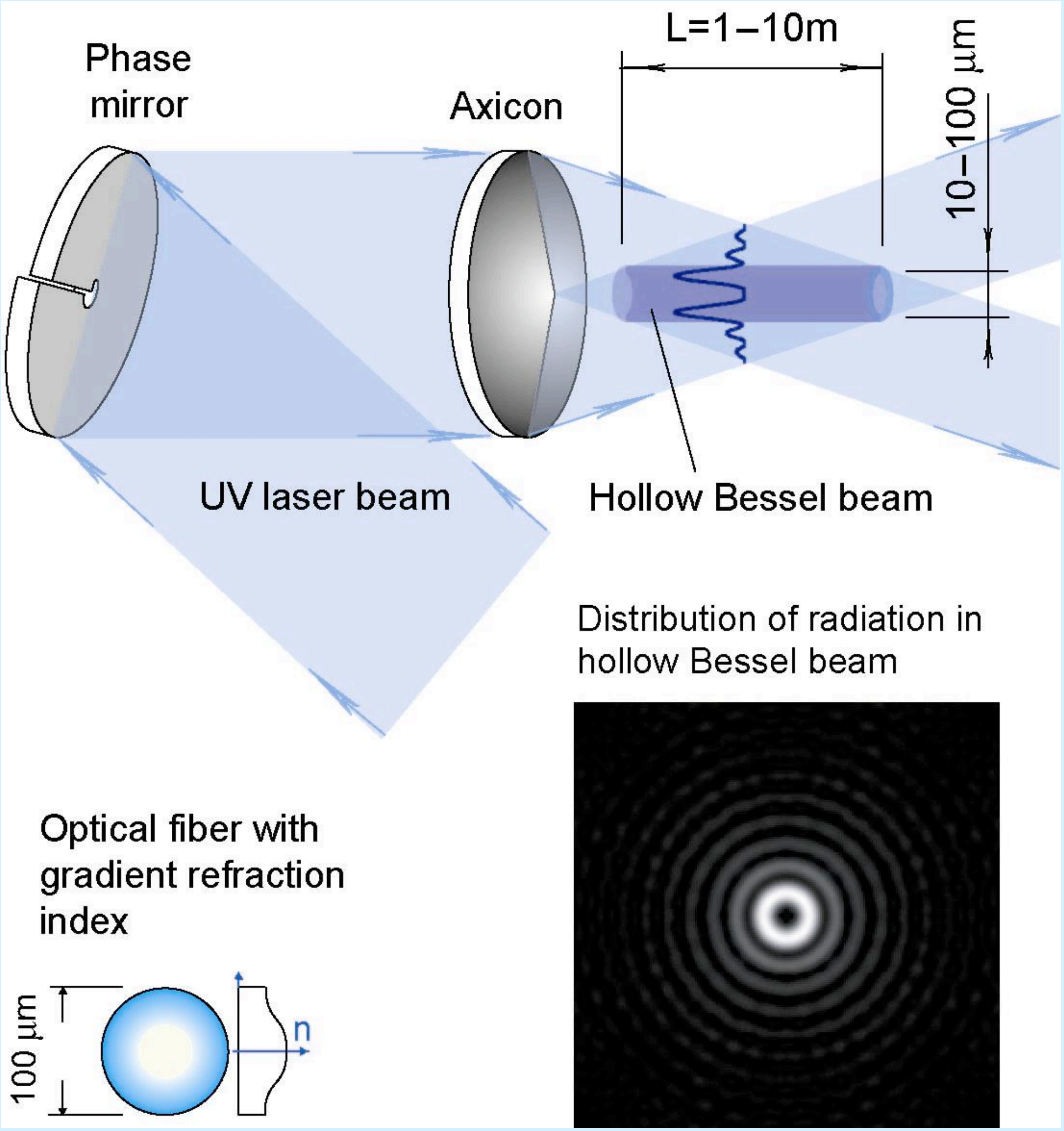


Simulations of I. Smetanin





Formation of hollow Bessel beams for guiding of THz



Electron balance in UV-ionized air plasma

(1) (2) (3) (4) (5)

$$\frac{\partial N_e}{\partial t} = N_{O_2}\sigma^{(3)}I^3 - N_e(k_1 N_{O_2}^2 + k_2 N_{O_2}N_{H_2O}) - k_3 N_e^2 - \frac{D_a}{\Lambda^2}N_e + \frac{I}{h\nu}N_{O_2^-}\sigma_{ph}$$

$$\frac{\partial N_{O_2^-}}{\partial t} = N_e(k_1 N_{O_2}^2 + k_2 N_{O_2}N_{H_2O}) - \frac{I}{h\nu}N_{O_2^-}\sigma_{ph}$$

$$\sigma^{(3)} = 3*10^{-29} - 8*10^{-32}\ \tilde{n}m^6 s^{-1}W^{-3},\ (k_1 N_{O_2}^2 + k_2 N_{O_2}N_{H_2O}) = 1{,}2*10^8\ s^{-1},$$

$$k_3 = 1{,}3*10^{-8}\ \tilde{n}m^3 s^{-1},\ \sigma_{ph} = 3*10^{-18}\ \tilde{n}m^2,\ \Lambda = r/2.4,\ D_a = 200\ cm^2 s^{-1}$$

! **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*10^7 W/cm^2**

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

(4) **Diffusion losses**

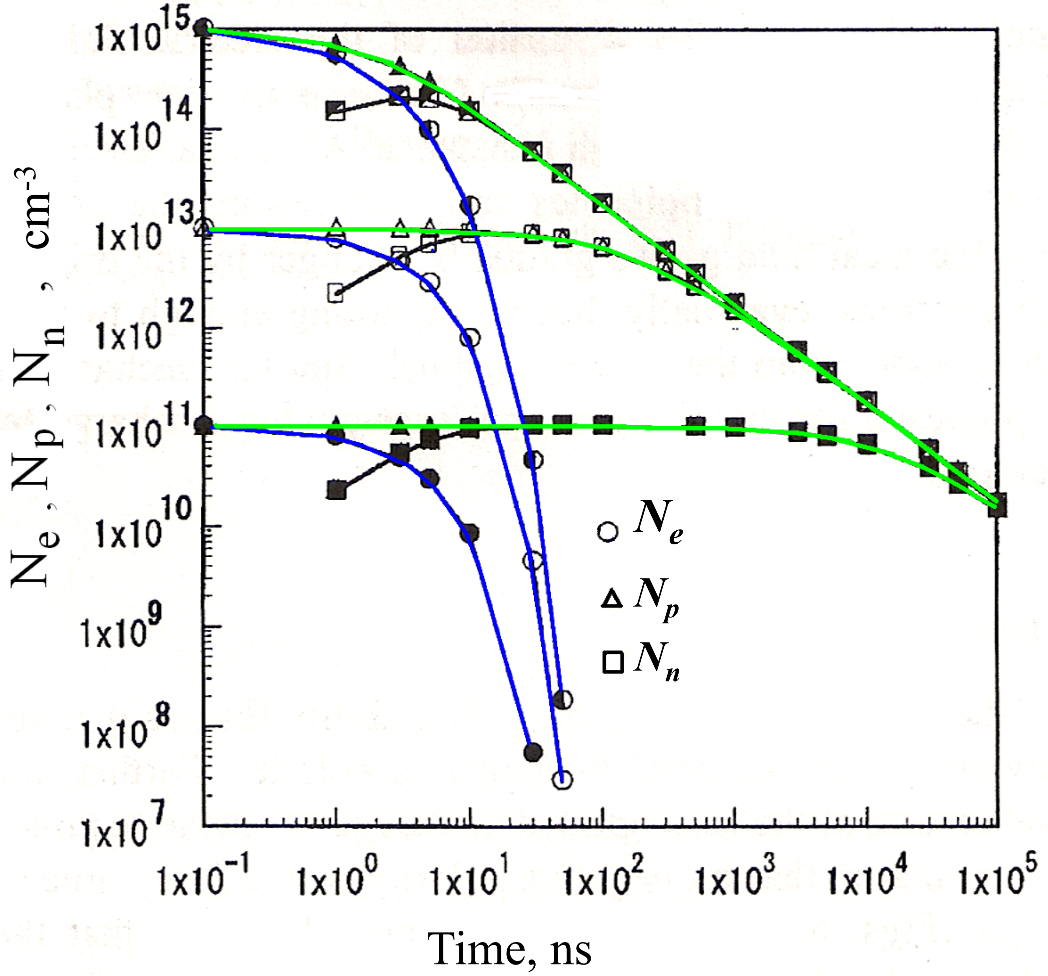
(5) **Photodetachment of O_2^-**

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

? **Less-known processes:**

- **Stepwise resonance photoionization (2$h\nu$+ $h\nu$)**
- **Photoionization and photoeffect at airosol impurities**

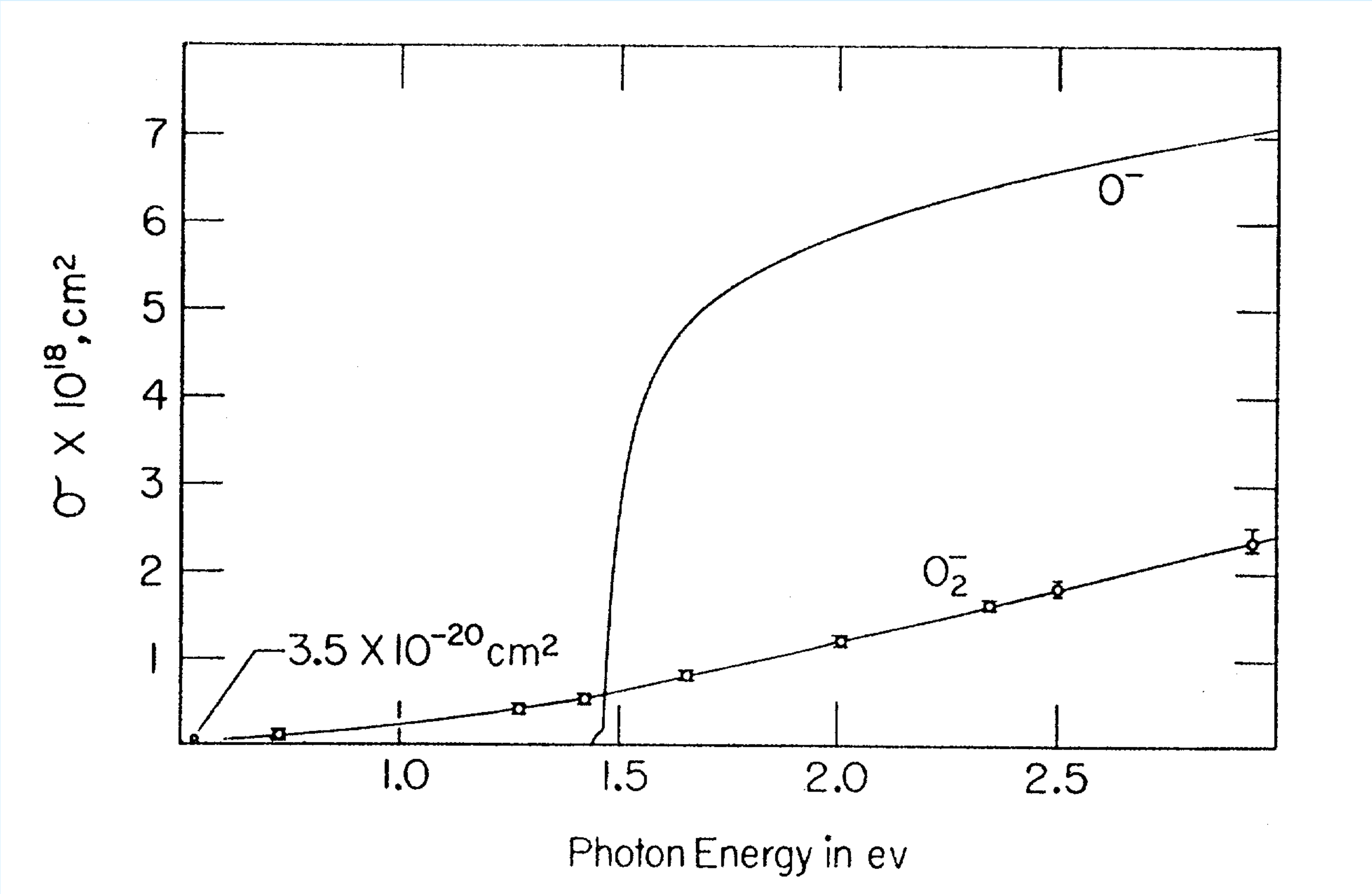
Dynamics of free electrons and ions in air



Miki & Wada (J. Appl. Phys. 80, 3208 (1996)):

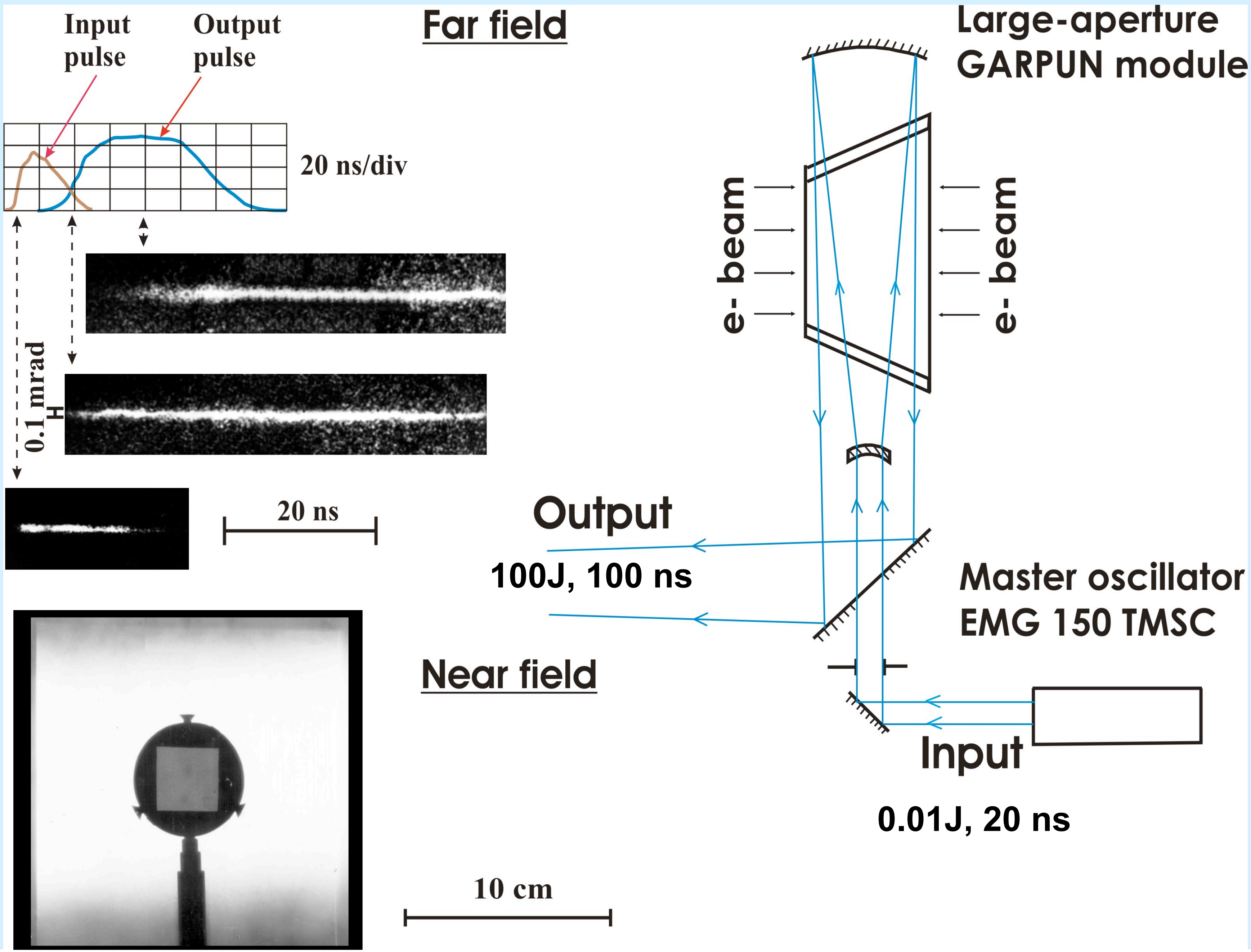
- **After switch off an ionization source (UV light) electrons fully disappear in ~10 ns because of an attachment to O_2, while ion concentration falls down to N_i~10^{10} cm^{-3} in ~100 µs due to recombination of O_2^- with O_2^+, O_4^+ and N_2^+, being independent on the initial ionization,**

Photodetachment cross section

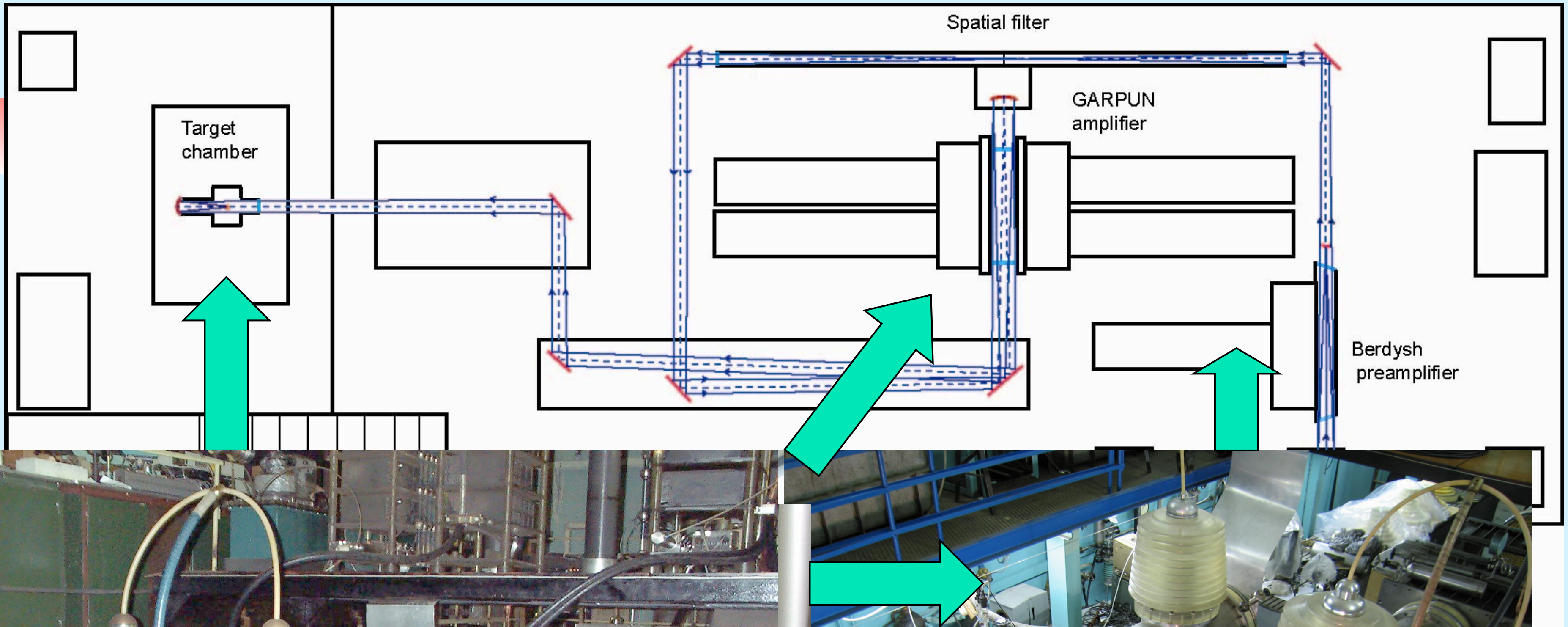


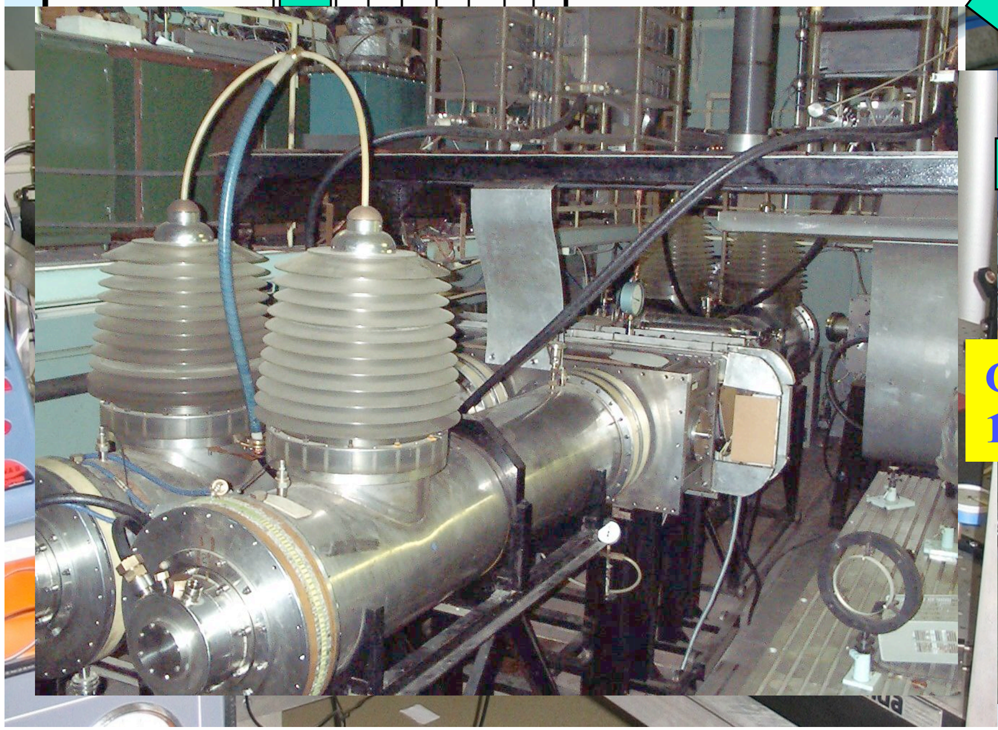
For O_2^- the bound energy ~ 0,5 eV and photodetachment process is available for λ≤ 2500 nm. For short wavelengths probability increases manifold (Burch *et al.*, Phys. Rev., 112, 171 (1958) and UV light provides both initial photoionization and the following photodetachment of electrons.

Injection-controlled operation of GARPUN KrF laser



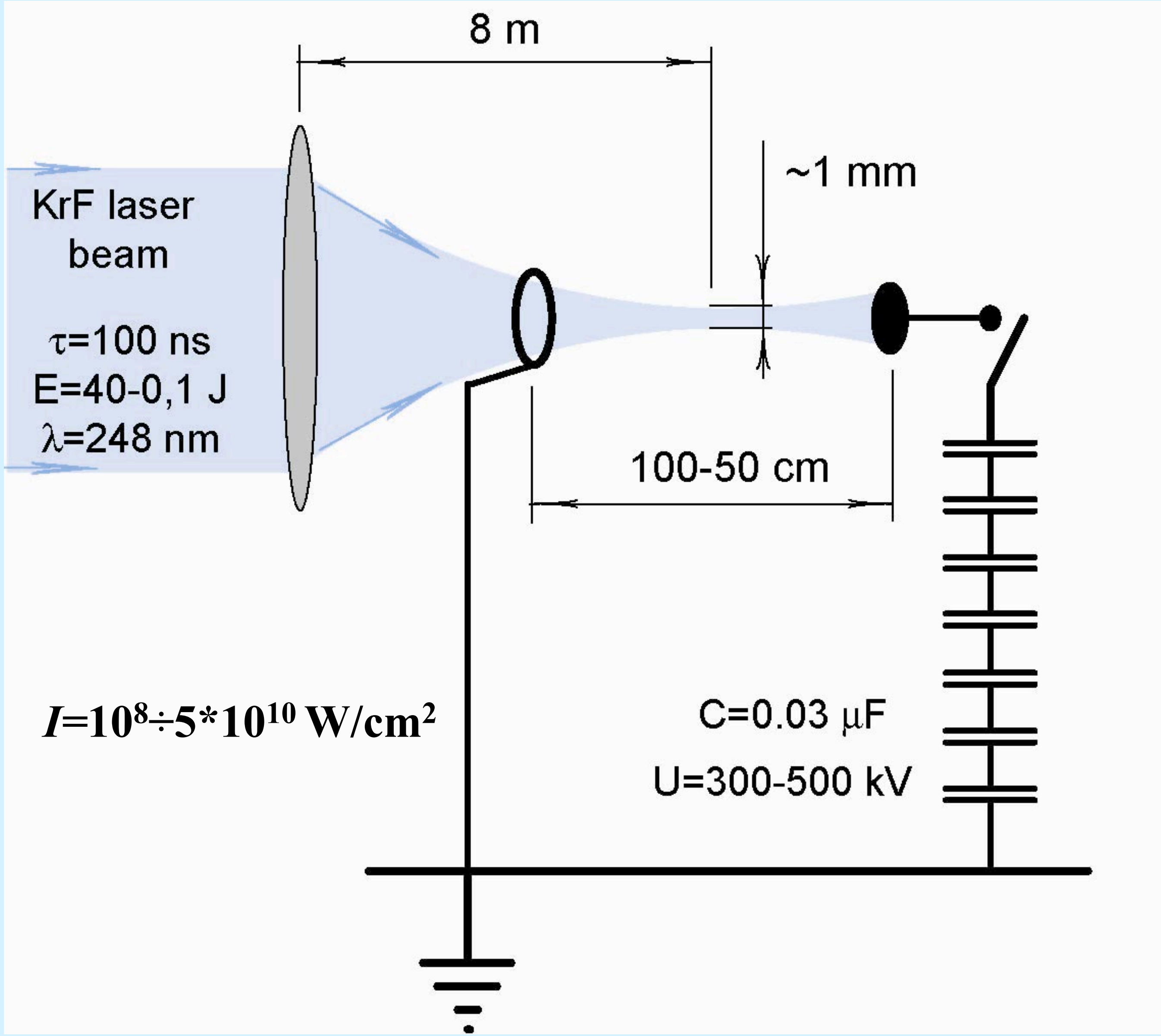
Hybrid Ti:Sa/KrF laser facility GARPUN-MTW for amplification of short & long pulses





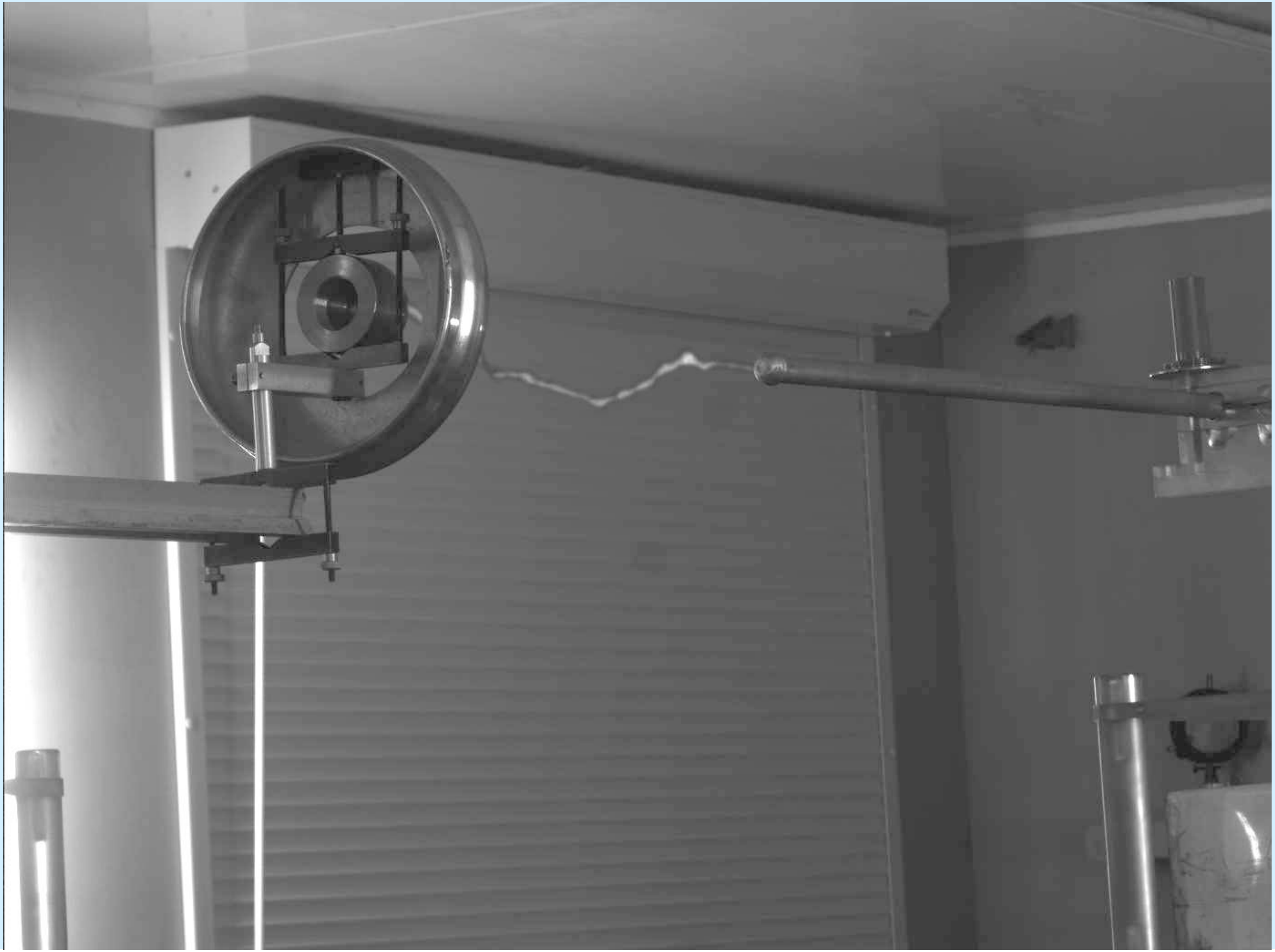
GARPUN e-beam-pumped amplifier: 0 fs;
16*18*100 cm, 100J, 100 ns, ~0.1mrad m)

Experiments on laser triggering of HV discharge

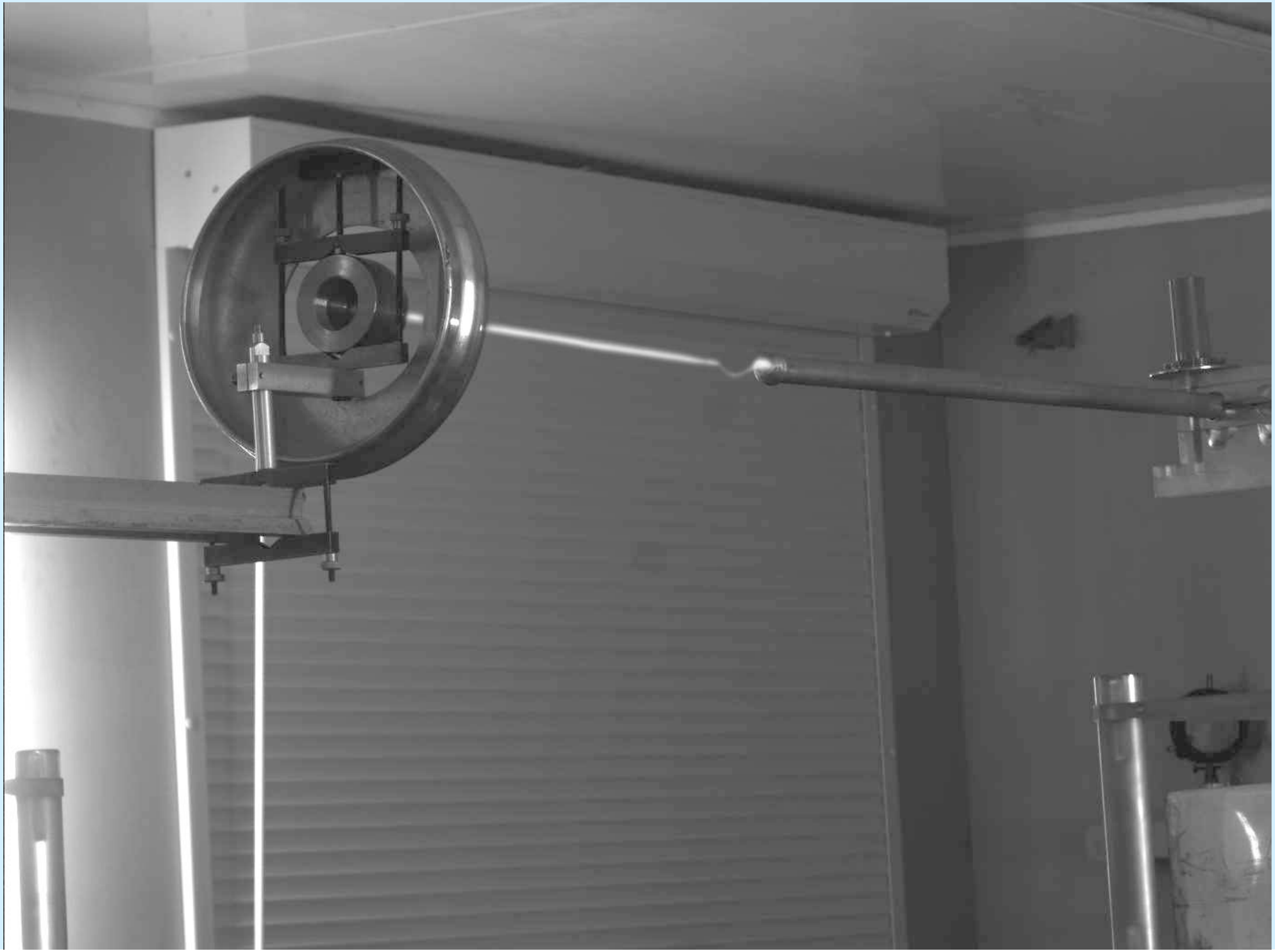


HV discharge gap

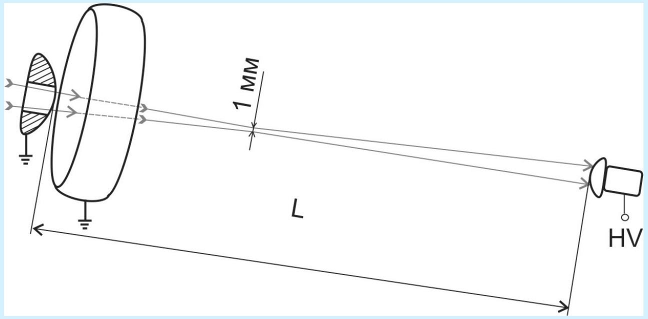
HV discharge without laser guiding

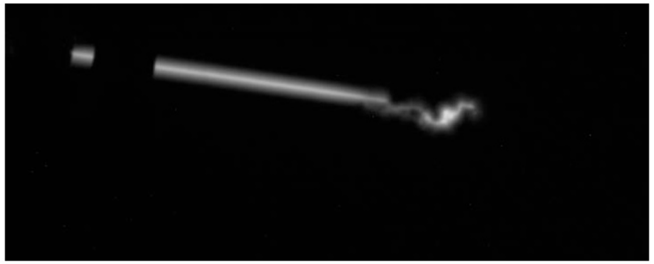


HV discharge with laser guiding



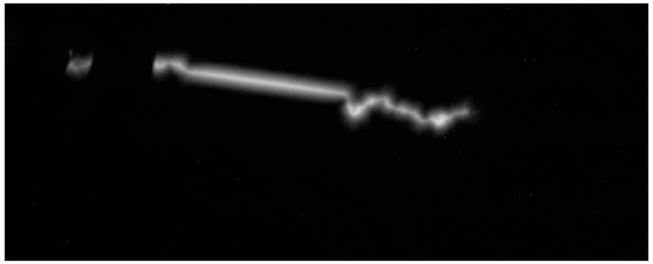
HV discharge at various conditions



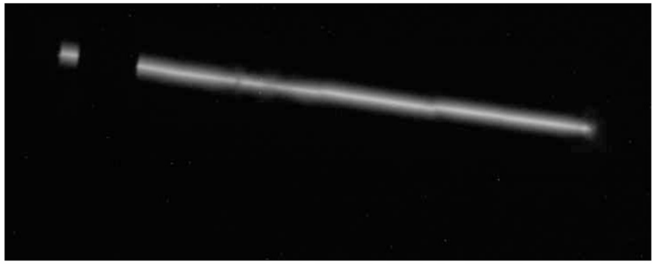


L=60 cm
E=0.17 J
U=+390 kV

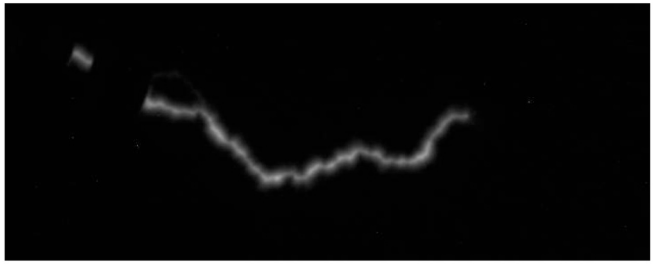
L=80 cm
E=25 J
U=0



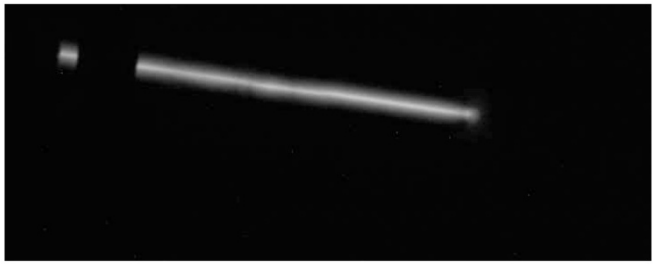
L=60 cm
E=0.044 J
U=+390 kV



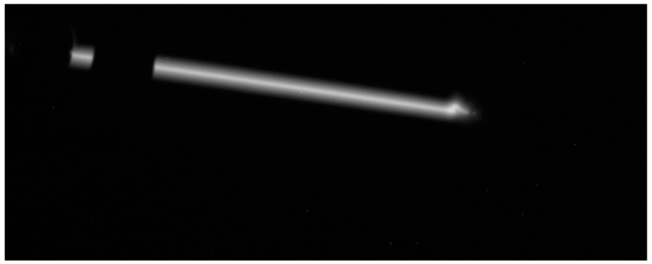
L=80 cm
E=19.2 J
U=+390 kV



L=60 cm
E=0.030 J
U=+390 kV

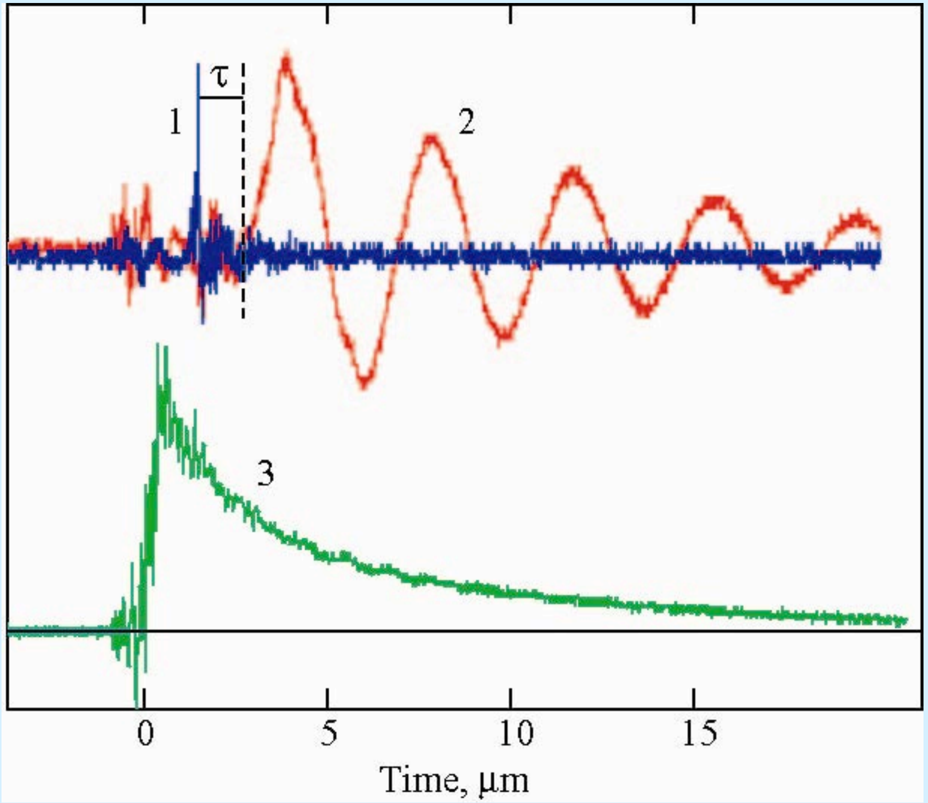


L=60 cm
E=25.6 J
U=+390 kV



L=60 cm
E=0.29 J
U=–390 kV

Electrical parameters of HV discharge



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

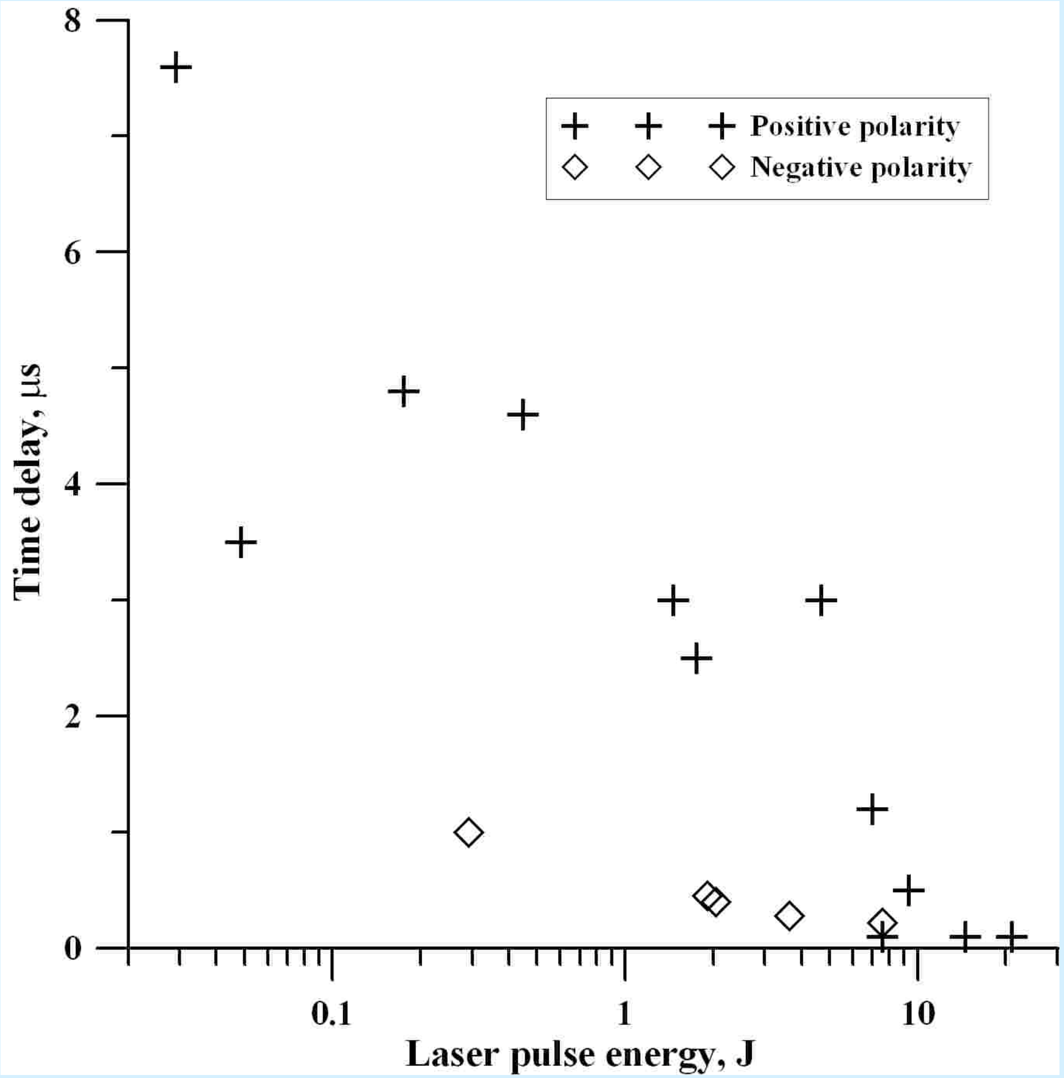
***T*=4 μs**
***C*=38 nF**
***L*=10 μH**

***R*=1,6 Ω (short circuit)**
***R*=2,2-2,3 Ω (nonguided discharge)**
***R*=1,8-2,2 Ω (guided discharge)**

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

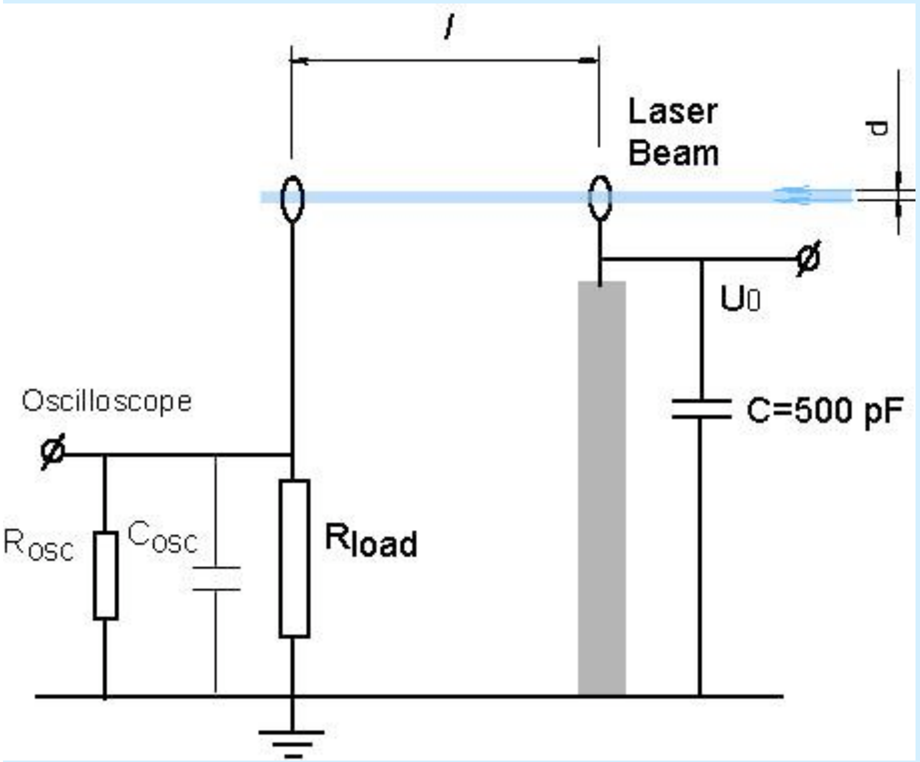
$$T = 2\pi / \sqrt{\frac{1}{L_c C} - \frac{R_c^2}{4L_c^2}} \qquad A_0 = \frac{CU_0}{\sqrt{1 - \frac{R_c^2 C}{4L_c}}}$$

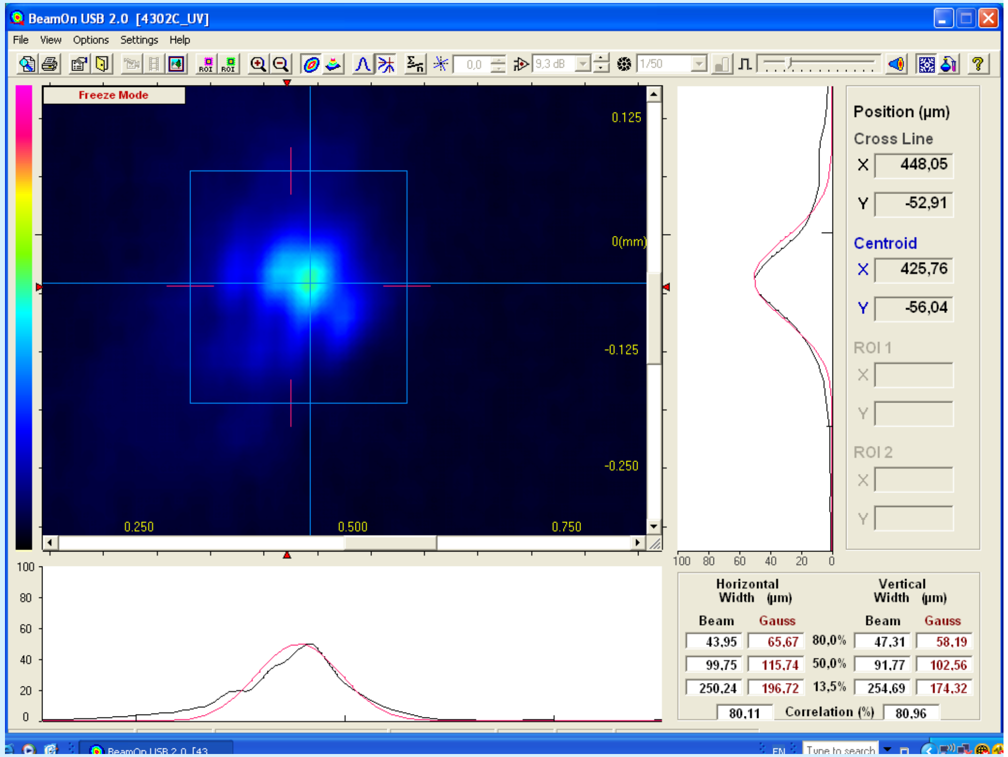
Guiding limits of HV discharge



- At U ~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 ~50 mJ.

Measurements of conductivity produced by KrF laser in air

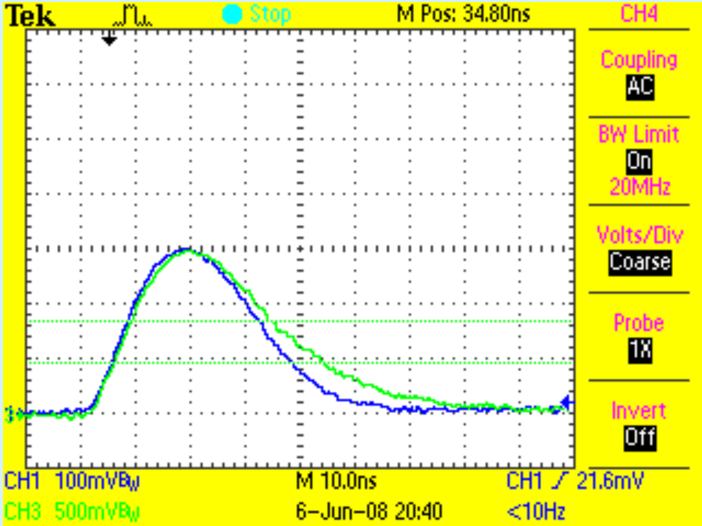




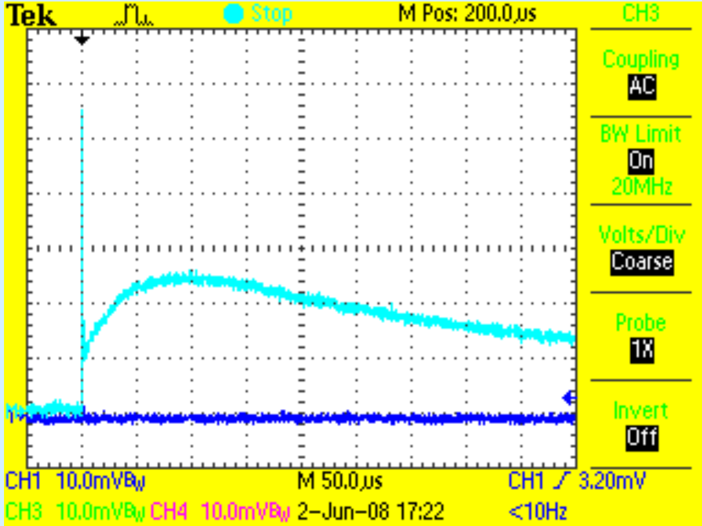
KrF laser: E_{las}= 5÷100 mJ, τ_{las}= 22 ns, F = 0.5, 2, 8 м; d_{las}= 25 µm÷ 1mm, I= 3*10^6 ÷10^{11} W/cm^2, l=2÷10 cm.

Distribution of radiation at the focal plane of the lens with F=2m. Focal spot diameter is ~100 µm.

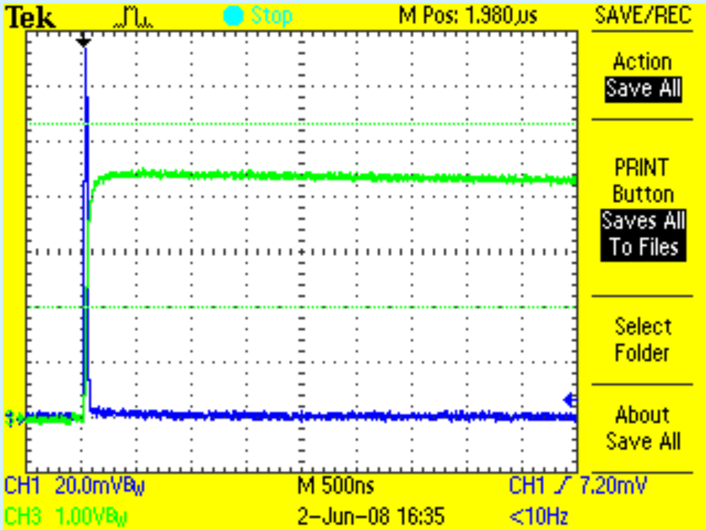
Oscilloscope traces



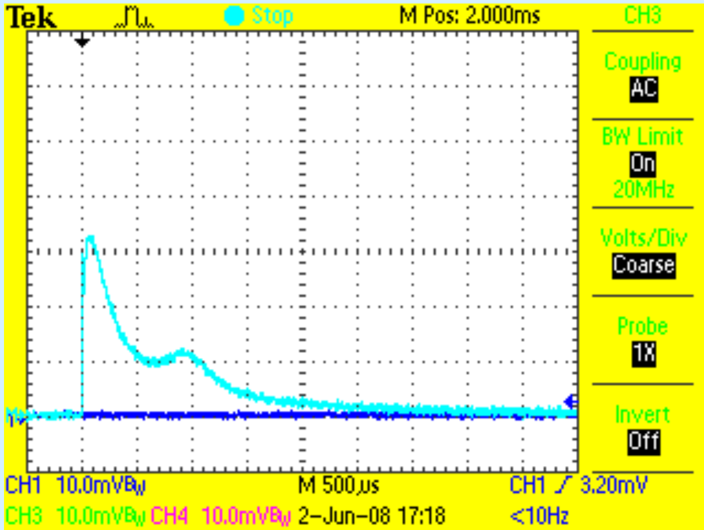
R_{load}=50Ω, 10 ns/div



R_{load}=1 MΩ, 50 µs/div

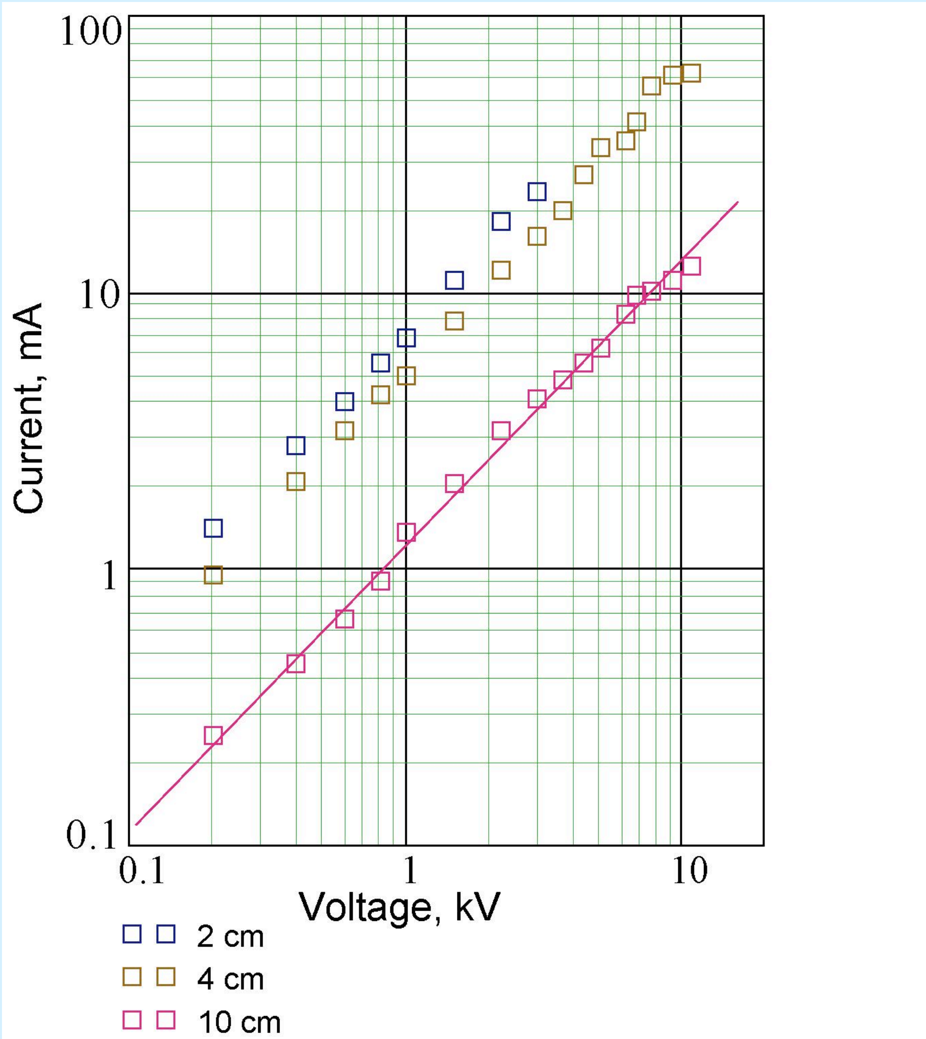


R_{load}=1 MΩ, 0.5 µs/div



$R_{н}$=1 MΩ, 500 µs/div

Current vs voltage dependences of photoionization discharge

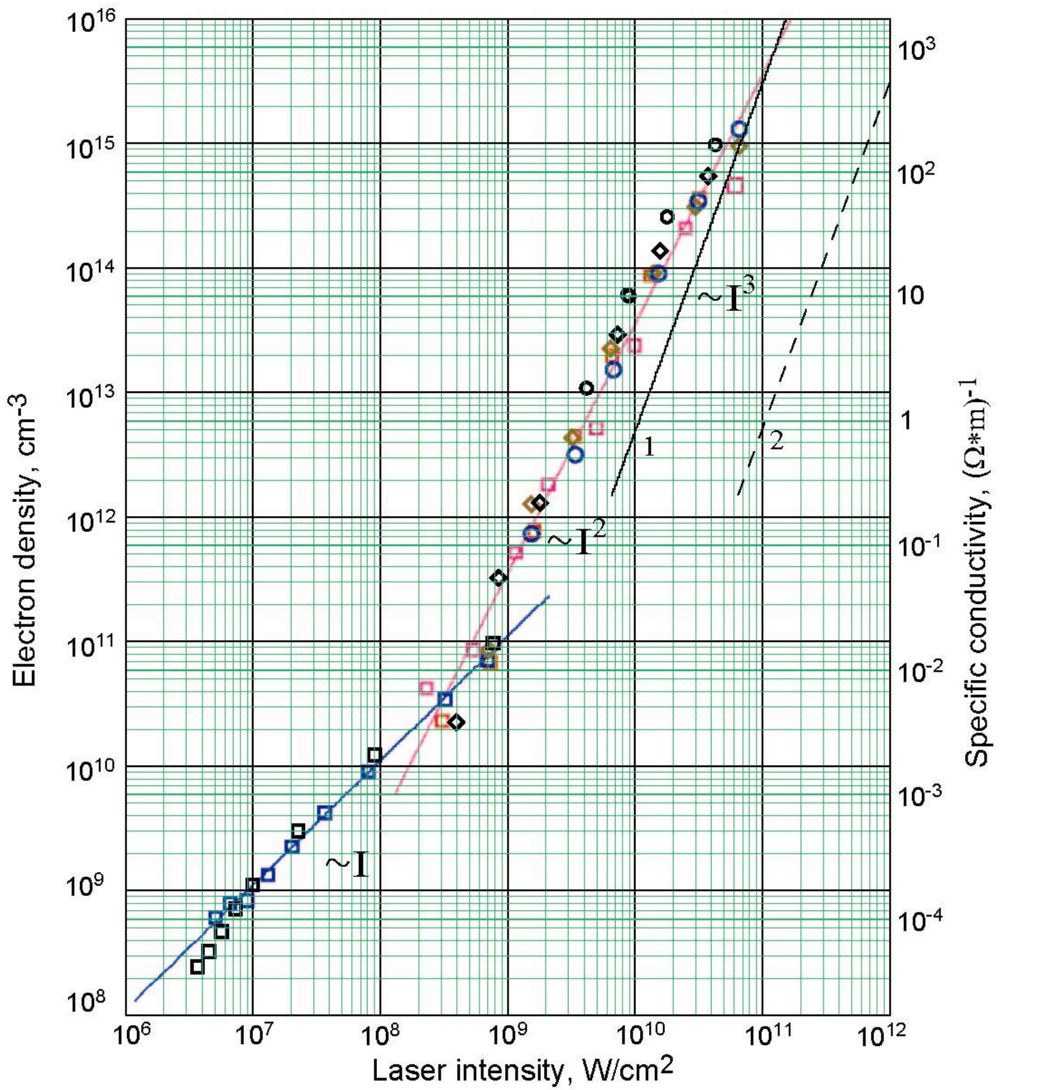


$$i_e = v_e S_{las} N_e e, \;\; v_e = \mu_e E = \mu_e \frac{U}{l}$$

$$N_e = \frac{i_e l}{\mu_e U S_{las} e}\;, \;\; \mu_e \approx 1\, \grave{\imath}^{\;2} \hat{A}^{-1} \tilde{n}^{-1}$$

$$\sigma_e = e \mu_e N_e$$

σ and N_e dependences on laser intensity and probable ionization processes



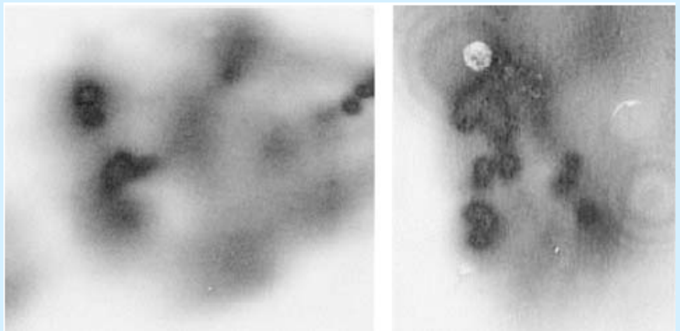
$I = 5*10^6 \div 5*10^8$ W/cm^2 linear dependence: $N_e \sim I$ – photoionization or photoemission of the impurities.

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

$I > 10^{11}$ W/cm^2 – air breakdown.

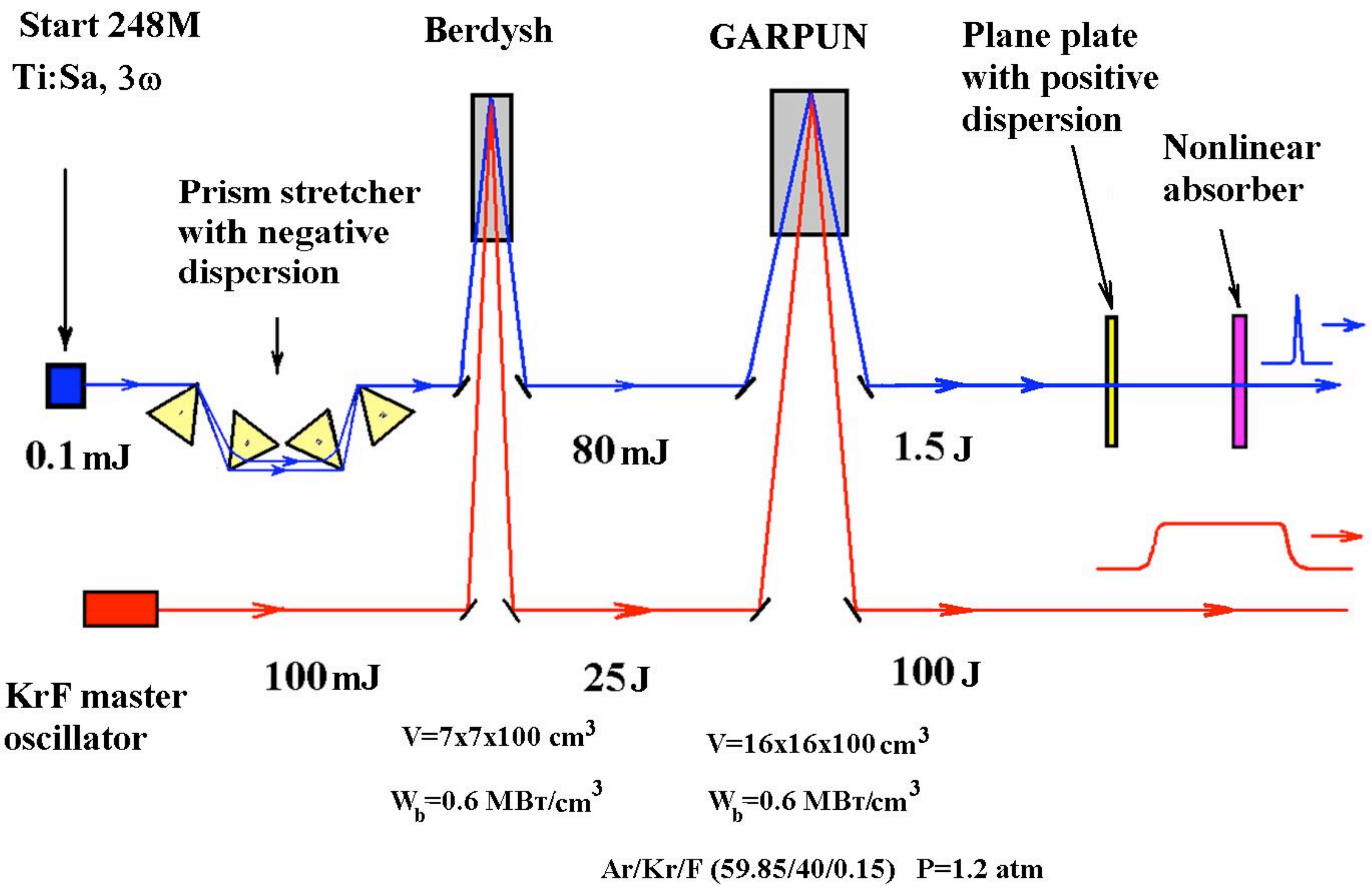
Benefits of UV short laser pulses for long-distance channels production

- **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 $P_{cr}=3{,}8\lambda^2/8\pi n_0 n_2 \approx$ 100 MW (λ=248; n_0 и n_2 – linear and nonlinear parts of the refraction index) Kerr self-focusing produces beam filaments with ~100 μm diameter and $N_e=10^{15}$-10^{16} cm^{-3} propagating at multi-km distance.**
- **P_{cr} for λ=248 nm is 30 times lower, than for λ=800 nm (Ti:Sa laser).**
- **Filaments are stable in adverse atmospheric conditions.**

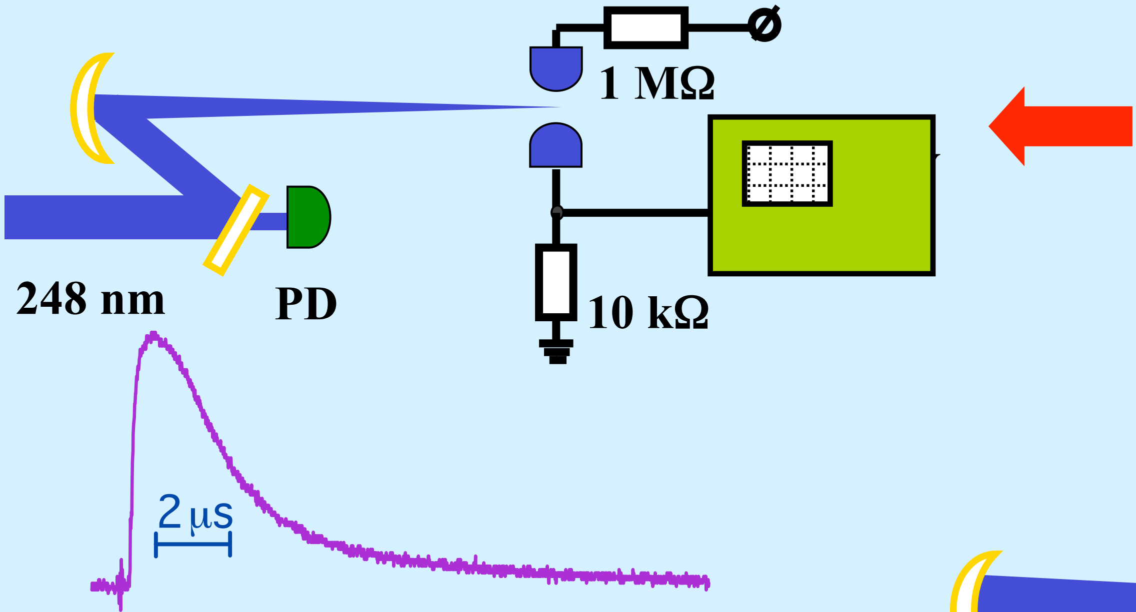


Filamentation of fs laser pulse along propagating length in dry air (left) and during the rain (right) (Mechain *et al.*, Appl. Phys. B, 80, 785 (2005).

Simulation of long & short pulses amplification

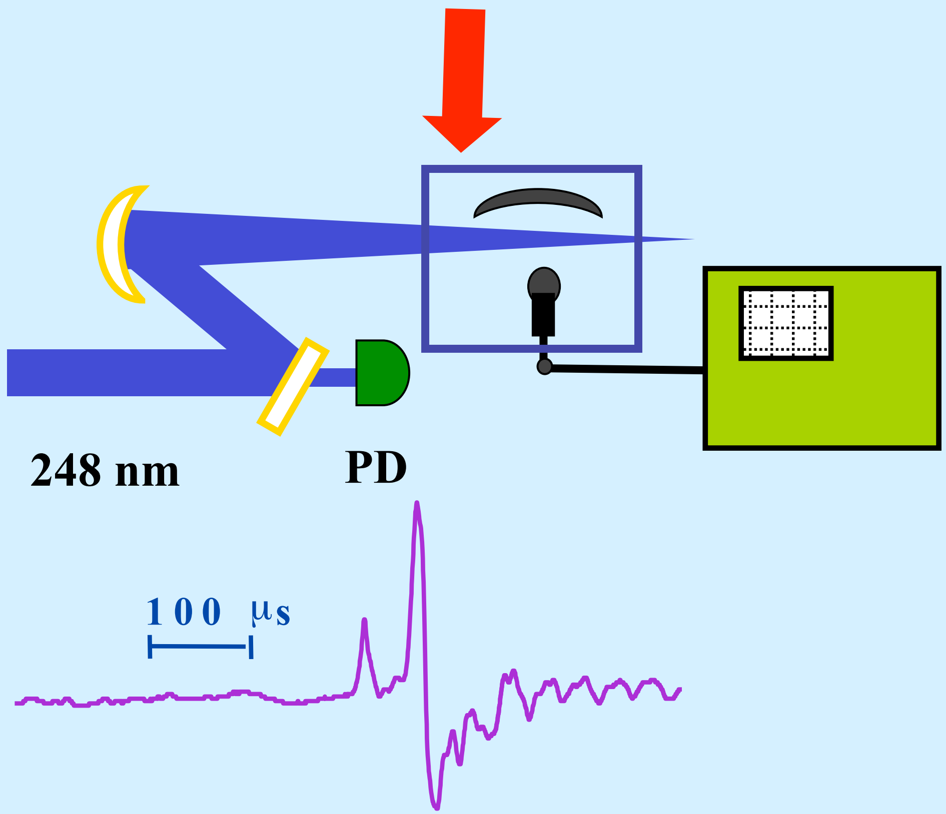


Layout of short-pulse laser-gas interaction



Photogalvanic measurements

Photoacustic measurements

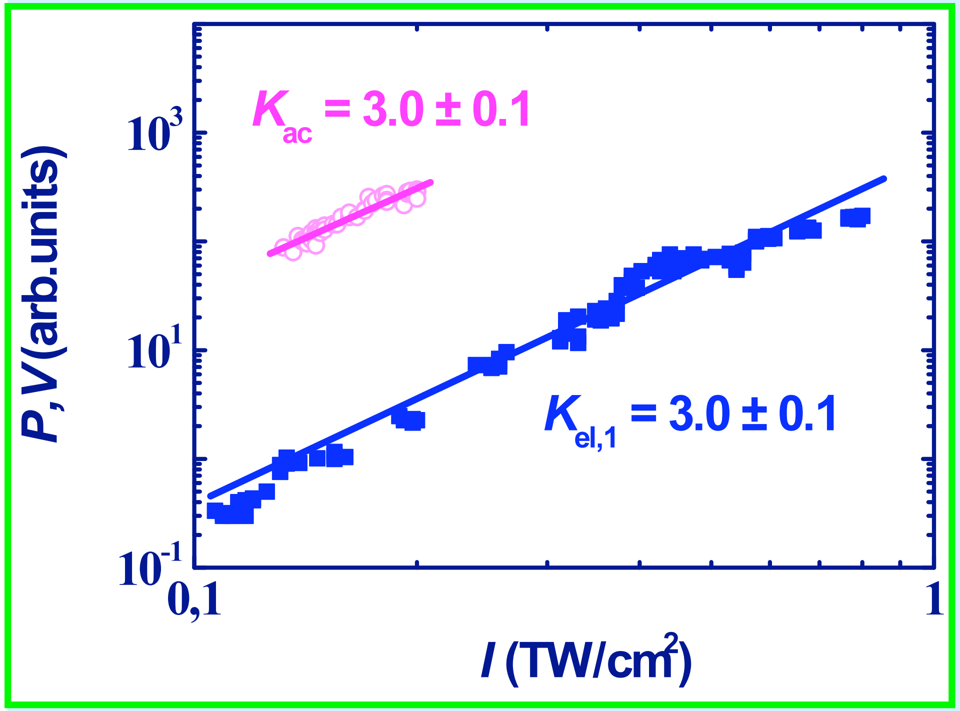


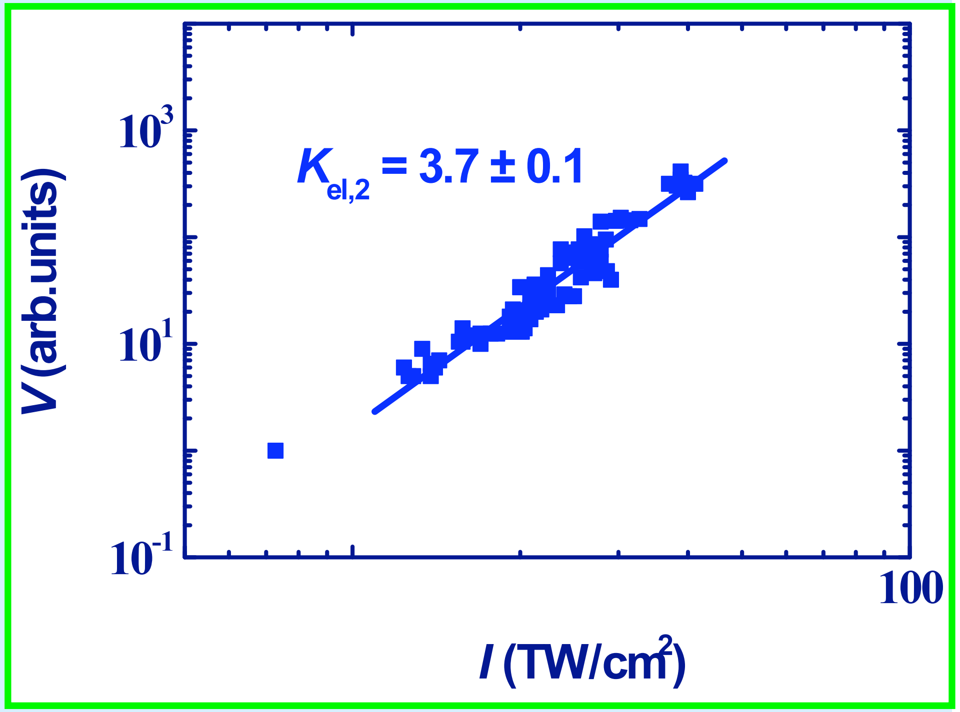
Laser pulse:

***E*< 0.5 mJ, *τ* ~60 fs**

***I*= 10^{11} – 5*10^{12} W/cm^2**

Short-pulse ionization of nitrogen





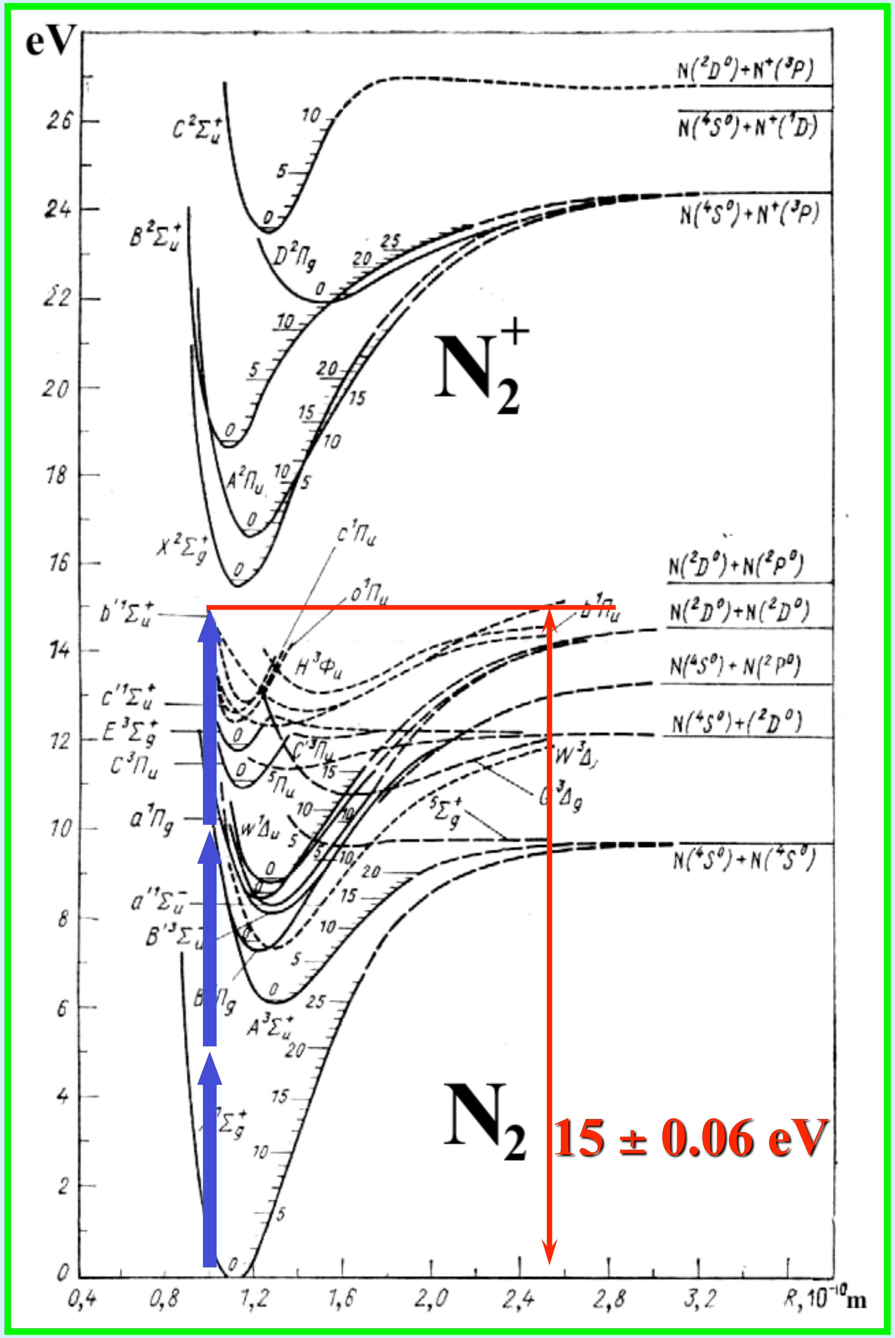
Intensity dependence of electric signal *V* and acoustic pressure *P* in the range 10^{11} – 10^{12} W/cm^2 with a slope coefficient 3 ± 0.1 - two-step resonance ionization (3$h\nu$ + $h\nu$).

Intensity dependence of electric signal *V* and acoustic pressure in the range 3*10^{12} – 5*10^{13} W/cm^2 with a slope coefficient 3.7 ± 0.1 – direct four-photon ionization

Nitrogen electronic terms

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 $E \sim 1$ MV/m

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



CONCLUSIONS

- **UV radiation of KrF laser (λ=248 nm, τ=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 ~ 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 (λ=248 nm, $\tau \sim$ 60 fs) the power law with an index 3 ± 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.**