Effects of picosecond terawatt UV laser beam filamentation and a repetitive pulse train on creation of prolonged plasma channels in atmospheric air

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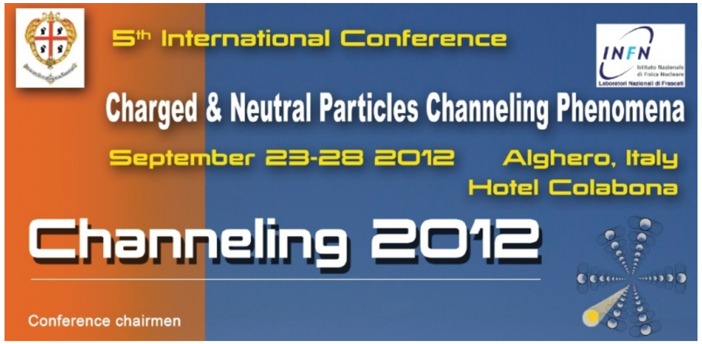
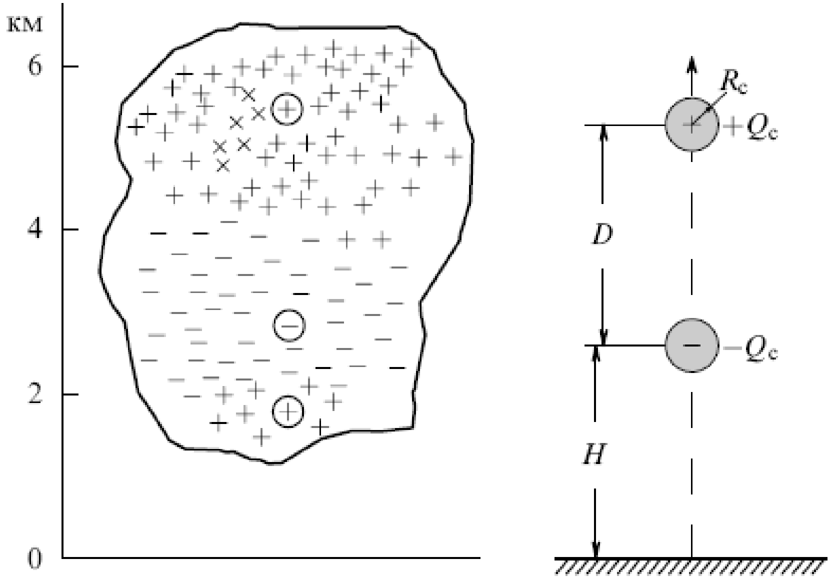


September 27, 2012

Outline

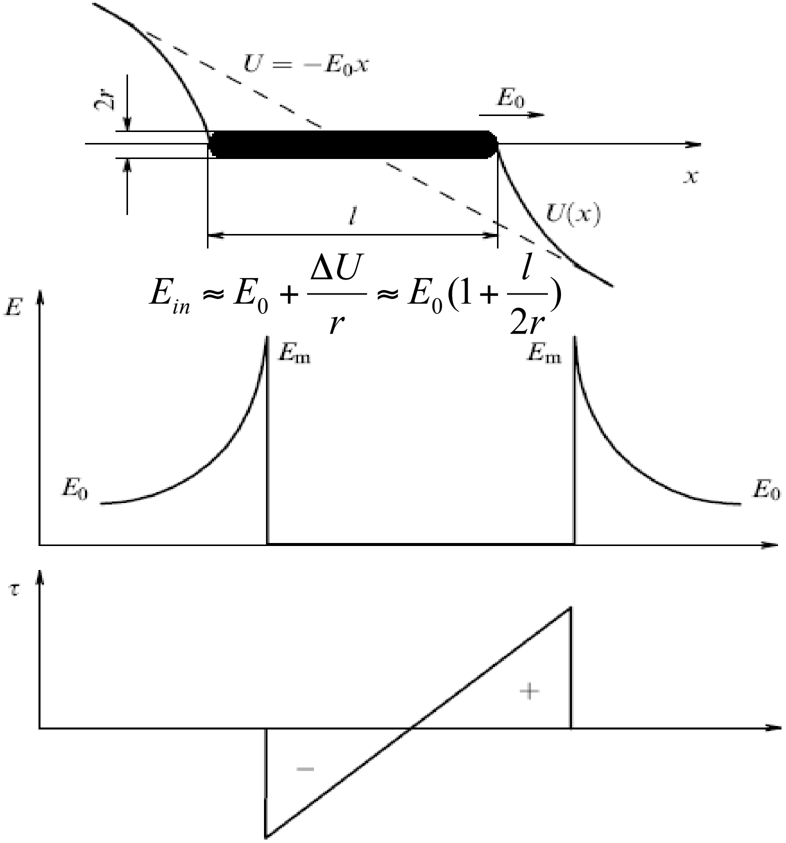
- Motivation. Laser-produced ionized channels in air for:
  - guiding of HV electric (lightning) discharges
  - transport of MW radiation
- Experiments at GARPUN KrF laser with GW, 100-ns UV pulse
- Generation of TW, ps pulse trains combined with 100-ns pulse at up-graded Ti:Saphire/KrF GARPUN-MTW laser facility
- Enhanced air ionization by combined UV radiation
- Conclusions

Polarization of the conducting plasma channel is the main mechanism of lightning triggering



Distribution of charges in the thunderstone cloud and equivalent dipole:

***H*≈*D*≈3 km; *Q_c*≈10 C. Potential relative to the ground in the middle of negative region *U*≈ –290 MV, near the lower boarder –180 MV. Average field strength ~1 кV/cm [Bazel'an & Raizer, 2000, *UPhN*, 170, 753].**



$$E_{in} \approx E_0 + \frac{\Delta U}{r} \approx E_0 (1 + \frac{l}{2r})$$

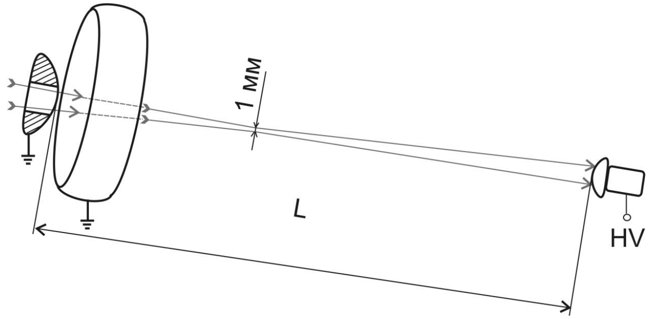
Charge flow along the channel leads to potential redistribution and field sharpening near the ends.

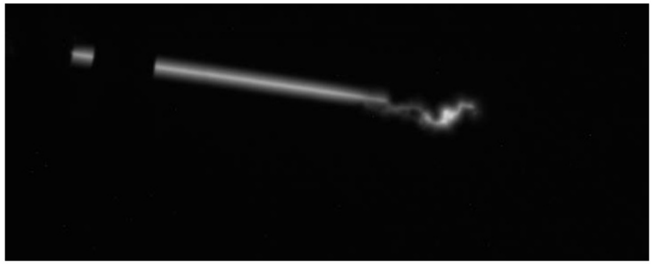
Lightning leader will be formed if in the 20-m length channel electron density *n_e* ~10^{12} cм$^{-3}$ (or 10^{15} cм$^{-3}$) will be kept for ~ 10 (0.1) μs, time of charge redistribution.


Self-breakdown HV discharge


Laser-guided HV discharge

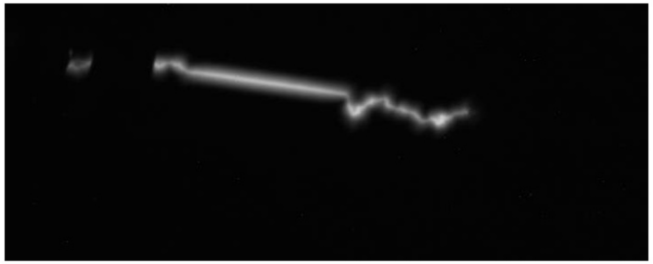
HV discharge at various conditions



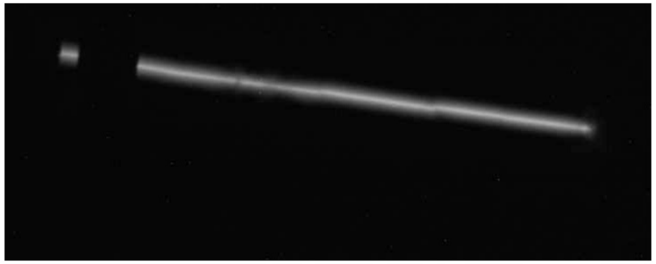


$L=60$ cm
$E=0.17$ J
$U=+390$ kV

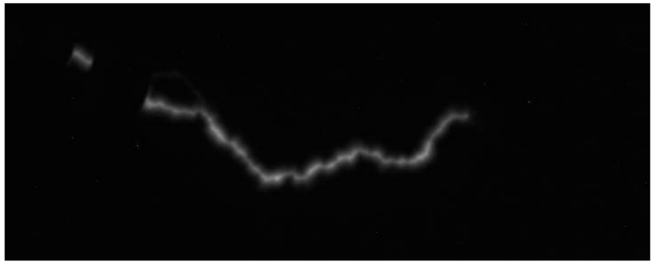
$L=80$ cm
$E=25$ J
$U=0$



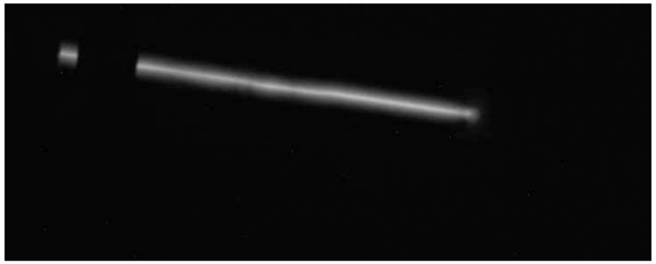
$L=60$ cm
$E=0.044$ J
$U=+390$ kV



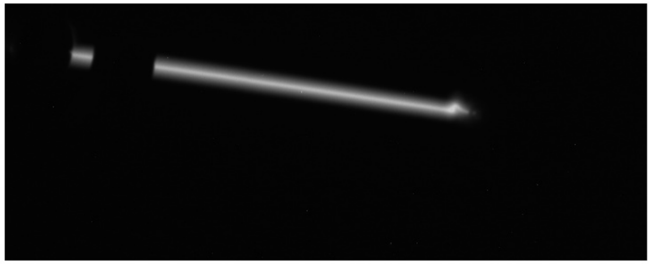
$L=80$ cm
$E=19.2$ J
$U=+390$ kV



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



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

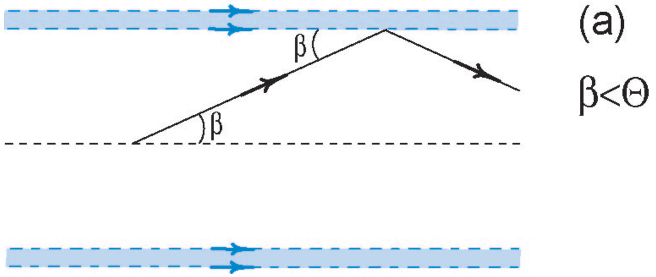


$L=80$ cm
$E=0.29$ J
$U=-390$ kV

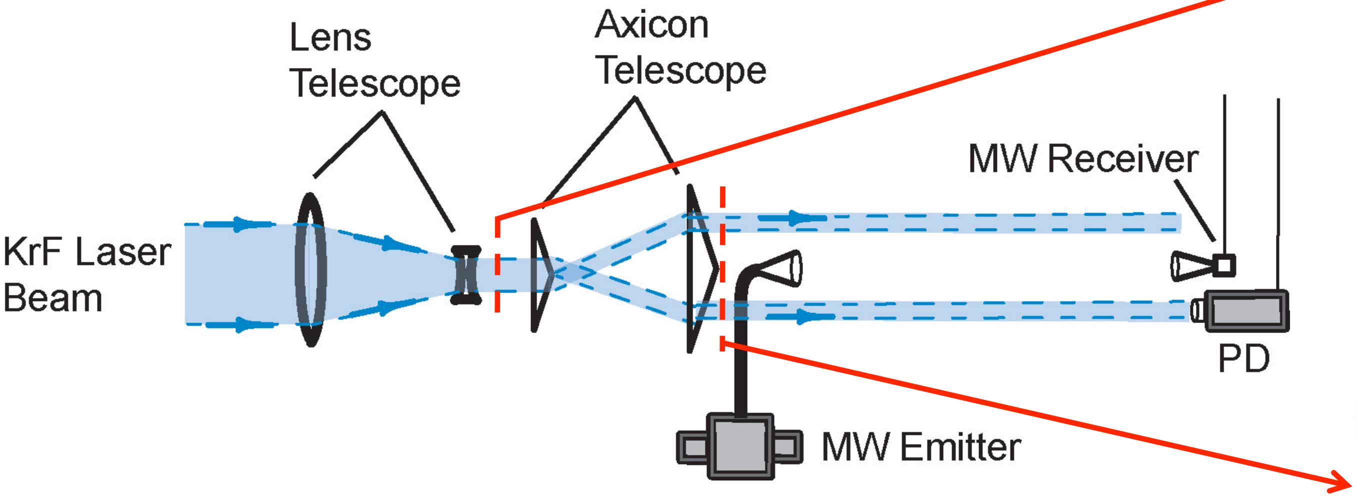
Guiding of microwaves

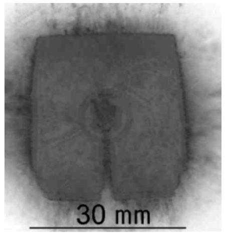
- **In a free space MWs have a large divergence $\beta \approx \lambda/D$; to attain $\beta \sim 10^{-3}$ rad**
- **for $\lambda_{MW} \sim 1$ cm, the antenna size of $D \sim 10$ m is required.**
- **Metal waveguides with a transverse size $D \sim \lambda$ and high wall conductivity provide excellent MW transfer.**
- **Similar tubular plasma waveguides with $D \sim \lambda$ were proposed on a base of filamentation of ultra-high intensity fs laser pulses in air [Dormidonov *et al*, 2007, *Proc. SPIE*, 6733, 67332S; Musin *et al*, 2007, *Appl. Opt.*, 46, 5593].**
- **Small propagation distance ~ 16 cm and short maintenance time ~10 ns were restricted by low electron conductivity and lifetime of filaments [Chateauneut *et al*, 2008, *Appl. Phys. Letts*, 92, 091104].**
- **Askar'yan's suggestion [*JETP*, 28, 732, 1969]: In plasma waveguide diffraction angle $\beta = \lambda/D$ should be less then the total reflection angle at the plasma-air boundary $\beta \le \Theta \approx \Omega_p / \left(\omega^2 + \nu_T^2\right)^{1/2}$; $\Omega_p = \sqrt{4\pi n_e e^2 / m_e}$ is plasma frequency, ν_T - transport frequency.**

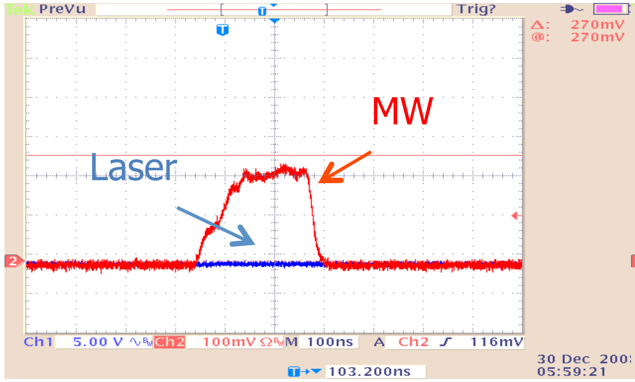
  Such sliding mode regime can be realized for $D \gg \lambda$ and at moderate plasma density 10^{11}-10^{14} cm^{-3}.

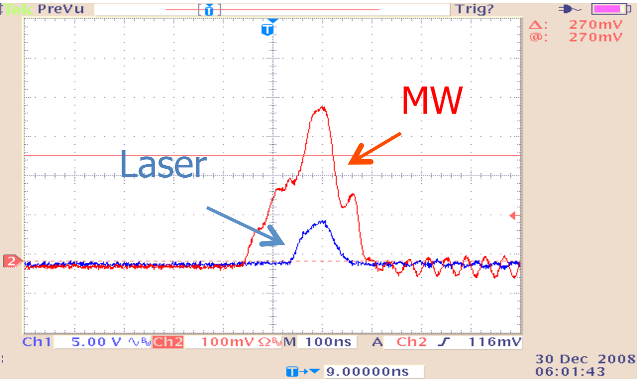


MW Guiding Experiments





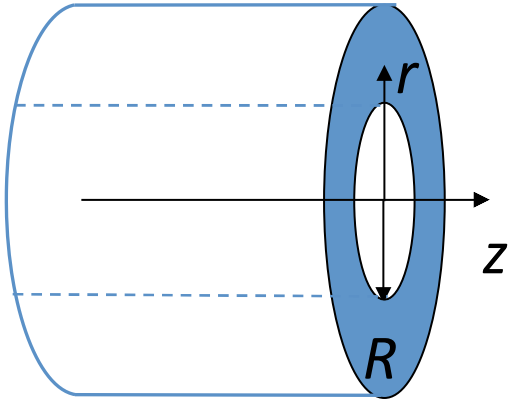




V.D. Zvorykin, *et al*, 2010, *Bull. of Lebedev Phys. Inst*, 37, 60

Axially-symmetric sliding modes in plasma waveguide

Minimum angle of incidence → **Lowest axially-symmetric modes**



***E_{01}* mode**

$$\frac{1}{\kappa_1}\frac{J_1(\kappa_1 R)}{J_0(\kappa_1 R)} = \frac{\varepsilon_p}{\kappa_2}\frac{H_1^{(1)}(\kappa_2 R)}{H_0^{(1)}(\kappa_2 R)}$$

***H_{01}* mode**

$$\frac{1}{\kappa_1}\frac{J_1(\kappa_1 R)}{J_0(\kappa_1 R)} = \frac{1}{\kappa_2}\frac{H_1^{(1)}(\kappa_2 R)}{H_0^{(1)}(\kappa_2 R)},$$

$$\kappa_1^2 = k_0^2 - h^2,\ \kappa_2^2 = \varepsilon_p k_0^2 - h^2,\ k_0 = \omega / c$$

Dimensionless parameters

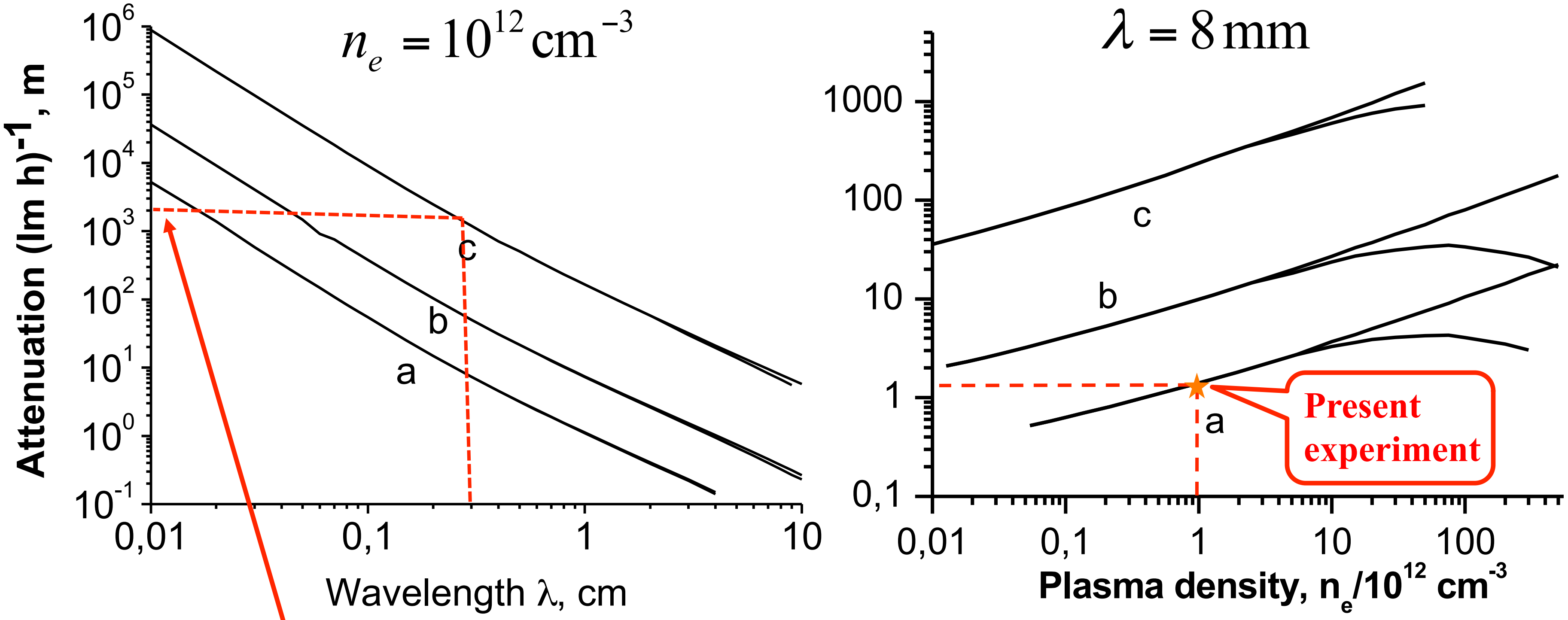
$$\mu^2 = \frac{(\Omega_p / \nu_T)^2}{1 + (\omega / \nu_T)^2}(k_0 R)^2$$

$$\kappa_1 R = x\mu,\ \kappa_2 R = y\mu,\ x^2 - y^2 = 1 - i\nu_T / \omega$$

Sliding modes exist for $\mu \geq \mu_{th} \approx 1$

V.D. Zvorykin, *et al*, 2010, *JETP Lett*, 91, 226

Attenuation lengths of the E_{01} and H_{01} modes

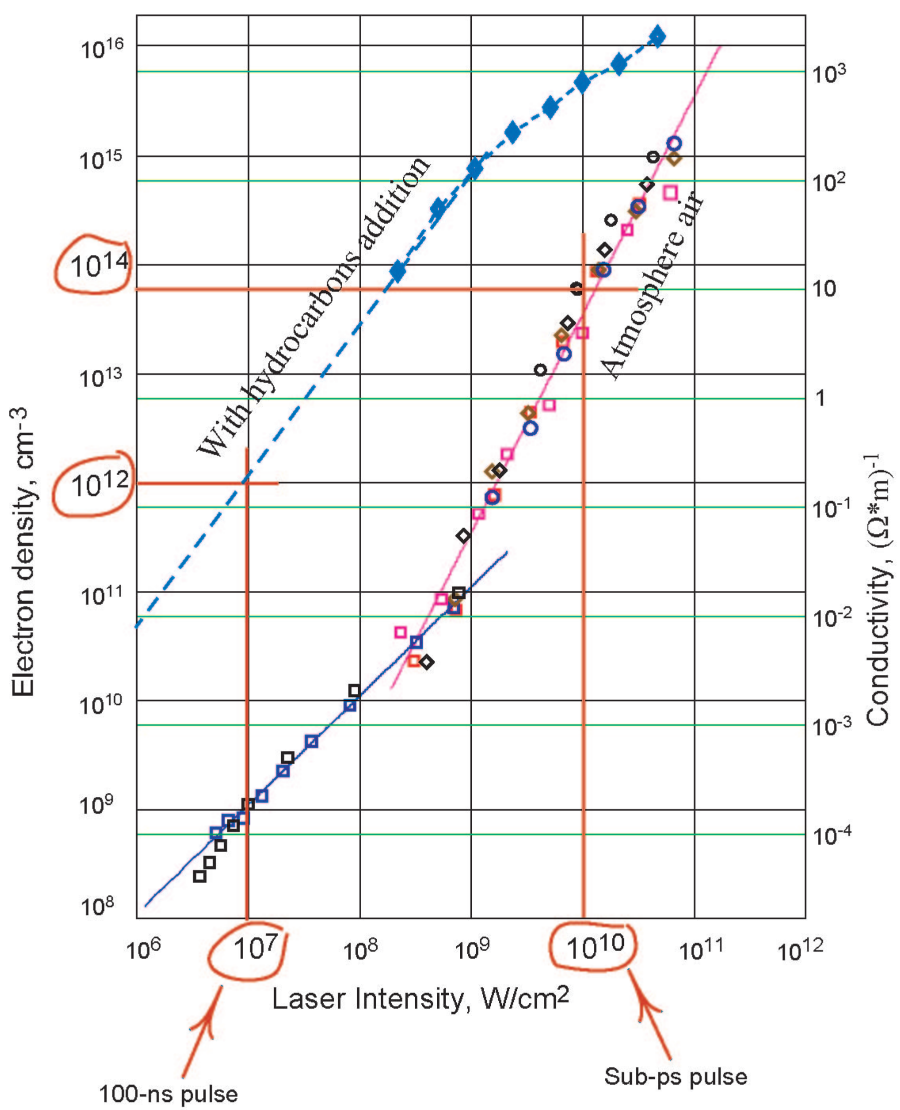


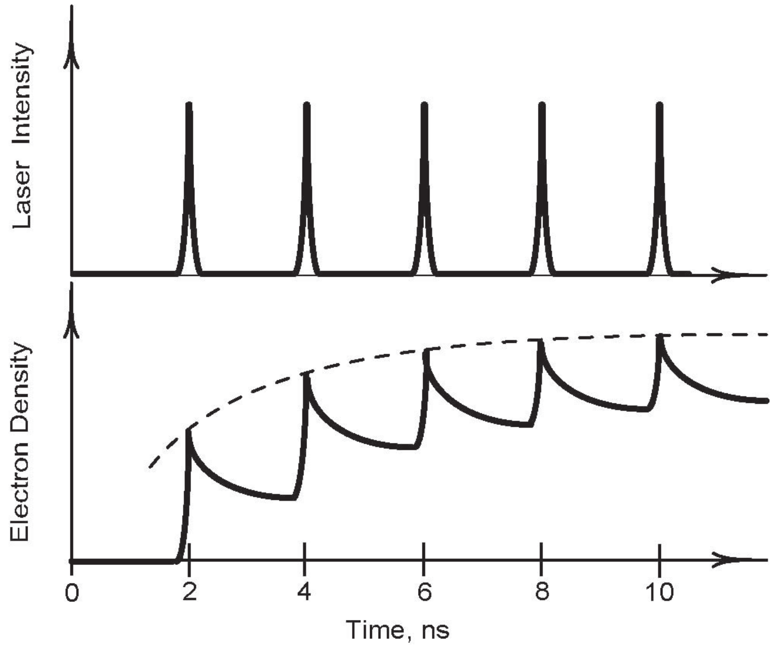
E_{01} (lower) and H_{01} modes (upper) in waveguides of radius R=5 cm (a), 10 cm (b), and 30 cm (c).

Attenuation length $(\mathrm{Im}\,h)^{-1} \propto R^3 \omega^{3/2} n_e^{1/2}$

MWs with λ~3 mm propagate in plasma waveguide (n_e=10^{12} cm^{-3}, R=30 cm) up to 2 km!

Air ionization by a train of ps pulses will allow us to accumulate electron density in plasma





- Ps pulses are more efficient in MPI processes as their probability increases with laser intensity $n_e \sim I^k \tau$ (k=2, 3).
- A consequence of ps pulses can accumulate n_e over the train time if photodetachment will prevail.

V.D. Zvorykin, *et al*, *RU Patent* #2406188 S1, Sep 15, 2009

Simple analysis of short pulses amplification

Amplification of a single short pulse $\tau << \tau_c$:

$$\frac{d\varepsilon}{dx} = g_0\left[1-\exp\left(-\varepsilon\right)\right]-\alpha\varepsilon, \quad \varepsilon = Q/Q_s,$$

$$Q_{opt} = Q_s\ln\left(g_0/\alpha\right) = 4.6 \div 6.0\,\text{mJ/cm}^2 \ \left(g_0/\alpha = 10 \div 20 \text{ for } W_p \sim 1\,\text{MW/cm}^2\right),$$

$$\left(\eta_{1ext}\right) = 1-\left(\alpha/g_0\right)\left[1+\ln\left(\alpha/g_0\right)\right] = 0.67 \div 0.8, \ \eta_{ext} = \left(\tau_c/\tau_p\right)\eta_{1ext} = 0.014 \div 0.016,$$

$$(\tau_c \approx 2\,\text{ns},\ \tau_p = 100\,\text{ns}),\ \eta = \eta_{ext}\eta_p \approx 0.004 \left(\eta_p \approx 0.25\right)$$

Amplification of a train of short pulses with time interval Δt:

$$g_{\Delta t} = g_0\frac{1-\exp\left(-\Delta t/\tau_c\right)}{1-\exp\left(-\varepsilon\right)\exp\left(-\Delta t/\tau_c\right)},$$

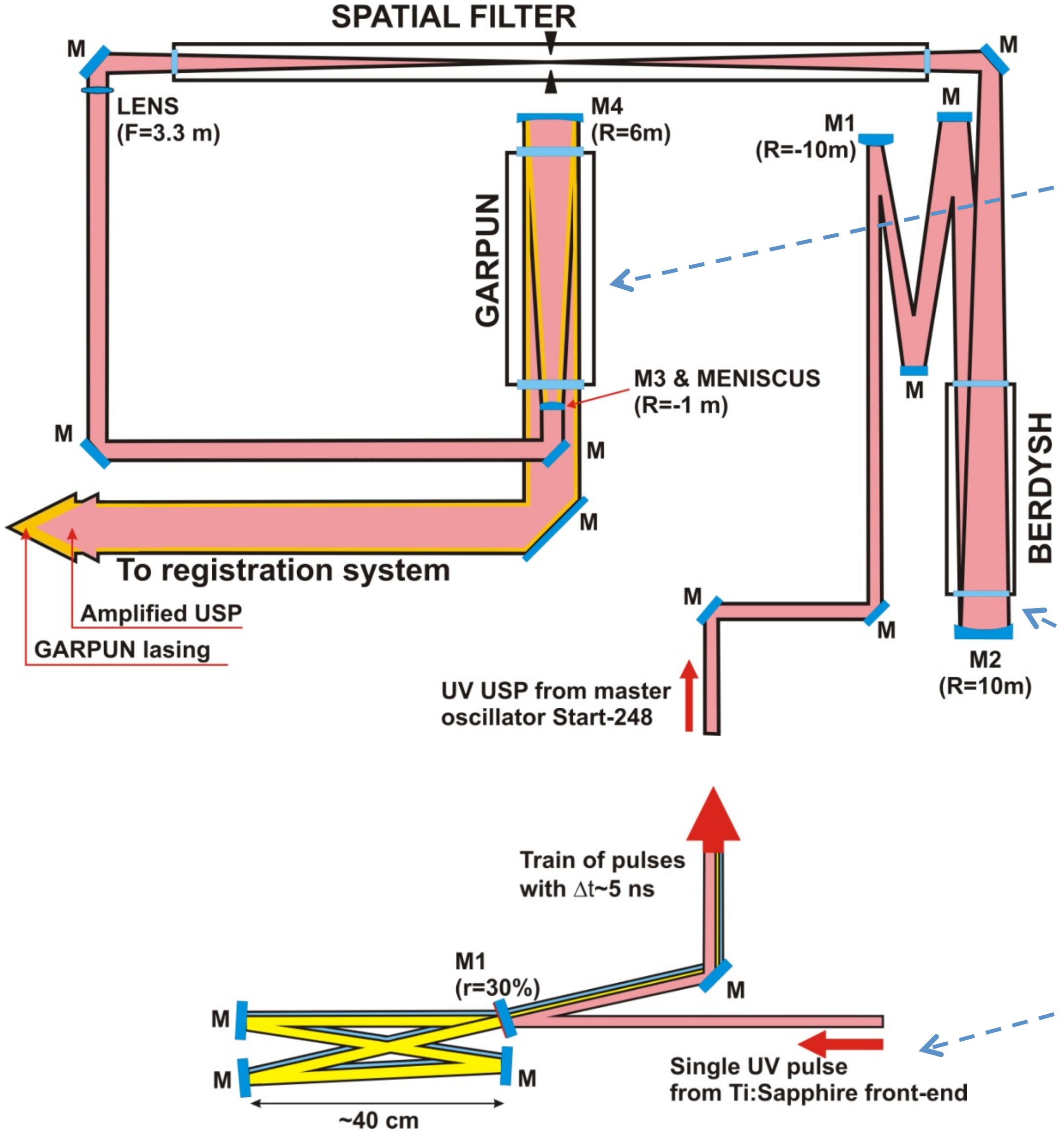
$$\eta_{ext} = \frac{1}{\Delta t/\tau_c}\left\{\frac{\left[1-\exp\left(-\Delta t/\tau_c\right)\right]\left[1-\exp\left(-\varepsilon\right)\right]}{1-\exp\left(-\varepsilon\right)\exp\left(-\Delta t/\tau_c\right)}-\frac{\alpha\varepsilon}{g_0}\right\},$$

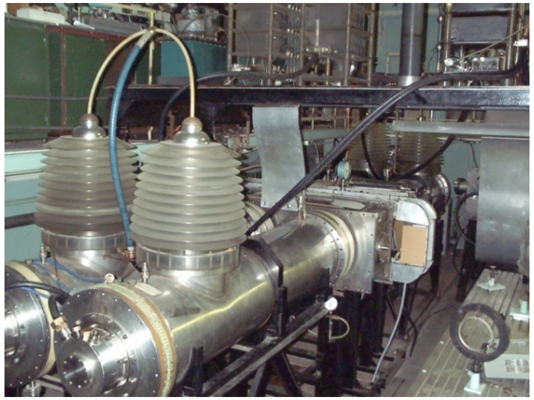
$$\varepsilon_{opt} = \ln\left\{2\exp\left(-\Delta t/\tau_c\right)+g_0/\alpha\left[1-\exp\left(-\Delta t/\tau_c\right)\right]^2\right\}$$

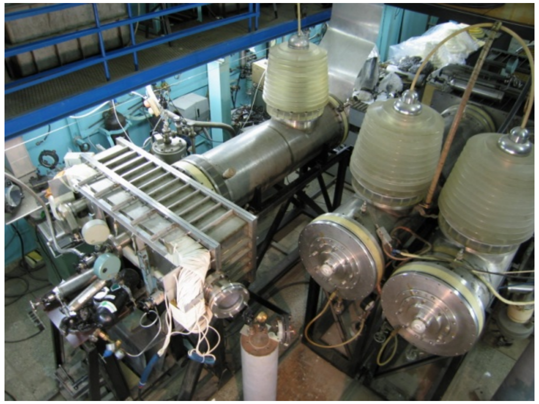
For $\Delta t = \tau_c \rightarrow Q_{opt} = 3.1 \div 4.3\,\text{mJ/cm}^2$, $\eta_{ext} = 0.38 \div 0.48,\ \eta = 0.095 \div 0.12$

V.D. Zvorykin, *et al*, 1997, *Bull. of Lebedev Phys. Inst*, No. 9-10, 20

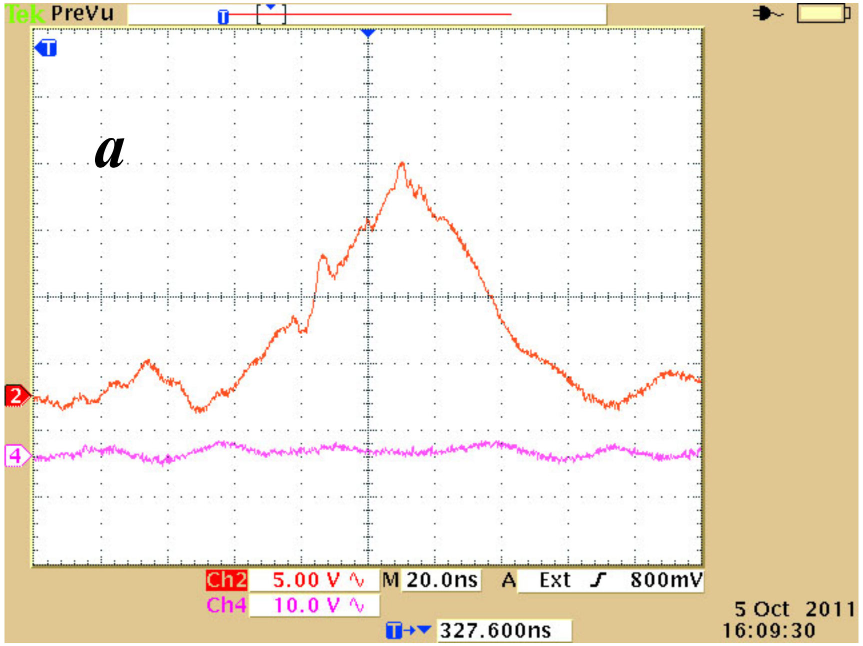
Simultaneous amplification of ps pulse train and 100-ns UV pulses at KrF/Ti:Saphire GARPUN-MTW laser

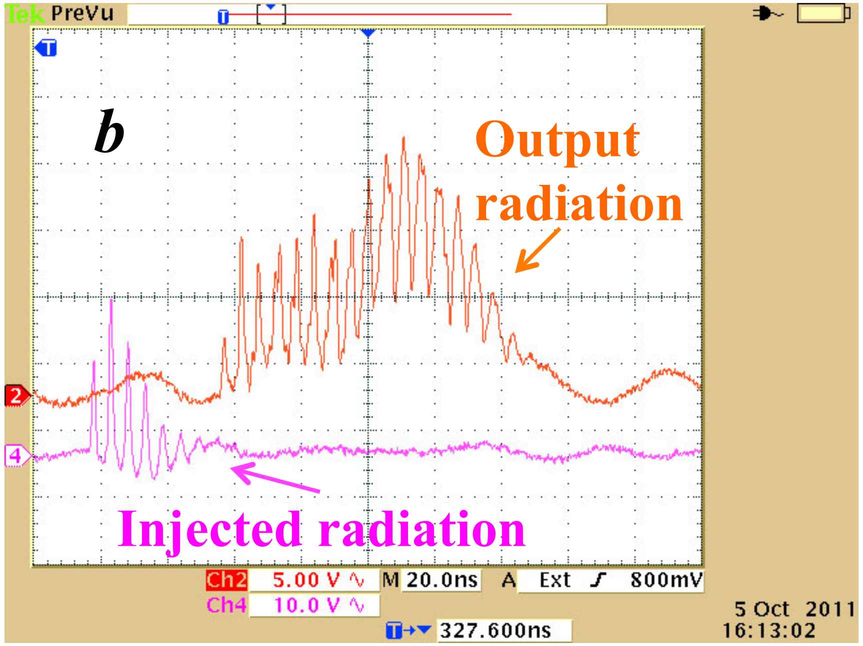


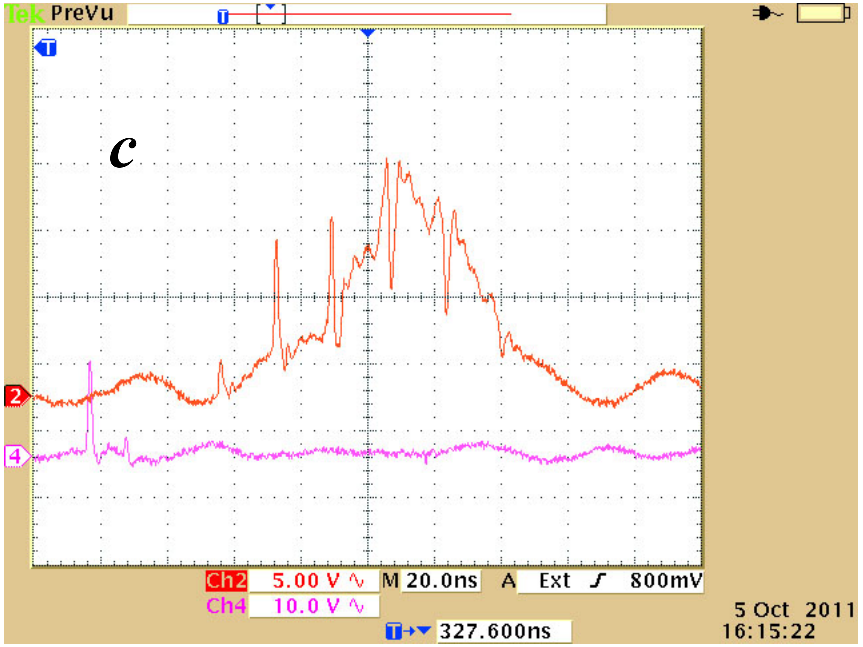




Combined UV pulses



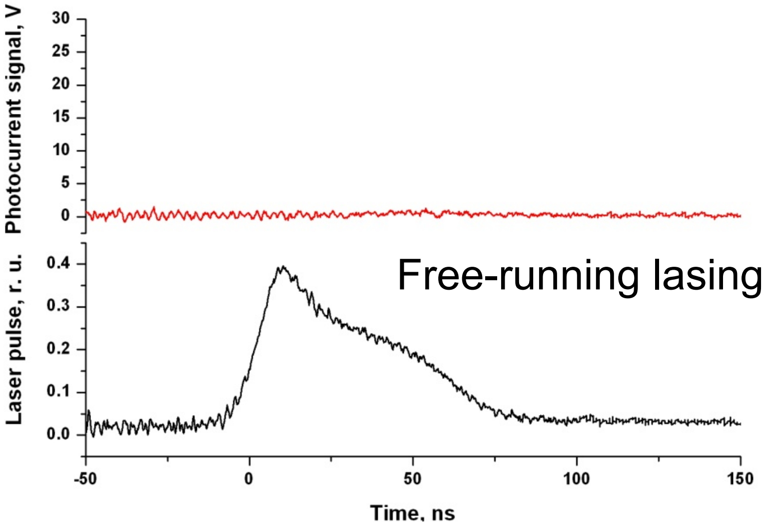


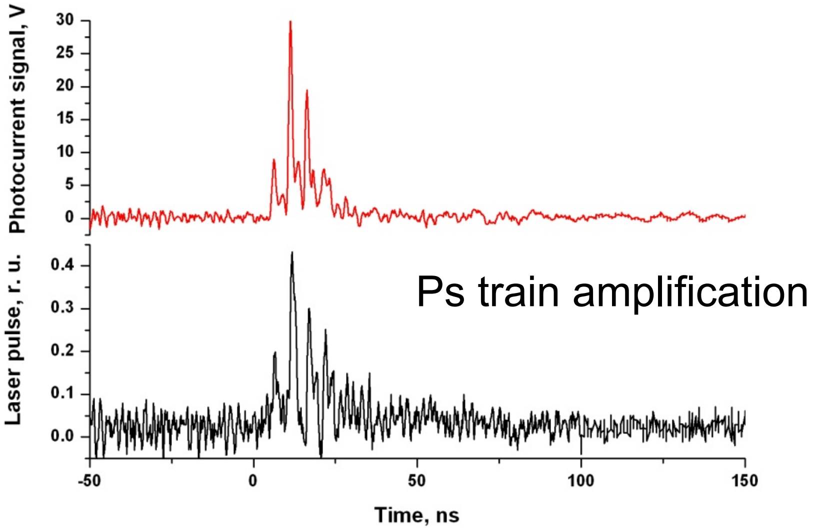


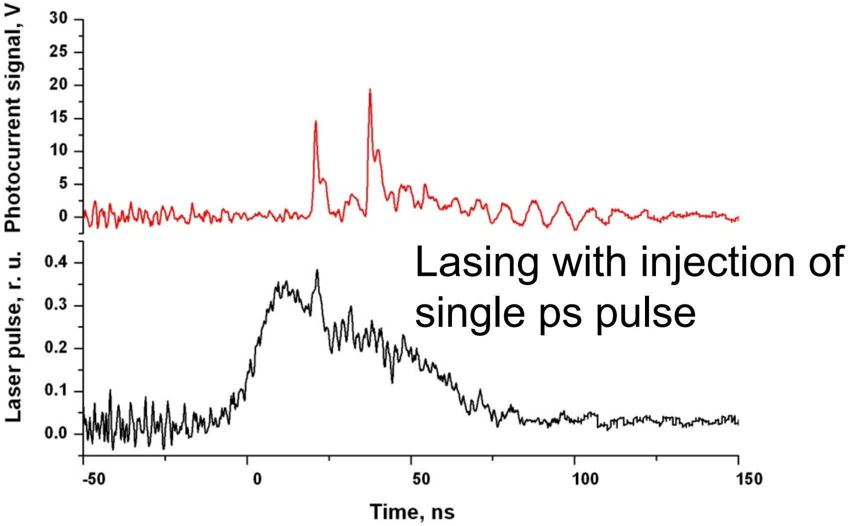
Free-running lasing (*a*), under injection of single ps pulse (*b*) and a train of ps pulses (*c*). Time scale 20 ns/div.

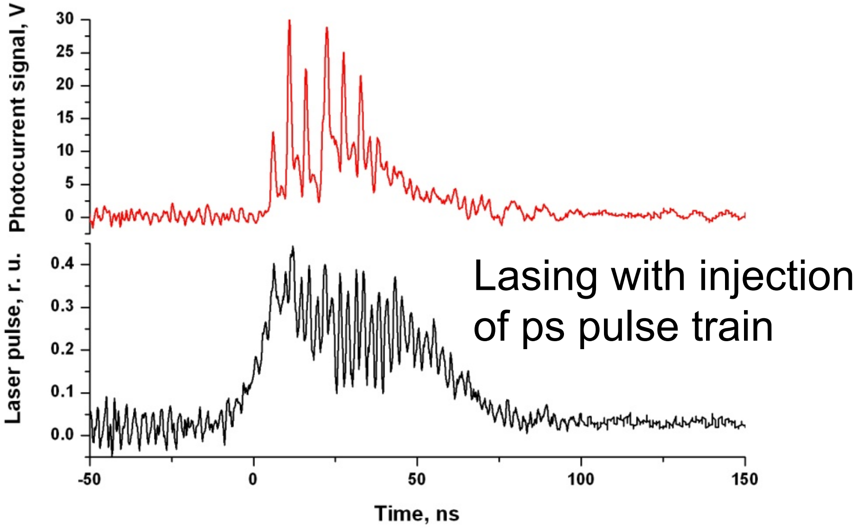
100-ns lasing pulse is modulated by ps spikes with total energy up to 30 J. Peak power of the spikes 0.2-0.3 TW exceeds free-running lasing in 1000 times

Photocurrent for combined pulses exceeds in 100 times photocurrent for a smooth 100-ns pulse


Free-running lasing

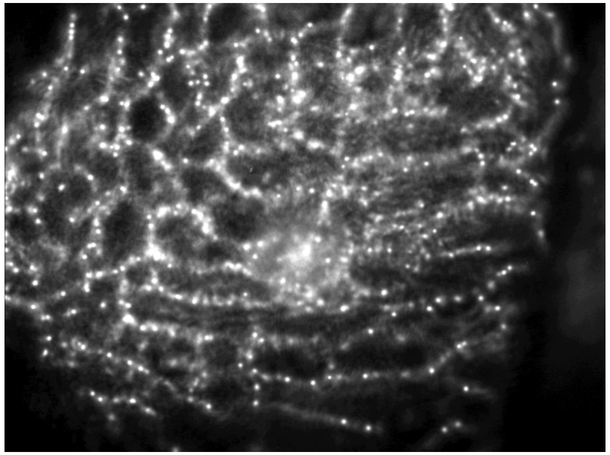

Ps train amplification


Lasing with injection of single ps pulse

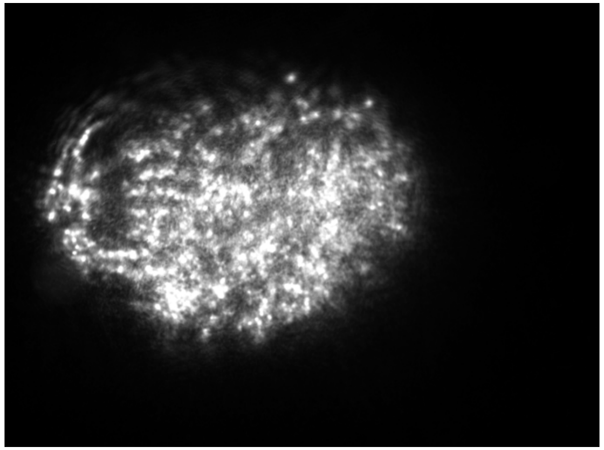

Lasing with injection of ps pulse train

A.A. Ionin *et al*, *Appl. Phys. Lett*, 2012, 100, 104105

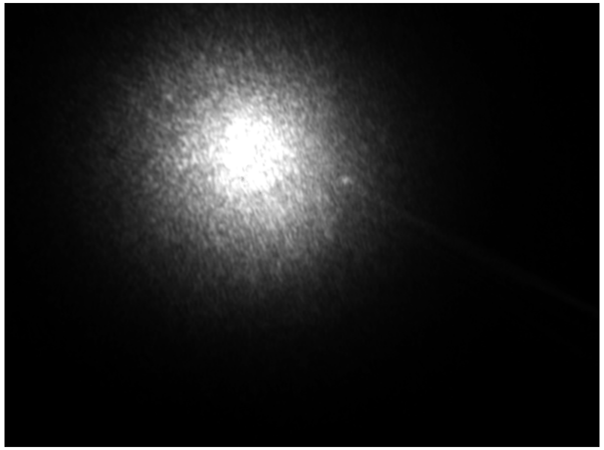
Filamentation of subps TW UV laser beam



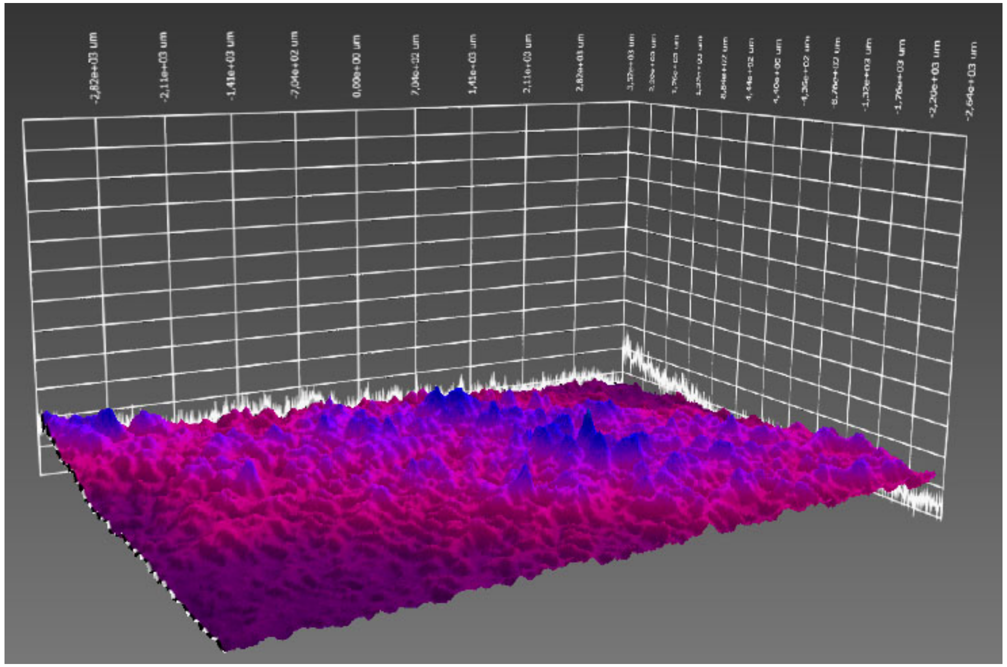
***F*-20 m**



***F*-30 m**



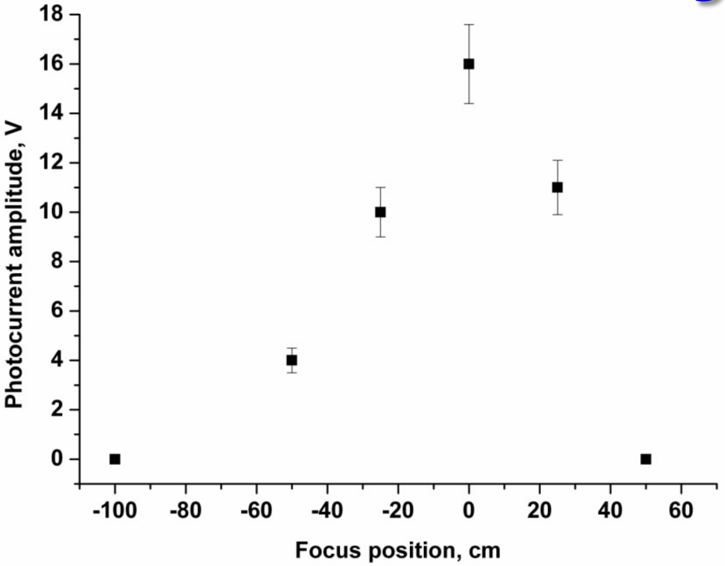
***F*=60 m**



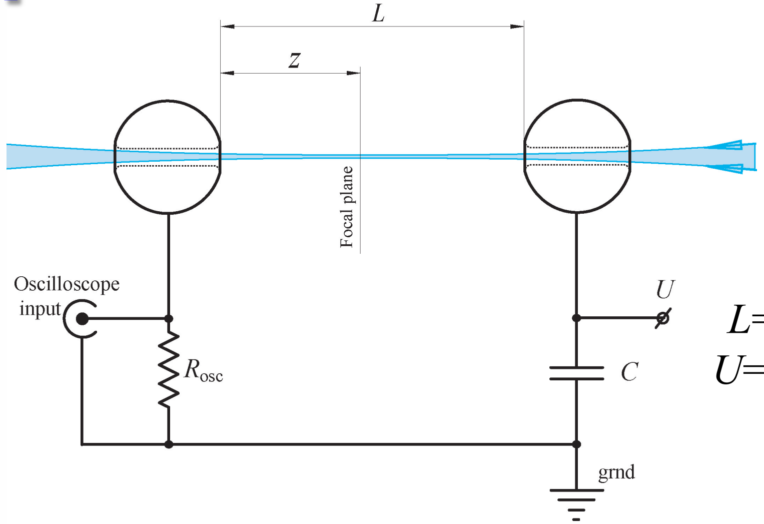
40 mm

KrF subps pulses with peak power of ~1 TW>>$P_{cr}=3{,}8\lambda^2/8\pi n_0 n_2 \approx 100$ MW due to Kerr self-focusing produce a bundle of filaments of ~100 µm diameter with $n_e=10^{15}$-10^{16} cm^{-3}

Conductivity of plasma channels

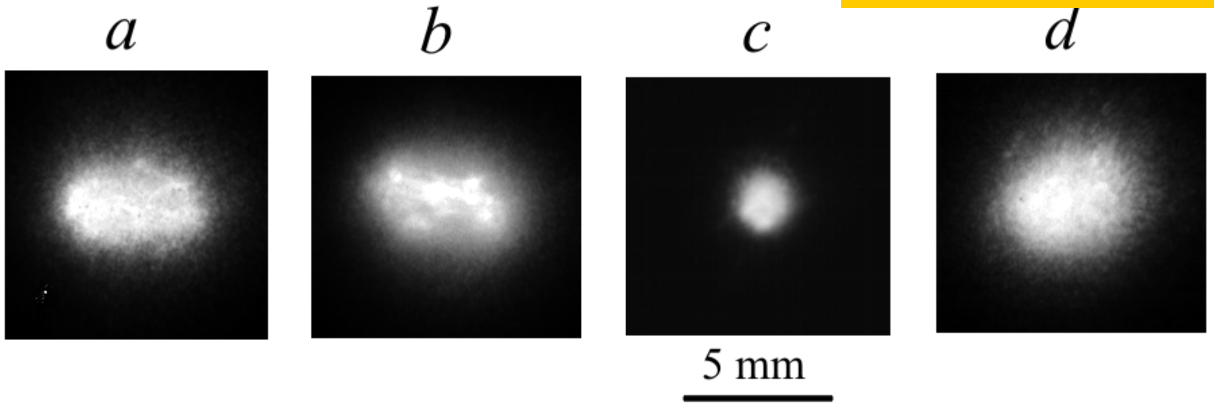


Photocurrent amplitude in dependence on focus position



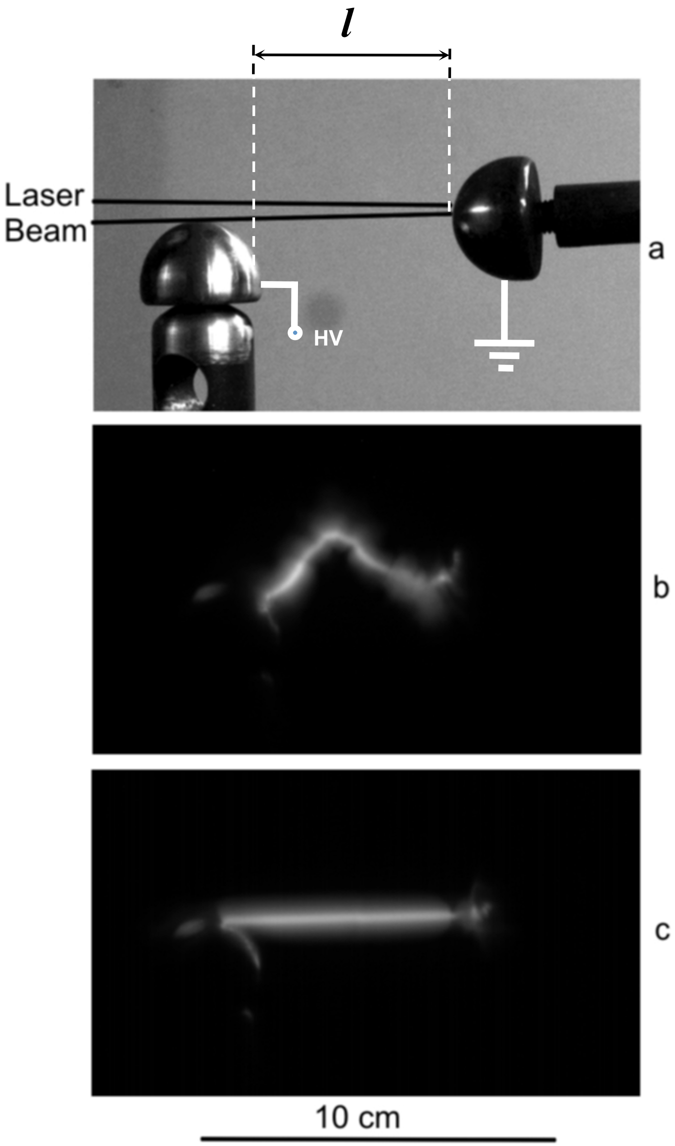
L=20 cm,
U=5–22 kV

For specific conductivity of plasma channel $\sigma_e = L/RS = 0.16\ (\Omega\cdot\text{cm})^{-1}$ estimated electron density $n_e = \sigma_e / e\mu_e \approx 1.6 \cdot 10^{15}\ \text{cm}^{-3}$, $\mu_e \approx 600\ \text{cm}^2\cdot(\text{V}\cdot\text{s})^{-1}$



Laser beam profiles for different distances from the focus: 50 cm before the focus (a, b), in the focus (c), and 50 cm behind the focus (d).

Guiding of HV discharge by combined pulse

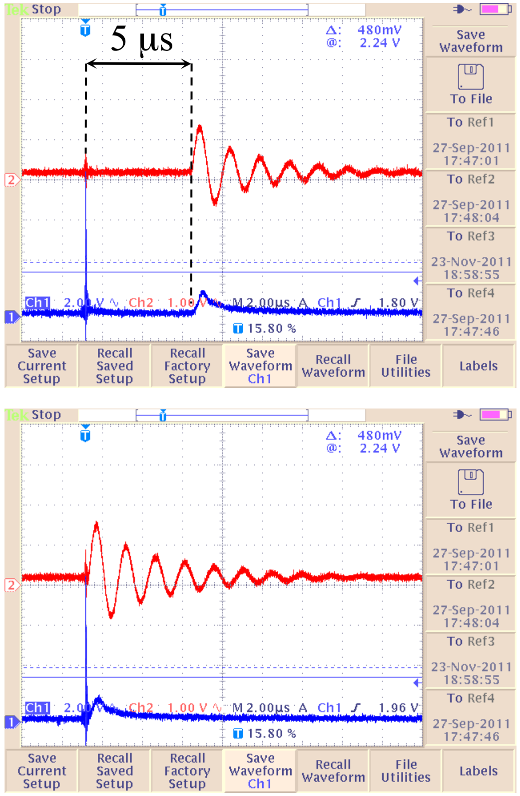


Discharge gap:
U=50 kV; *l*=1.5 cm; *E*≈30 kV/cm.

Discharge triggered by a smooth laser pulse:
U=50 kV; *l*=4 cm.

Discharge triggered and guided by combined laser pulse: *U*=50 kV; *l*=7 cm.

Oscillograms of discharge current, laser pulse and plasma emission



CONCLUSIONS

- **A train of UV picoseconds pulses with subTW peak power was obtained at hybrid Ti:Sapphire/KrF GARPUN-MTW laser facility being combined with 30-J, 100-ns pulse of a free-running oscillation.**

- **The advantages of combined radiation for production of long-lived plasma channels: photocurrent sustained by the combined pulse is two orders of magnitude higher and HV breakdown distance is twice longer than for the long UV pulse only.**

- **Further investigations are going on including TW UV pulses filamentation and its effect on extended HV discharge triggering and long-distance sliding-mode MW transfer in atmospheric air.**

Acknowledgments

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