Multiple Filamentation of UV Supercritical Laser Beam in Atmospheric Air

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The 6th International Conference Channeling 2014 - Charged & Neutral Particles Channeling Phenomena

Capri (NA), Italy, October 5-10, 2014

Outline

- **History of laser beam filamentation and motivation for research:**
  - **guiding of HV electric (lightning) discharges**
  - **transport of MW radiation in plasma waveguides**
  - **filament induced breakdown spectroscopy (FIBS)**
  - **backward atmospheric N_2 laser**
- **Ti:Saphire/KrF GARPUN-MTW laser facility**
- **Filamentation of supercritical UV laser radiation**
- **Conclusions**

Historical notes

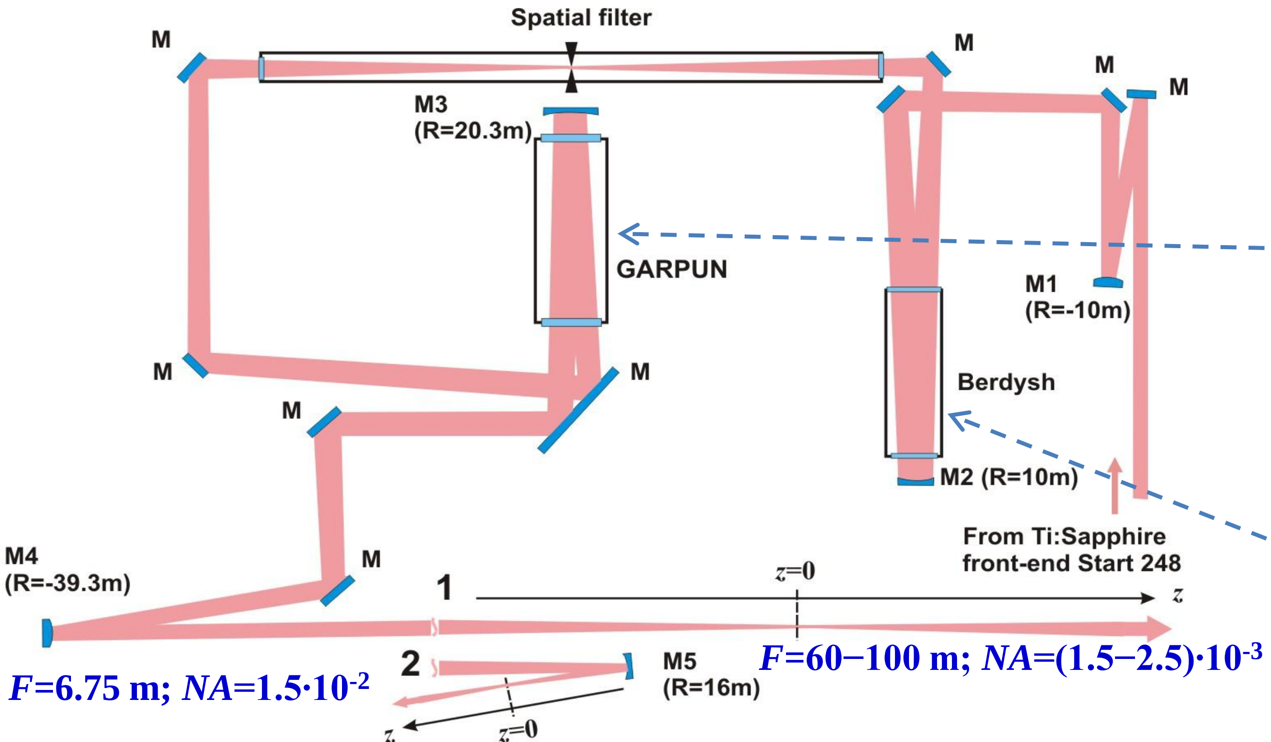
- **Self-focusing (filamentation) of laser radiation was firstly suggested by Askar'yan (*Sov. Phys. JETP*, 1962, 15, 1088) and observed by Pilipetskii & Rustamov in organic liquids for Q-switched 20 MW, ns laser pulses (*JETP Lett.*, 1965, 2, 55). For theory see Akhmanov et al, *Sov. Phys. Usp*. 1968, 10, 609.**

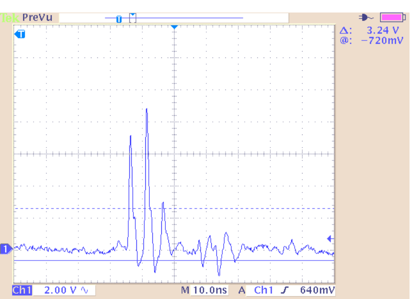
- **Commonly observed in liquids and solids, filaments damage solid-state laser amplifiers and put power limit for short pulses (Basov, et al, *Sov. Phys. JETP*, 1966, 23, 16).**

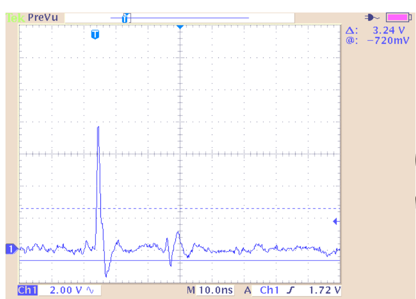
- **With Ti: Sapphire laser, which generates ultra-short pulses (USP) in fs range at wavelength ~ 800 nm, filamentation was also observed in atmospheric air (Braun et al. *Opt. Lett*, 1995, 20, 73); nowadays it has a big room for applications.**

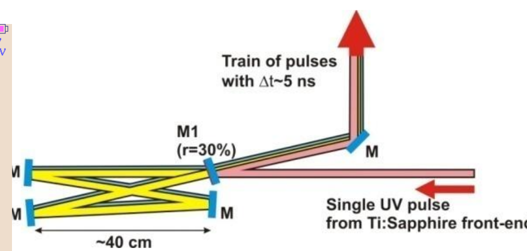
- **KrF laser due to a short radiation wavelength λ=248 nm, unique possibility to generate pulses of different waveforms and duration from subps to 100 ns can produce extended plasma channels for various applications.**

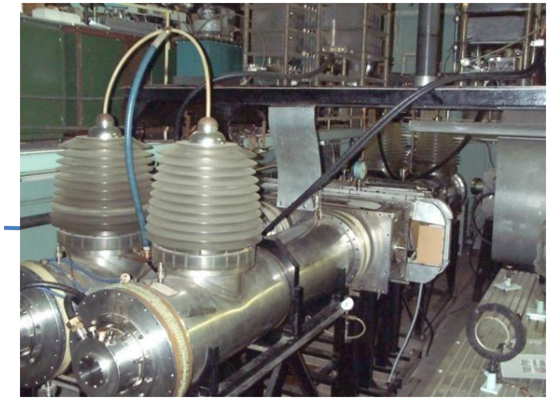
Amplification of a train of ps, sub-TW UV pulses at Ti:Saphire/KrF GARPUN-MTW Laser

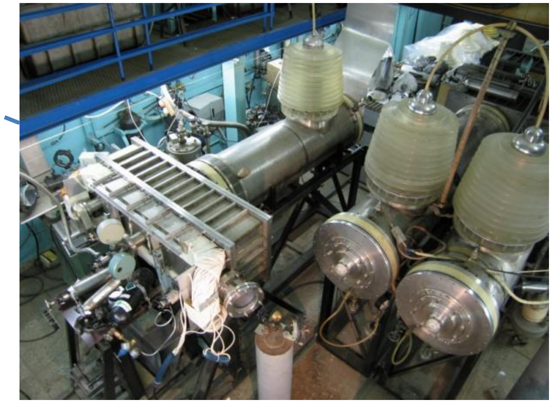








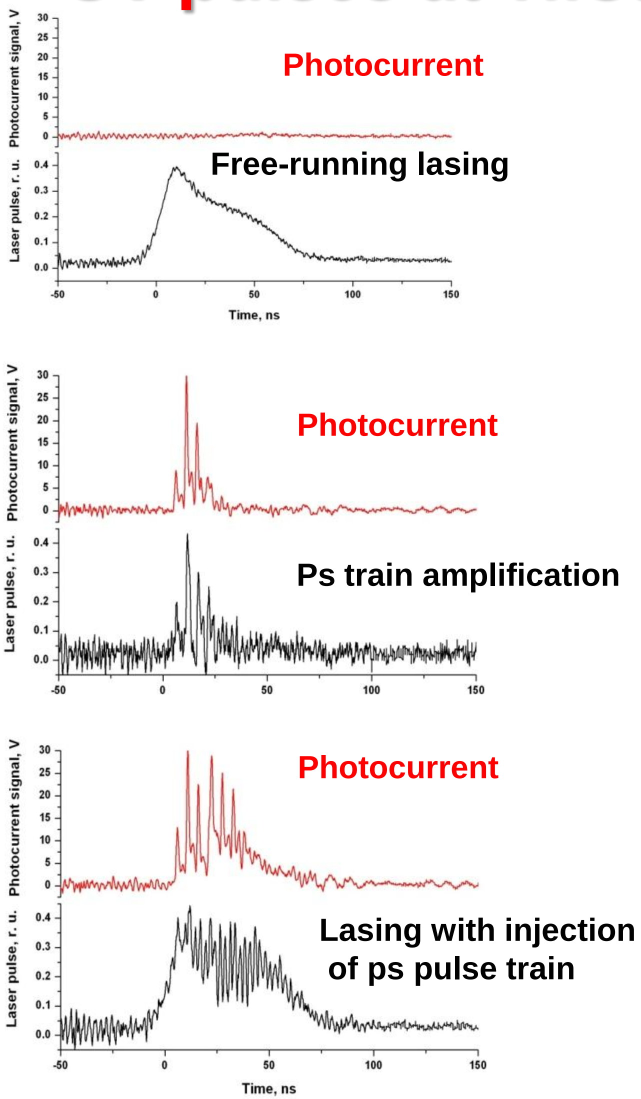


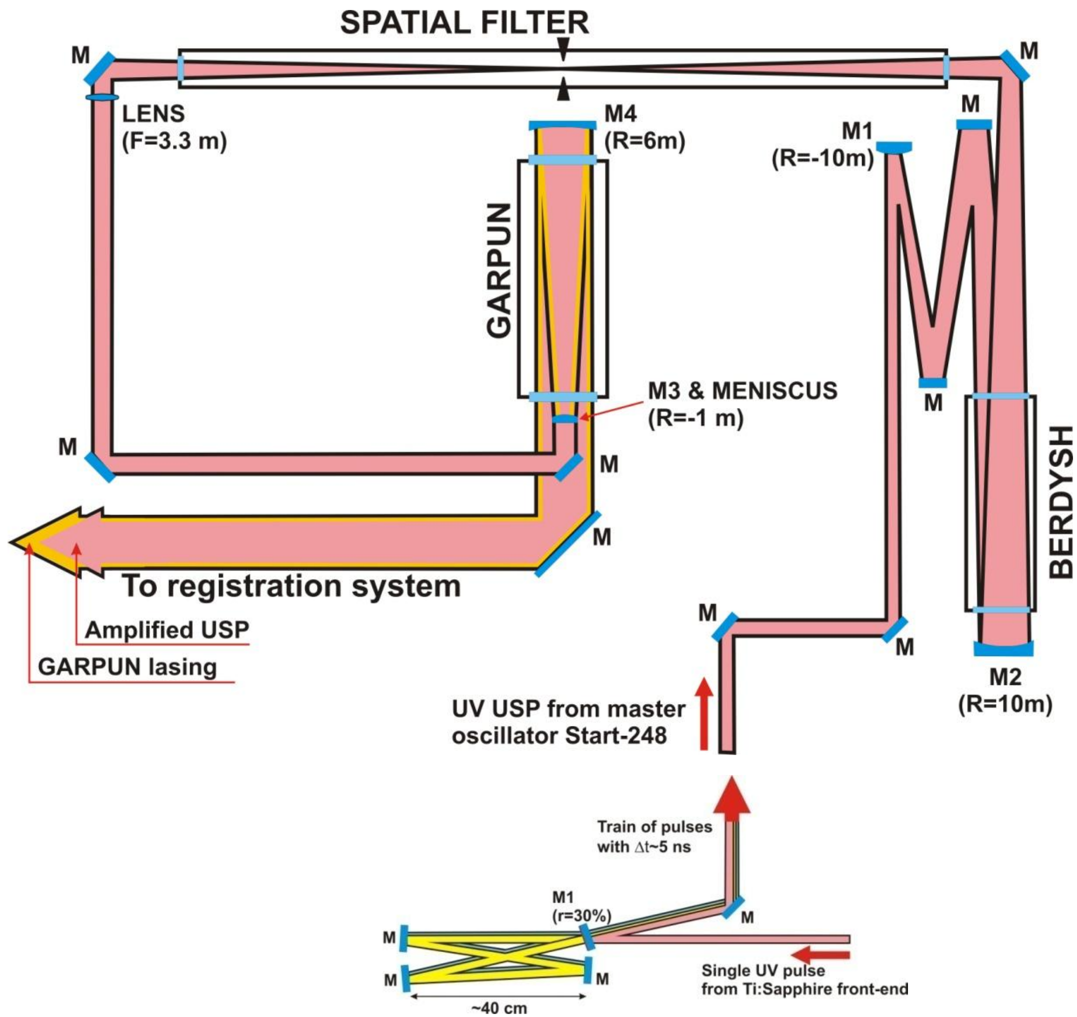


Single USP: $E_1 \leq 1$ J; $\tau_p < 1$ ps; $P_1 \sim 1$ TW; train : $E \leq 2$ J; $P_1 : P_2 : P_3 \ldots = 3:5:1.5:0.5\ldots$, $\Delta t = 3–5$ ns

Zvorykin et al, *Quantum electron.* 2014, 44, 431.

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

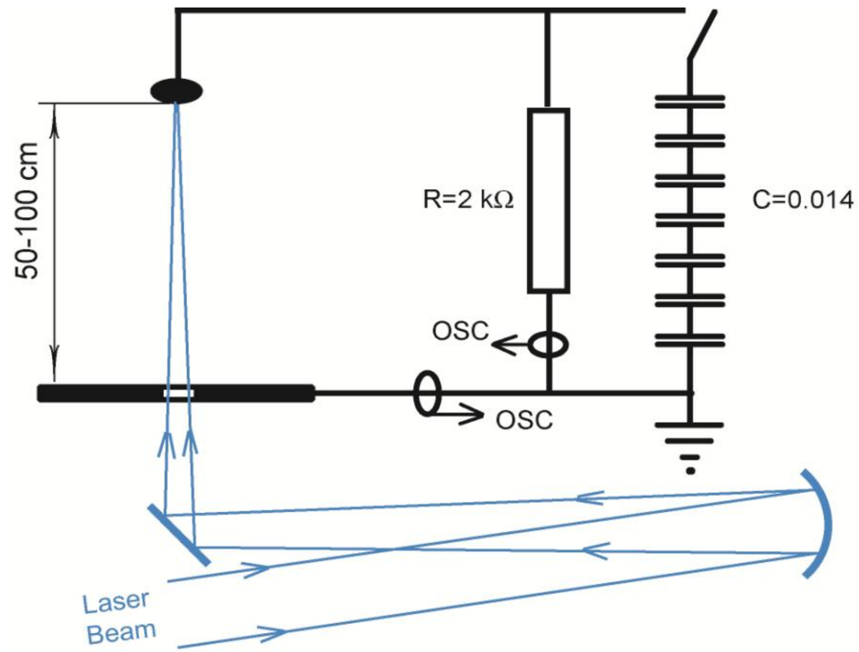




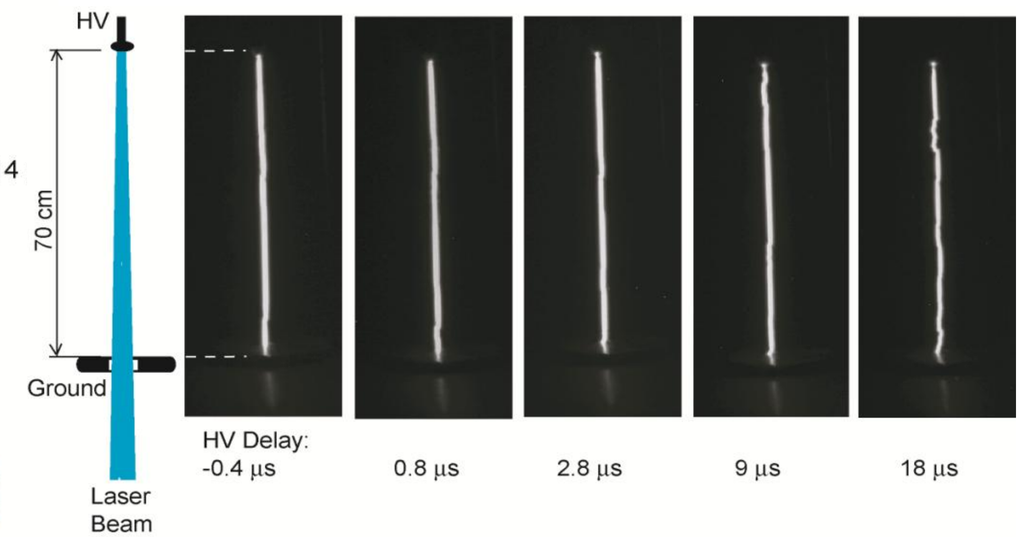
Combination of the USP train and 100-ns lasing pulse is an effective tool for air ionization and maintenance electron density in a plasma channel for a long time, while spatial matching of both radiations is an issue.

Guiding of HV discharge by combined UV radiation

Layout of experiments



Images of discharges initiated by combined laser pulse (E_L= 6.3 J) for different delays of applied voltage (U= 420 kV).

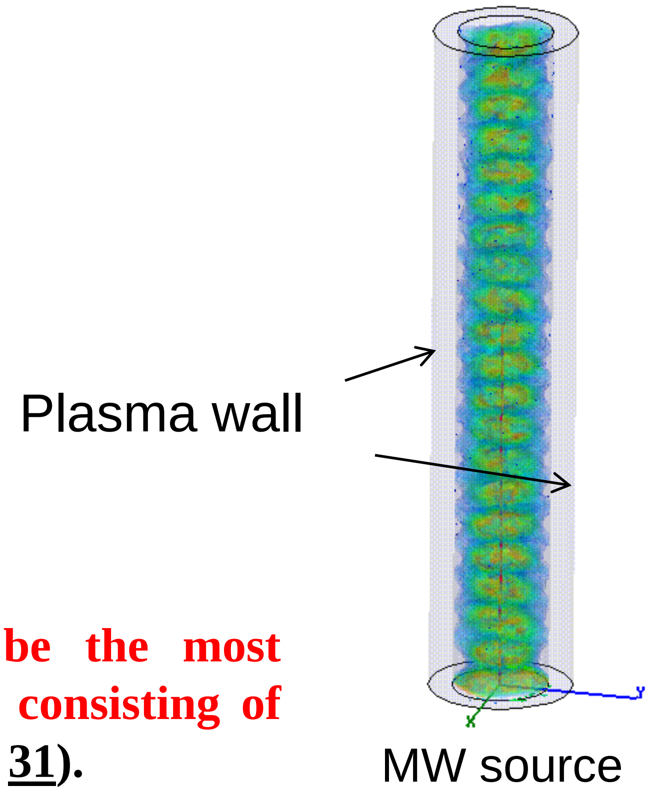


A combined laser pulse produces long ionization trace in air which initiates HV discharge and guides it along 70-cm gap.

Zvorykin et al, *Quantum electron.* 2013, 43, 239.

A sliding-mode hollow-core plasma waveguide for directed transfer of MW radiation

- **Firstly proposed by Askar'yan (*Sov. Phys. JETP*, 1969, 28, 732) with a powerful tubular UV laser beam as a source for multi-photon air ionization. It was realized with 1 GW, 100 ns KrF laser (V.D. Zvorykin, *et al*, 2010, *Bull. of Lebedev Phys. Inst*, 37, 60; V.D. Zvorykin, *et al*, 2010, *JETP Lett*. 2010, 91, 226).**
- **As a refractive index in air plasma is slightly less than in air, for waveguide radius $R_{wg} >> \lambda_{MW}$ internal reflection at the air-plasma boundary confines radiation in the central core of a waveguide. Physically this sliding-mode regime is similar to light propagation in optical fibers.**



USP train or combined radiation seems to be the most attractive to produce a sliding-mode waveguide consisting of plasma filaments (Zvorykin et al. *Appl. Opt.* 2014, 31).

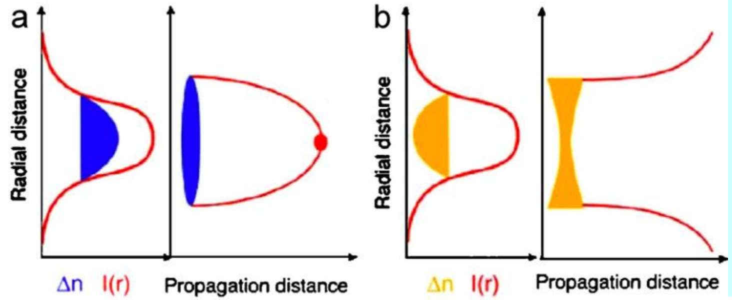
Comparison of filamentation of IR and UV radiation

Kerr focusing

$$n = n_0 + n_2 I(r,t)$$

Critical power

$$P_{cr} = 3.77\lambda_0^2 / 8\pi n_0 n_2$$



Plasma defocusing

$$n \approx n_0 - \rho(r,t)/2\rho_c,\ \rho_c = \varepsilon_0 m_e \omega_0^2 / e^2,$$

$$\rho = \sigma_K I^K \rho_{at} \tau_p$$

$$\sigma_{Br} = \frac{e^2}{\varepsilon_0 m_e c n_0} \frac{\tau_c}{(1+\omega^2\tau_c^2)} \approx \frac{e^2}{\varepsilon_0 m_e c n_0 \tau_c \omega^2}$$

The collapse is stopped when plasma defocusing balances Kerr focusing

$$n_2 I = \frac{\rho(I)}{2\rho_c} + \frac{(1.22\lambda_0)^2}{8\pi n_0 w_0^2};\ \rho(I) = \sigma_K I^K \rho_{at} \tau_p$$

Scaling for filament parameters :

$$I \sim \left(\frac{0.76 n_2 \rho_c}{\sigma_K \rho_{at} \tau_p}\right)^{\frac{1}{K-1}};\ \rho(I) \sim \left[\frac{(0.76 n_2 \rho_c)^K}{\sigma_K \rho_{at} \tau_p}\right]^{\frac{1}{K-1}};$$

$$w_0 \sim \left(\frac{2P_{cr}}{\pi}\right)^{1/2} \left(\frac{0.76 n_2 \rho_c}{\sigma_K \rho_{at} \tau_p}\right)^{-\frac{1}{2(K-1)}}$$

Wavelength λ, nm	800	248
n_2, $cm^2 \cdot W^{-1}$	$(2.8–3.0)\cdot 10^{-19}$	$(8–10)\cdot 10^{-19}$
P_{cr}, GW	3.4–3.6	0.1–0.12
O_2 (W_i=12.06 eV): K; σ_K, $s^{-1}\cdot(cm^2\cdot W^{-1})^K$	8; $2.8\cdot 10^{-96}$	3; $1.4\cdot 10^{-28}$
N_2 (W_i=15.58 eV): K; σ_K, $s^{-1}\cdot(cm^2\cdot W^{-1})^K$	11; $6.3\cdot 10^{-140}$	4; $3.2\cdot 10^{-44}$

Parameters of single filaments for the IR and UV radiation (according to Couairon & Berge calculations)

UV light (λ = 248 nm) | IR light (λ = 800 nm)

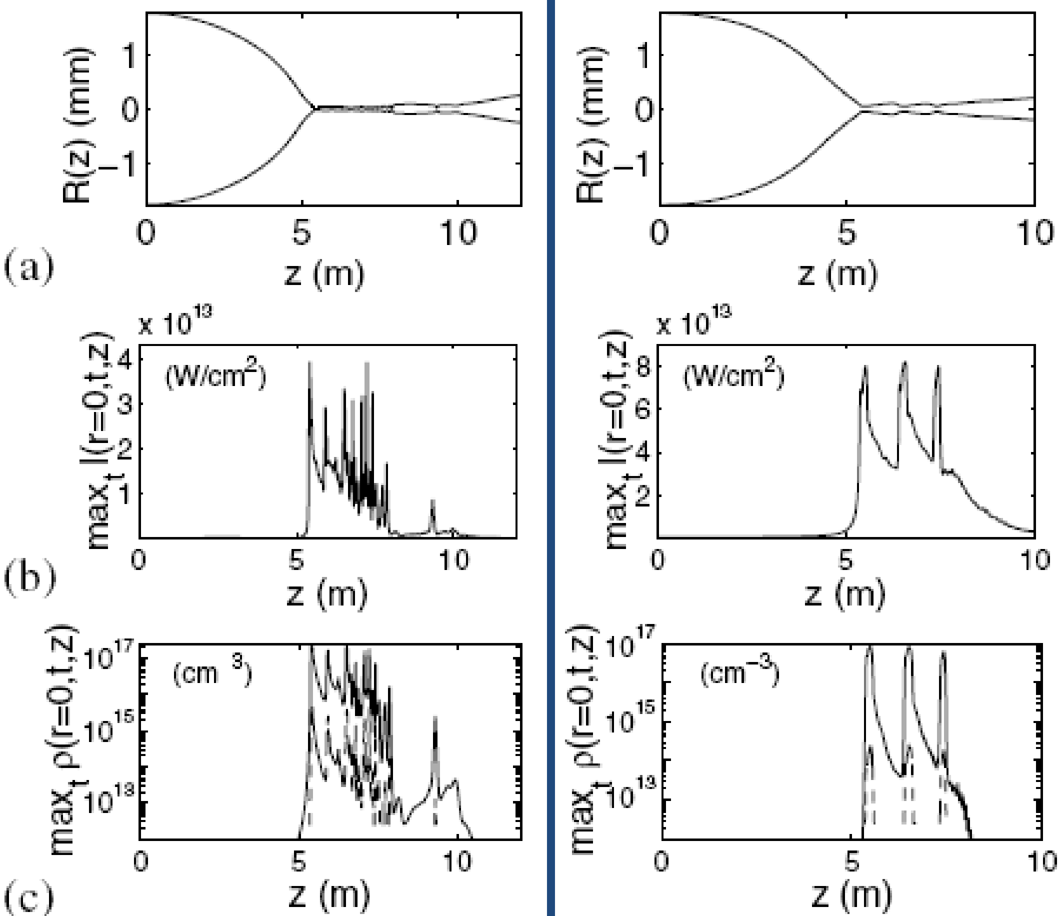
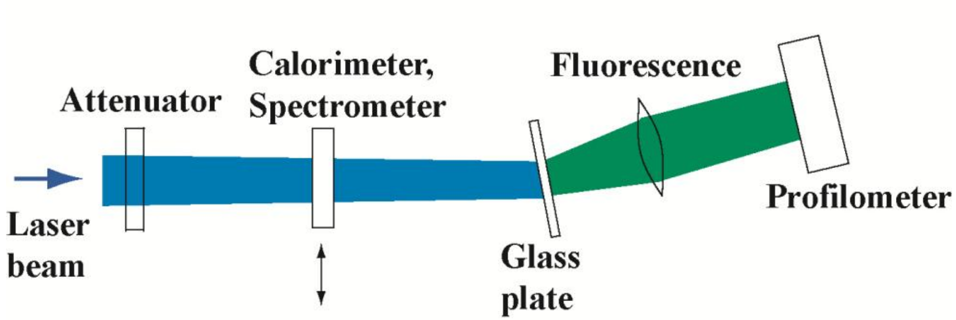
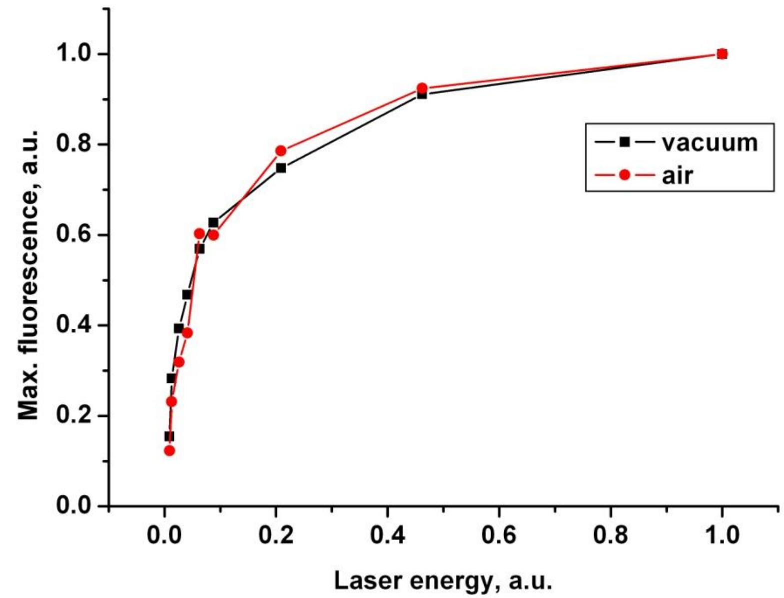


FIG. 2. (a) Beam radius, (b) peak intensity, and (c) electron density as functions of z for a UV pulse (left column) and an IR pulse (right column) propagating in air.

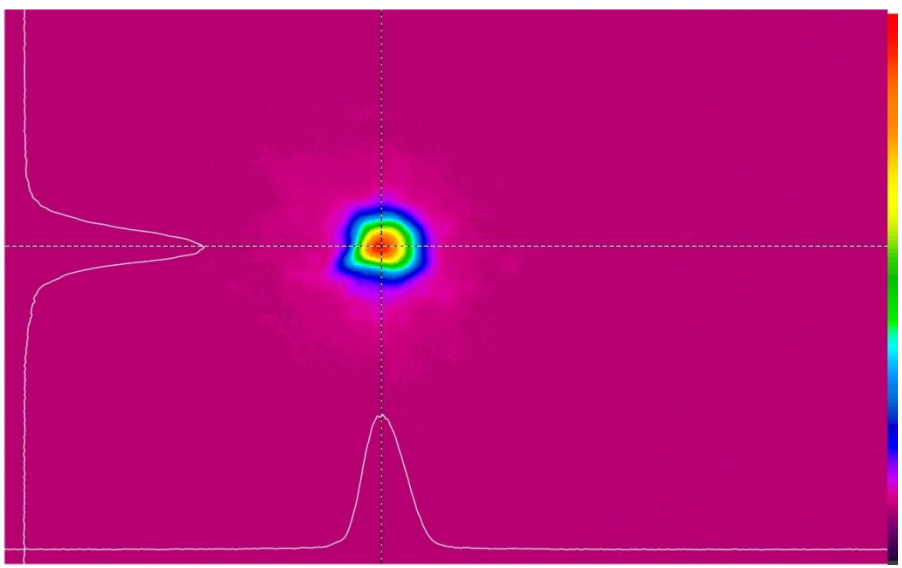
- According to scaling formulas and numerical simulations (PRL, 88, 135003 (2002)) peak intensities in single filaments $I \sim 10^{13}$ W/cm^2, electron densities $\rho \sim 10^{16} \div 10^{17}$ cm^{-3}, and filament size $w_0 \sim 100$ μm are approximately equal for both UV and IR wavelengths.
- A big room for experimental values for UV radiation still exists. Present experiments were performed at frequency-tripled Ti:Sapphire front-end ($\tau_{1/2} \sim 100$ fs) of GARPUN-MTW laser facility to find critical power and diameter of filaments.

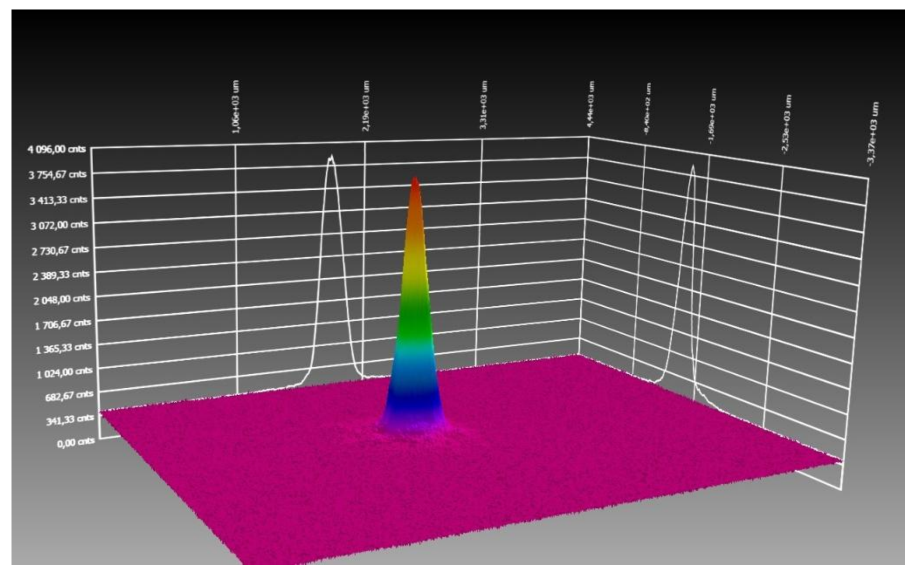
Filaments registration





Glass fluorescence under UV irradiation was measured with Ti: Sapphire front-end. A single filament produced by 0.2 mJ, 100-fs USP has 20 cm length which is much more than diffraction (Reyleigh) length of focused beam.

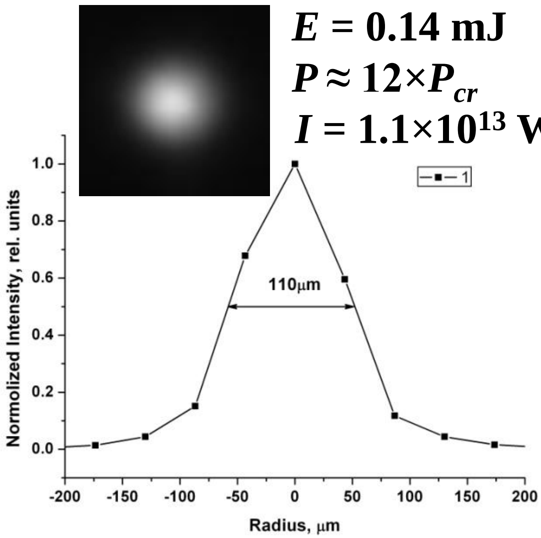




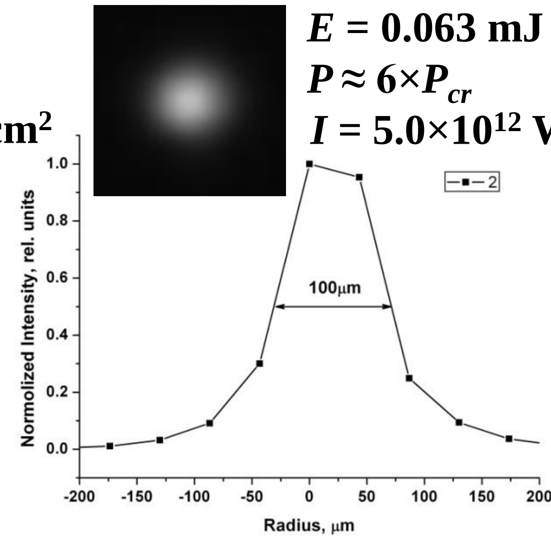
Single filaments of 100-fs UV laser pulse

For higher peak powers of 100-fs UV USP $10 \cdot P_{cr} \geq P \geq P_{cr}$ a single filament of $d_{0.5} \approx 100$ μm diameter was observed

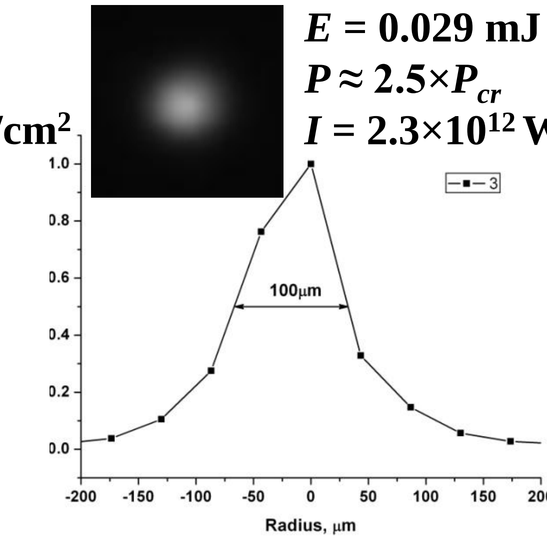
$E = 0.14$ mJ
$P \approx 12 \times P_{cr}$
$I = 1.1 \times 10^{13}$ W/cm^2



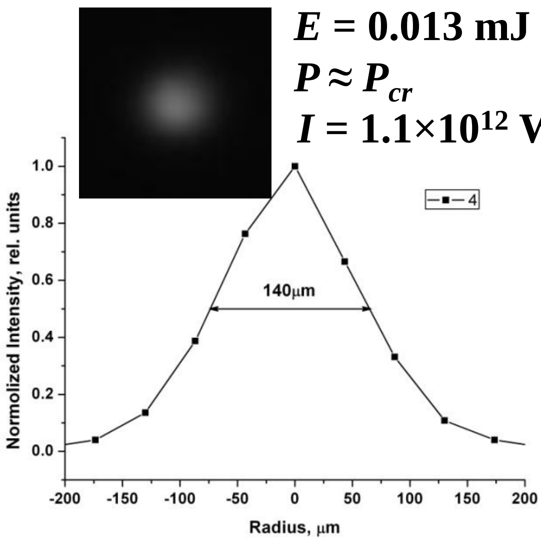
$E = 0.063$ mJ
$P \approx 6 \times P_{cr}$
$I = 5.0 \times 10^{12}$ W/cm^2



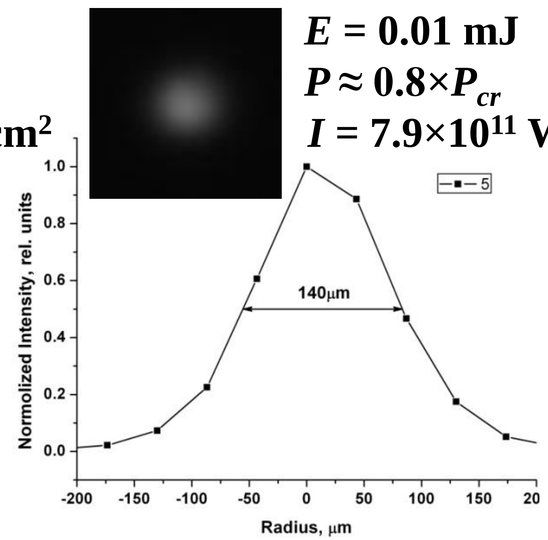
$E = 0.029$ mJ
$P \approx 2.5 \times P_{cr}$
$I = 2.3 \times 10^{12}$ W/cm^2



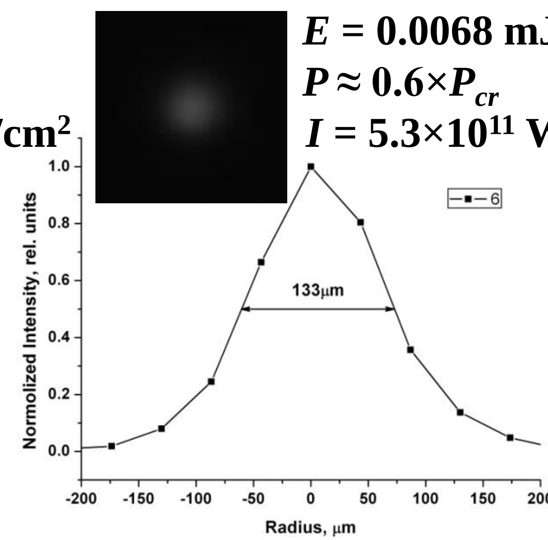
$E = 0.013$ mJ
$P \approx P_{cr}$
$I = 1.1 \times 10^{12}$ W/cm^2



$E = 0.01$ mJ
$P \approx 0.8 \times P_{cr}$
$I = 7.9 \times 10^{11}$ W/cm^2



$E = 0.0068$ mJ
$P \approx 0.6 \times P_{cr}$
$I = 5.3 \times 10^{11}$ W/cm^2



For lower powers $P \leq P_{cr}$ filaments were not observed while $d_{0.5} \approx 130$ μm

Multiple filamentation of a supercritical UV laser beam

- For $P >> P_{cr}$ modulation instability breaks the beam to multiple filaments (Campillo et al., *Appl.Phys. Lett*., 1973, 23, 628.

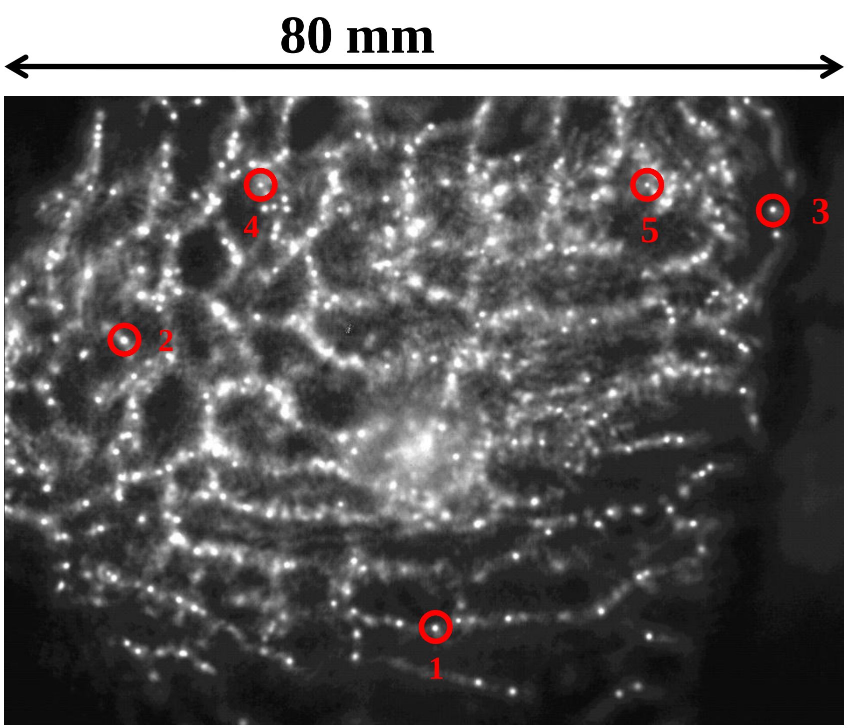
- Theory of the linear power partitioning (Roskey et al, *Appl. Phys. B*, 2007, 86, 249) predicts that a number of filaments is $N \sim P/P_{cr}$, while experiments with very high 100 TW peak power at λ ~ 800 nm evidence about saturation of filaments density due to their mutual interaction (Henin et al, *Appl. Phys. B*, 2010, 100, 77).

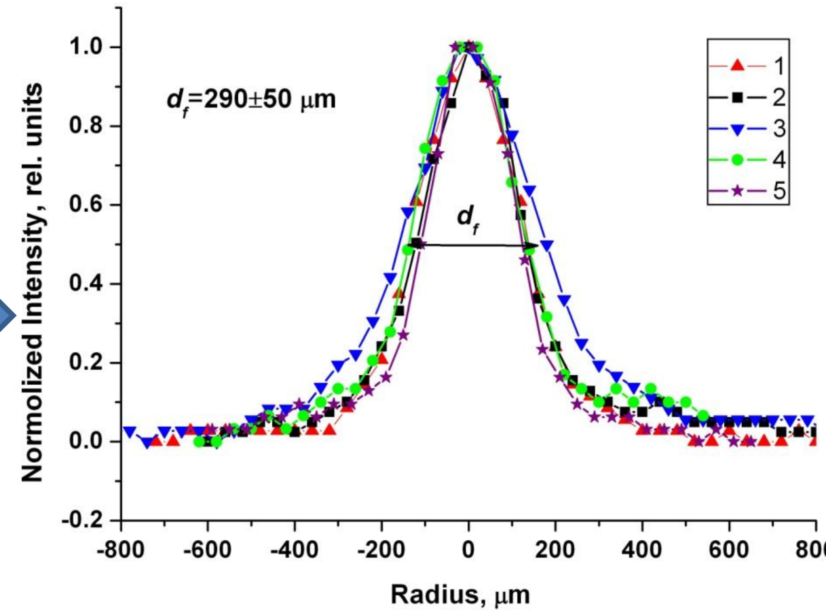
- For UV laser beam at λ=248 nm wavelength filamentation is 30 times easier to achieve that enables us to investigate multifilamentation dynamics at TW power level available at GARPUN-MTW laser facility.

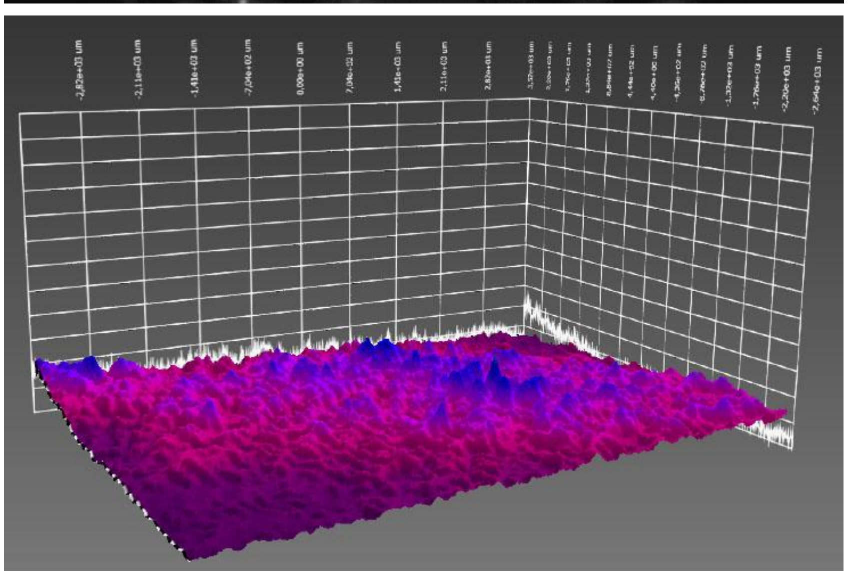
- Filamentation of a single USP of ~1ps pulse duration and sub-TW peak power ($P/P_{cr} > 1000$) is compared with filamentation of a USP train when they both propagate along 100-m distance in various focusing geometries.

Multiple filamentation of 1-ps UV USP beam

$E_1 = 0.23$ J; $P_1 \approx 2000 \times P_{cr}$; $z = -75$ m

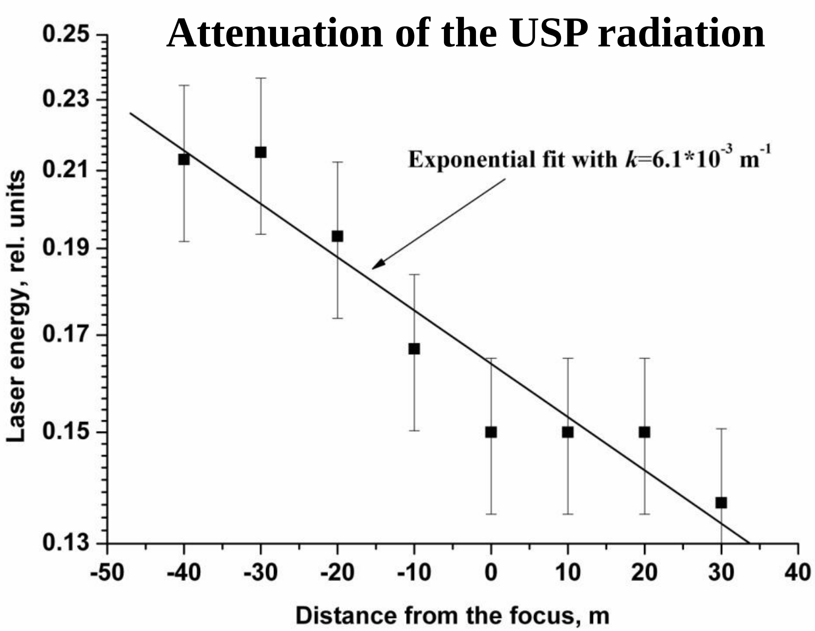






About 500 filaments contain 30% of the total pulse energy while the rest is in the background radiation. Filaments are grouped along the boundaries of CaF_2 window blocks, which introduce phase aberrations into the beam. Diameter of filaments is in the range 240–340 μm.

Parameters of multiple filaments of UV USP beam



Absorbed laser energy:

$$\frac{dE}{dz} = \kappa E = 1.2 \cdot 10^{-5}\ \text{J/cm}\ (\text{for } E = 0.2\text{J})$$

Number of electrons per beam length:

$$\frac{dN_e}{dz} = \frac{1}{3h\nu}\frac{dE}{dz} = 5 \cdot 10^{12}\ \text{cm}^{-1} (\text{for } h\nu = 5\text{eV})$$

Number of filaments: $N_f \approx 500$

Number of electrons per filament length:

$$\frac{dN_{ef}}{dz} = \frac{1}{N_f}\frac{dN_{ef}}{dz} = 10^{10}\ \text{cm}^{-1}$$

Electron density in filaments:

$$\rho = \frac{1}{S_f}\frac{dN_{ef}}{dz} = (1.5 \pm 0.5) \cdot 10^{13}\ \text{cm}^{-3},$$

where $S_f = \frac{\pi d_f^2}{4}; d_f = (290 \pm 50)\ \mu\text{m}$

Power in a filament:

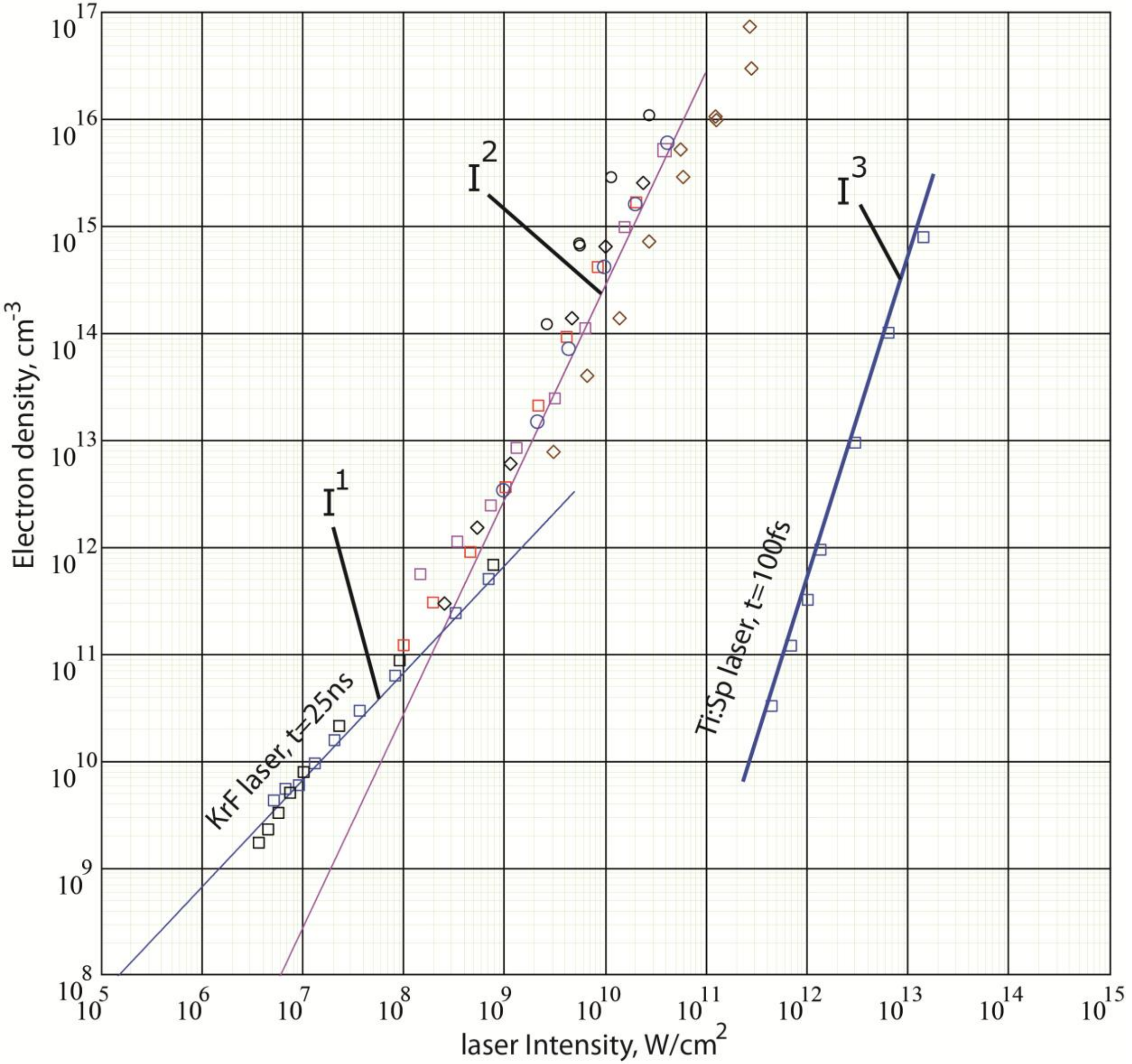
$P_f = 0.3P/N \approx 1.2 \cdot 10^8$ W$\approx P_{cr}$

Intensity in filaments:

$I = P_f / S_f = (1.8 \pm 0.6) \cdot 10^{11}$ W/cm^2

- **Filaments for 1-ps UV USP are quite different of those for 100-fs pulse: their diameter is 3 times bigger, while intensity and electron density are lower in 10^2 and 10^3 times.**
- **Diffraction balances Kerr self-focusing instead of plasma defocusing.**
- **Resonance processes (REMPI instead of direct MPI and SRS) supposedly give additional input into nonlinear matter polarization.**

Air ionization by UV radiation



Electron density vs. laser intensity

- **For USP (τ~100 fs),**
  I = 3*10^11^ ÷ 1.5*10^13^ W/cm^2^
  $\rho \sim I^3 \cdot \tau$ – 3-photon O_2 ionization (MPI).

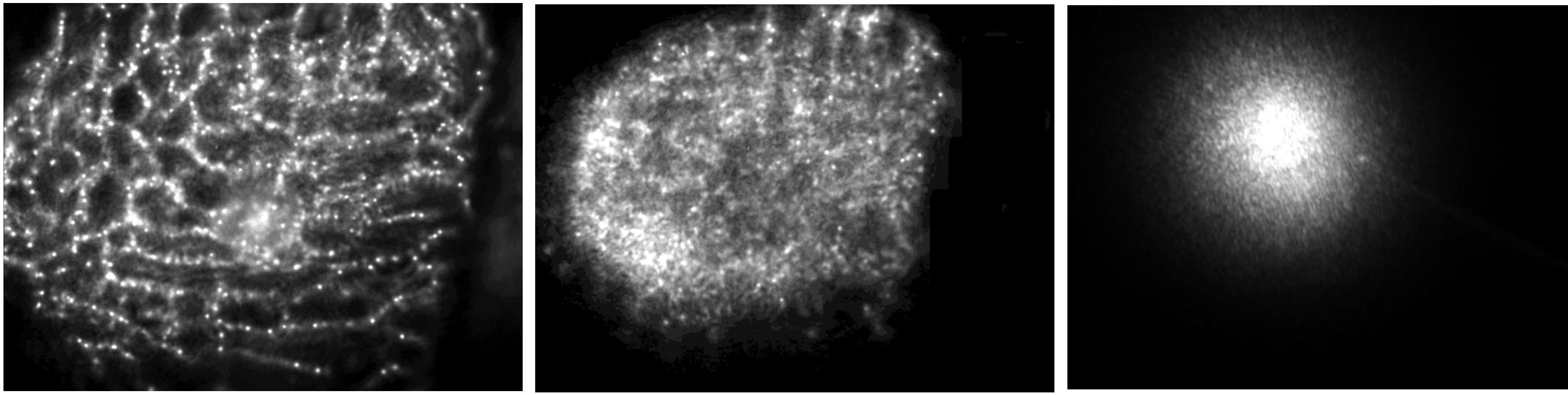
- **For long pulses (τ~25 ns), $I = 10^8 \div 10^{11}$ W/cm^2 $\rho \sim I^2 \cdot \tau$ – (2+1) resonance enhanced multiphoton O_2 ionization (REMPI).**

- **For $I = 5{*}10^6 \div 5{*}10^8$ W/cm^2 $\rho \sim I \cdot \tau$ – photoionization of impurities or photoemission of aerosol particles.**

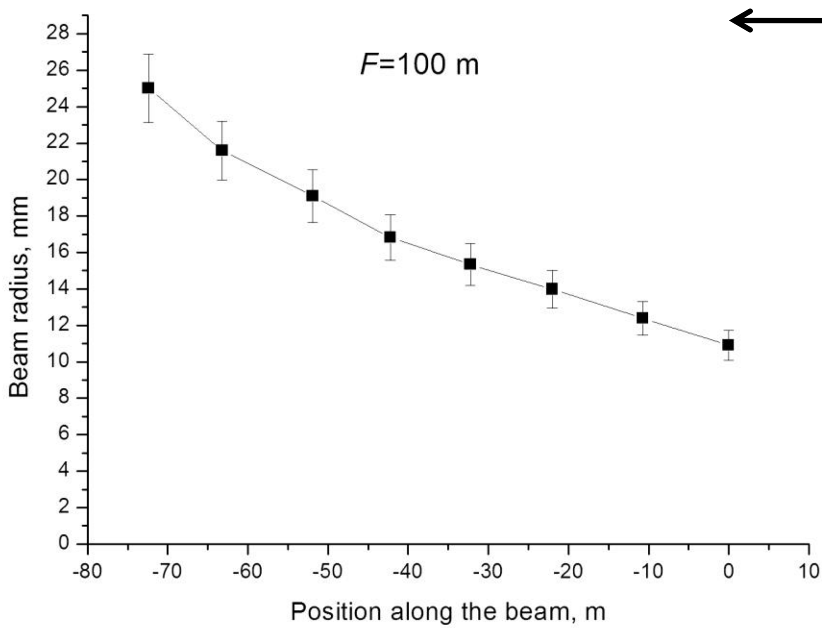
Focusing of a multiply-filamented USP beam (F = 100 m)

$E_1 = 0.23$ J; $P_1 \approx 2000\times P_{cr}$

z=-75 m | z=- 50 m | z=0

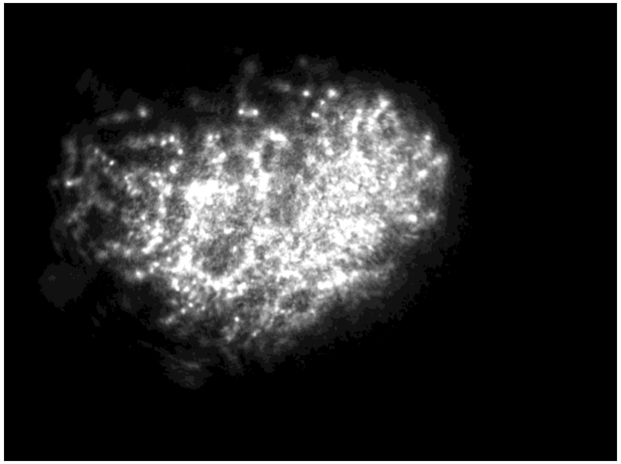


40 mm

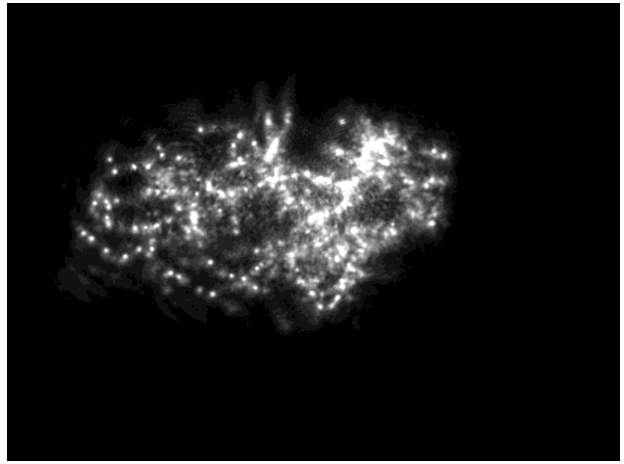


Linear focusing was observed for multiply-filamented UV USP beam which allows us to combine it with low-intensity 100-ns lasing pulse.

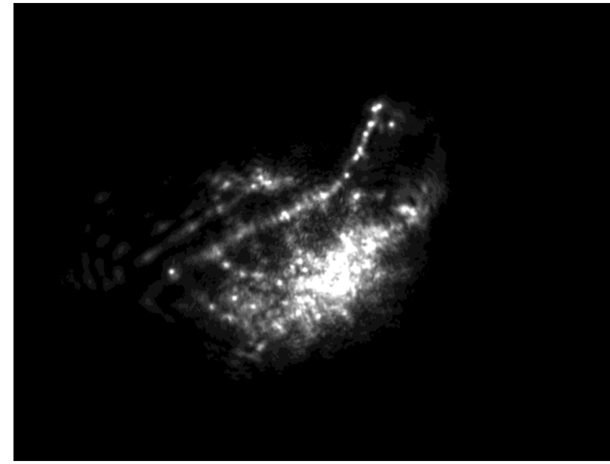
Multiple filamentation of USP beam in dependence on power (F = 60 m; z = - 22.5 m)



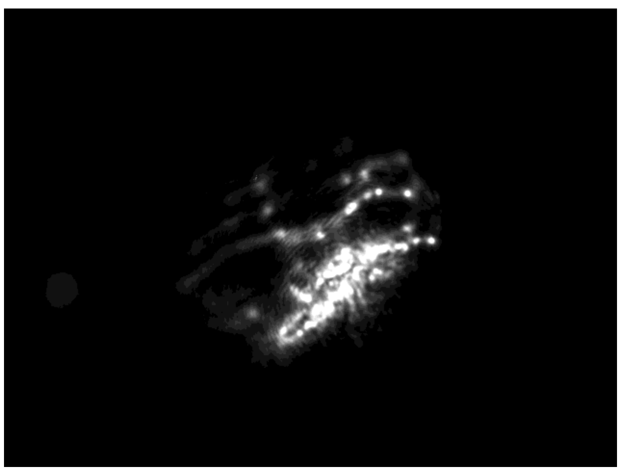
E_1=0.16 J; P_1=1330×P_{cr}



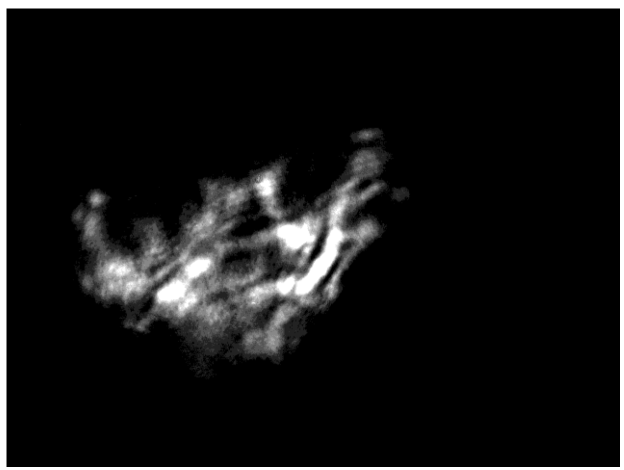
E_1=0.084 J; P_1=700×P_{cr}



E_1=0.048 J; P_1=400×P_{cr}



E_1=0.016 J; P_1=133×P_{cr}



E_1=0.004 J; P_1=33×P_{cr}

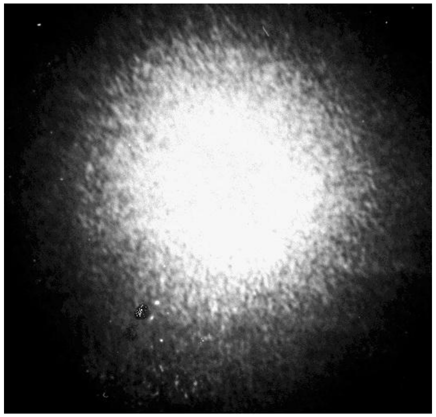
30 mm

- In front of the linear focus a number of filaments decreases for lower USP energy.
- At E_1=0.004 J (P_1 = 0.004 TW = 33P_{cr}) individual filaments coalesce into hot spots of bigger size ~1 mm.

Filamentation of a single USP behind the focus (F = 60 m)

z = 0

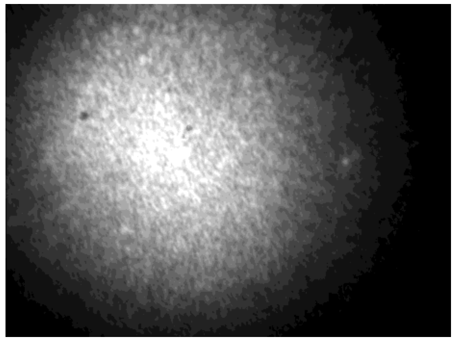
E_1= 0.2 J;
P_1= 1660×P_{cr}



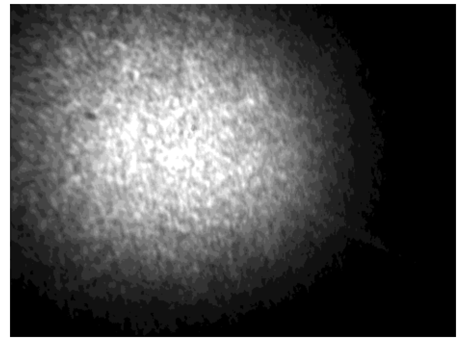
10 mm

z = 37.5 m

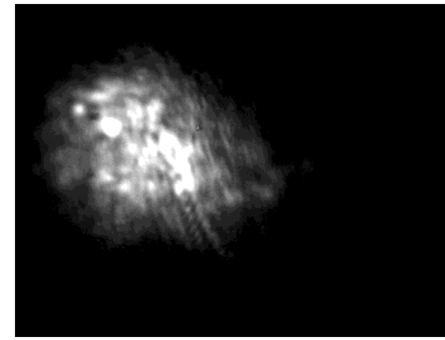
E_1=0.12 J;
P_1=1000 ×P_{cr}



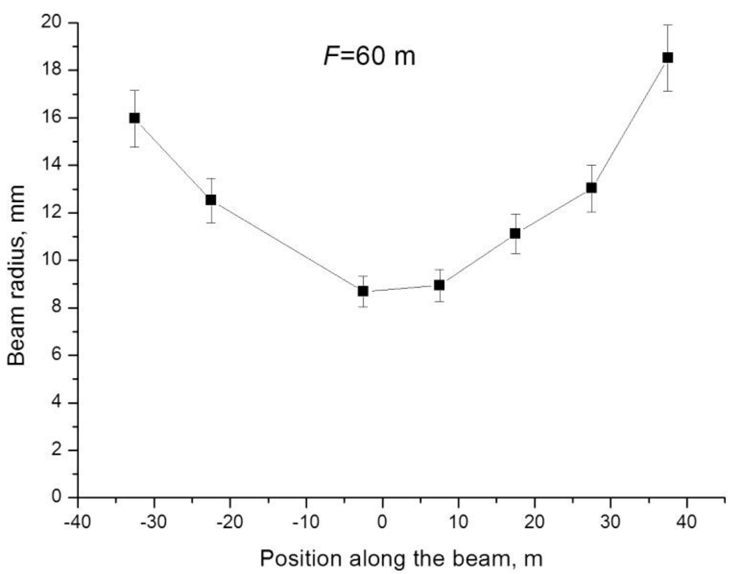
E_1=0.09 J;
P_1=750 ×P_{cr}



E_1=0.02 J;
P_1=166 ×P_{cr}

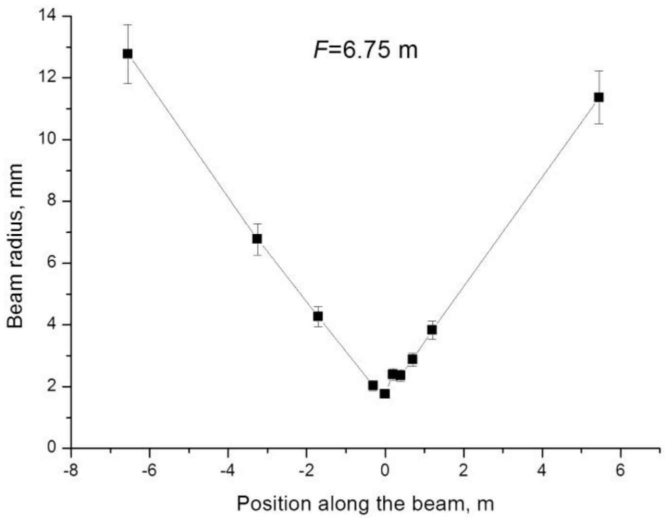


30 mm

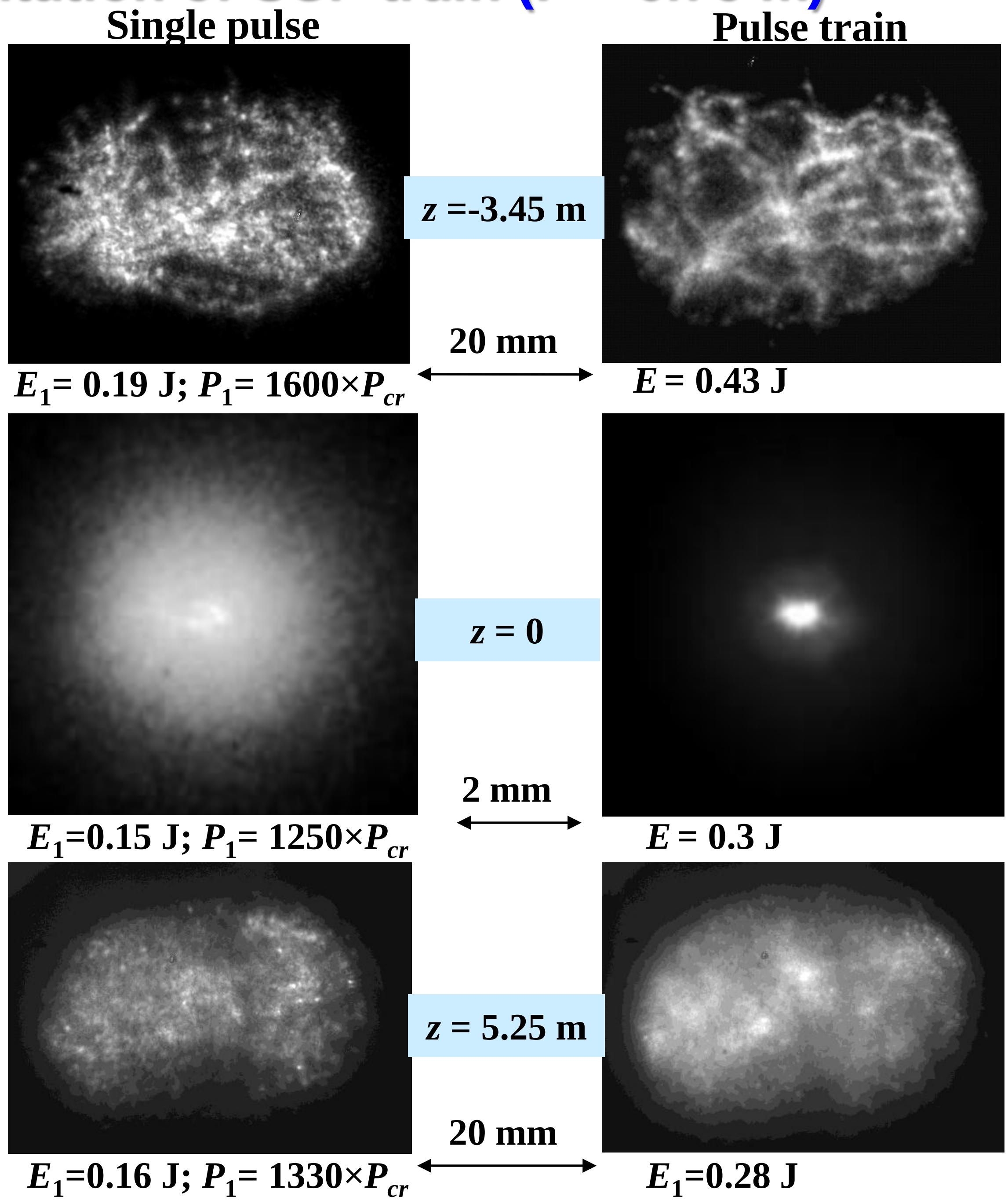


- **The mean radius of the USP beam obeys a linear focusing with the caustic waist radius ~9 mm corresponding to the beam divergence ~1.5×10^{-4} rad;**
- **In the focal plane the maximal density of filaments is achieved and they are overlapped;**
- **In the expanding beam behind the focus filamentous structure reappears;**
- **Beam diameter and amount of filaments decrease at lower USP energy; filaments coalesce into hot spots of bigger size ~1 mm.**

Multiple filamentation of USP train (F = 6.75 m)



- Linear beam focusing was observed for a single USP;
- For the USP train individual small-size filaments tend to coalesce into hot spots of bigger size ~1 mm;
- This effect is the most pronounced nearby the focus;
- Behind the focus multi-filamentous structure reappears with the same tendency towards coalescence of individual filaments for the USP train.



CONCLUSIONS

- **A train of UV picoseconds pulses with TW peak power was generated at hybrid Ti:Sapphire/KrF GARPUN-MTW laser facility. It can be combined with 30-J, 100-ns pulse of a free-running lasing.**

- **Multiple filamentation of a single 1-ps UV pulse, as well as the pulse train with peak powers P/P_{cr} >1000 was investigated in air along 100-m distance. In various focusing geometries (NA=1.5·10^{-2}– 1.5·10^{-3}) multi-filamentous super-critical single-pulse beam demonstrated linear focusing behavior. For lower power as well as for the pulse train coalescence of individual filaments into 1-mm size hot spots was observed.**

- **Parameters of filaments for 1-ps pulse are quite different of those for 100-fs pulse. Radiation diffraction balances Kerr self-focusing instead of plasma defocusing. Probably resonance processes (REMPI and SRS) introduce into nonlinear matter polarization.**