Nonlinear Optics of the UV TW Laser Beam

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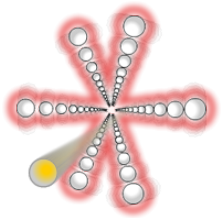

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Outline

- Introduction: Laser beam filamentation ? a “diffraction-free” channeling of photons over the Rayleigh length
- Multiple filamentation of TW-level, sub-ps UV pulses at Ti:Saphire/KrF GARPUN-MTW laser facility: Supposed mechanism and limitations of the attained ultra-short pulse (USP) energy and beam focusing
- Kerr self-defocusing of filaments in Xe and coherent narrow-angle IR emission
- Filaments regularization by means of amplitude masks
- Conclusions

Self-focusing and filamentation history

- Suggested by Askar'yan more than 50 years ago (*Sov. Phys. JETP*, 1962, 15, 1088) a self-focusing of laser radiation in transparent solid dielectrics, liquids and gases was investigated through decades.

- A "new age" began with a development of extremely powerful Ti: Sapphire lasers. Kerr self-focusing of the IR USP radiation ($\lambda \sim 800$ nm) produces filament-like light and plasma channels of sub-mm diameter that propagates in atmospheric air over tens and even a few hundred meters (Braun et al. *Opt. Lett*, 1995, 20, 73); nowadays the filamentation has a big room for applications.

- For the UV USP with peak powers up to $P \sim 10$ TW obtained in 1990s with KrF lasers ($\lambda = 248$ nm) filaments were not registered. In our experiments at Ti:Saphire/KrF GARPUN-MTW laser facility with $P \sim 1$ TW multiple filamention was observed (Zvorykin et al, *Quantum electron.* 2010, 40, 381). Parameters of UV filaments found in our case differ of those in the IR.

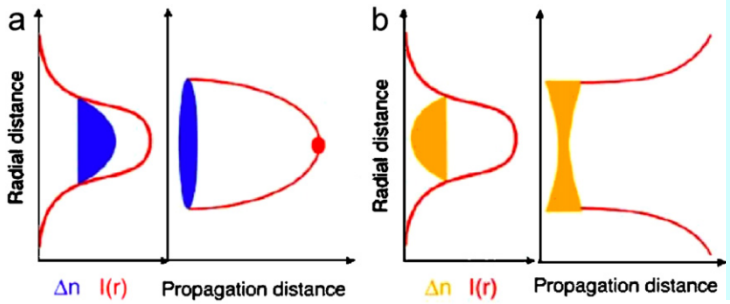
Standard filamentation model

Kerr self-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

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

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

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

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 :

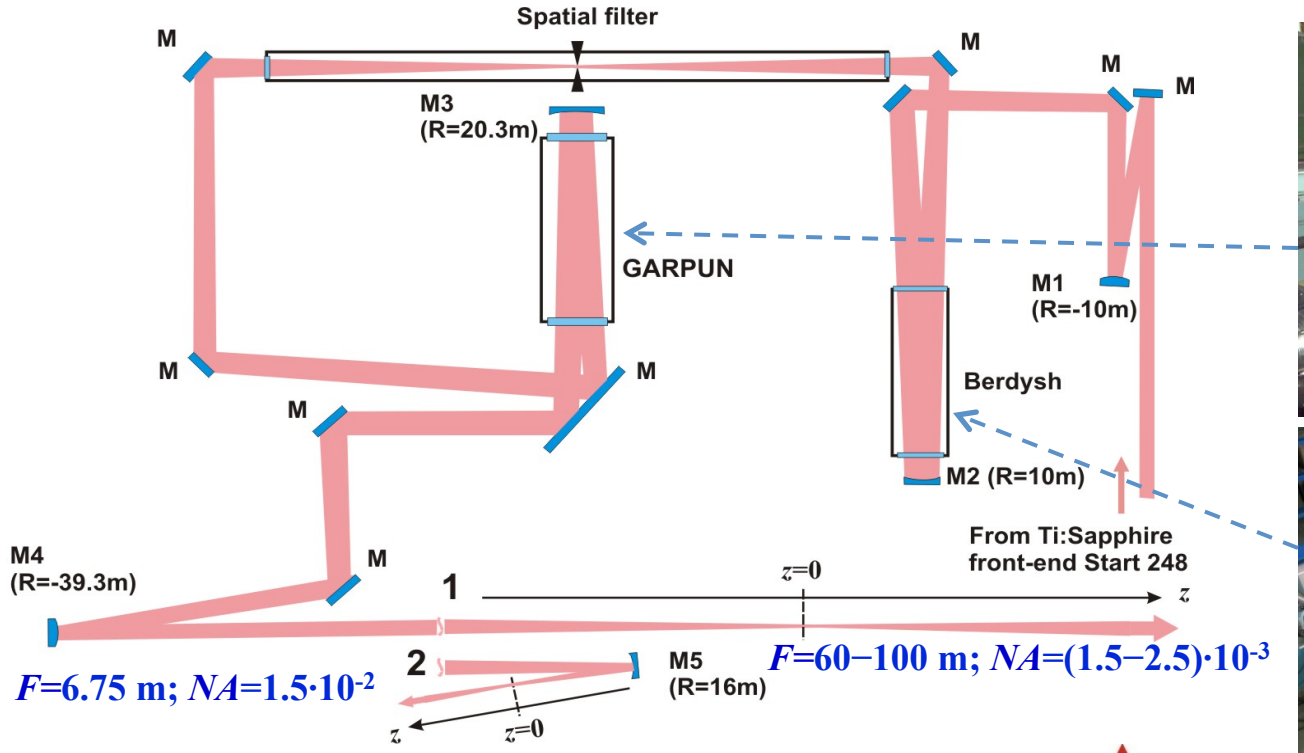
$$I \sim \left(\frac{0.76 n_2 \rho_c}{\sigma_K \rho_{at} \tau_p}\right)^{\frac{1}{K-1}};\ \rho(I): \left[\frac{(0.76 n_2 \rho_c)^K}{\sigma_K \rho_{at} \tau_p}\right]^{\frac{1}{K-1}};$$

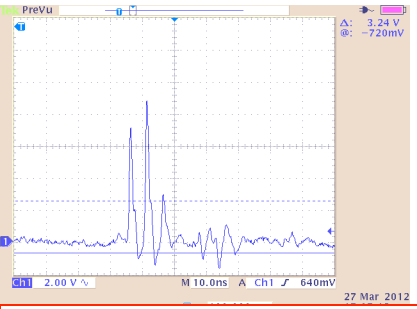
$$w_0: \left(\frac{2P_{cr}}{\pi}\right)^{1/2} \left(\frac{0.76 n_2 \rho_c}{\sigma_K \rho_{at} \tau_p}\right)^{-\frac{1}{2(K-1)}}$$

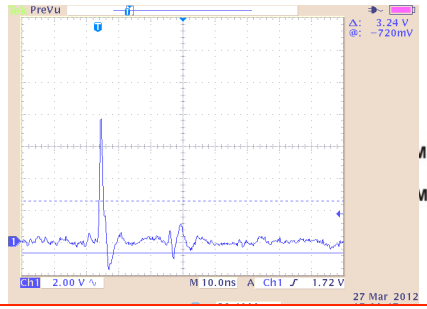
Scaling formulas and simulations (PRL, 2002, 88, 135003) gives w_0 ~ 100 mm, I~10^{13} W/cm^2, r~$10^{16} \div 10^{17}$ cm^{-3} for both UV and IR wavelengths.

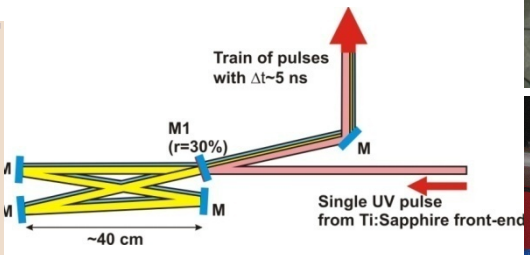
Wavelength λ, nm	800	248
n_2, cm^2·W^{-1}	$(2.8–3.0)\cdot10^{-19}$	$(8–10)\cdot10^{-19}$
P_{cr}, GW	3.4–3.6	0.1–0.12
O_2 (W_i=12.06 eV): K; σ_K, s^{-1}·(cm^2·W^{-1})^K	8; $2.8\cdot10^{-96}$	3; $1.4\cdot10^{-28}$
N_2 (W_i=15.58 eV): K; σ_K, s^{-1}·(cm^2·W^{-1})^K	11; $6.3\cdot10^{-140}$	4; $3.2\cdot10^{-44}$

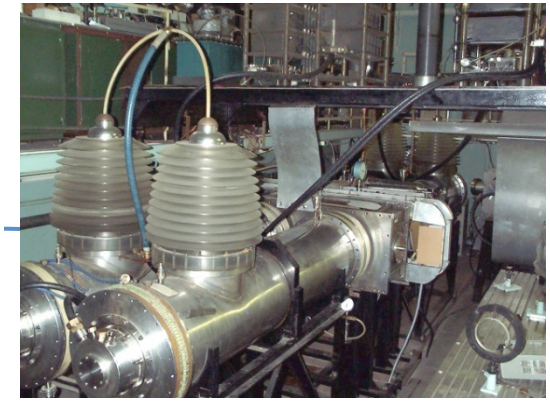
Amplification of a train of ps, sub-TW UV pulses at Ti:Saphire/KrF GARPUN-MTW Laser

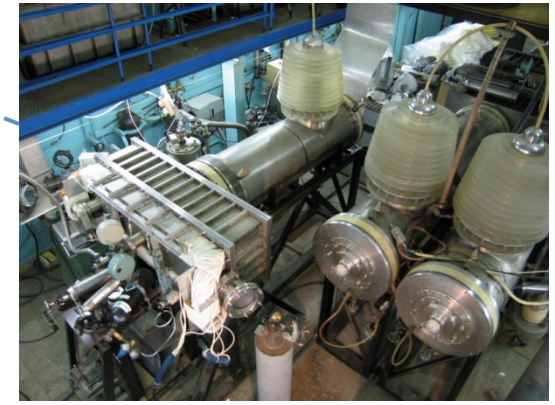


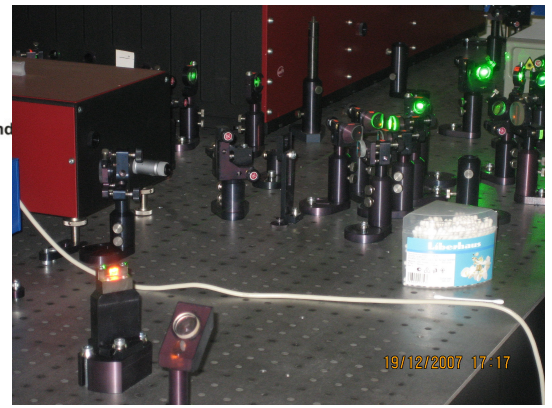








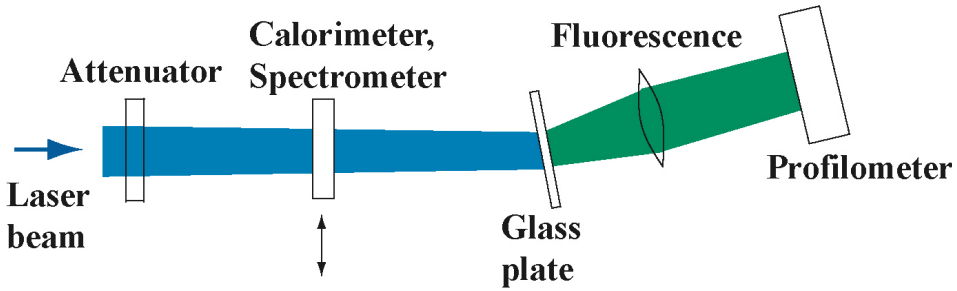


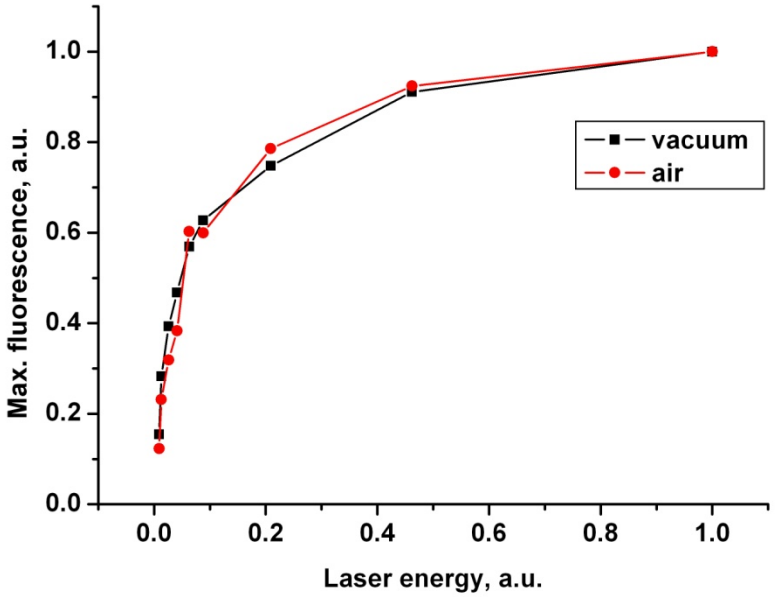


Single USP: $E_1 \leq 1$ J; $\tau_p < 1$ ps; $P_1 \sim 1$ TW; train : $E \leq 2$ J; P_1:P_2:P_3…=3:5:1.5:0.5…, Δt =3–5 ns

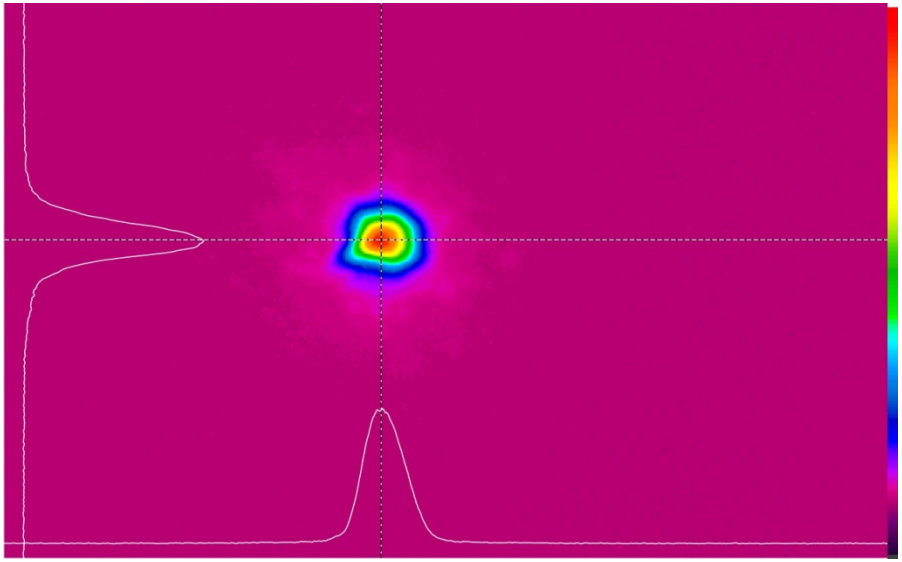
Zvorykin et al, *Quantum electron.* 2014, 44, 431.

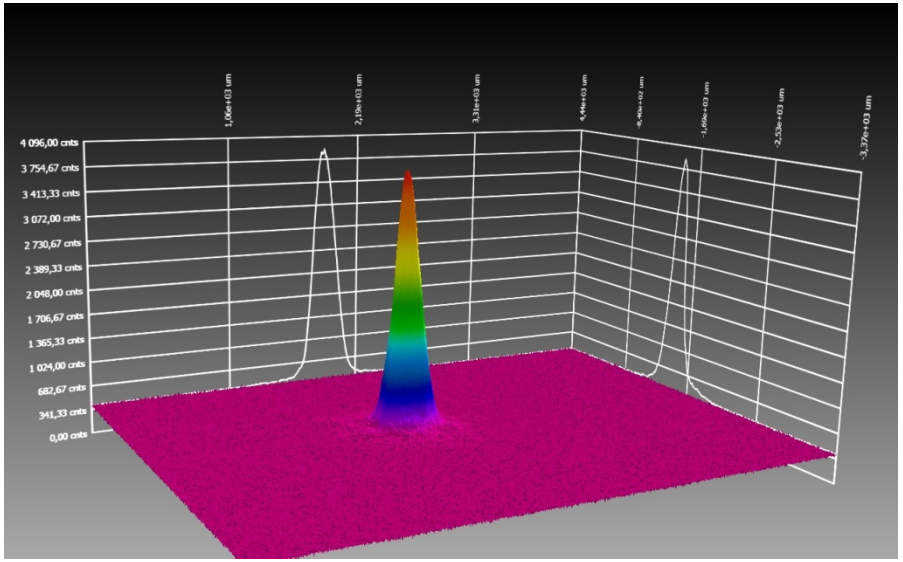
Filaments registration



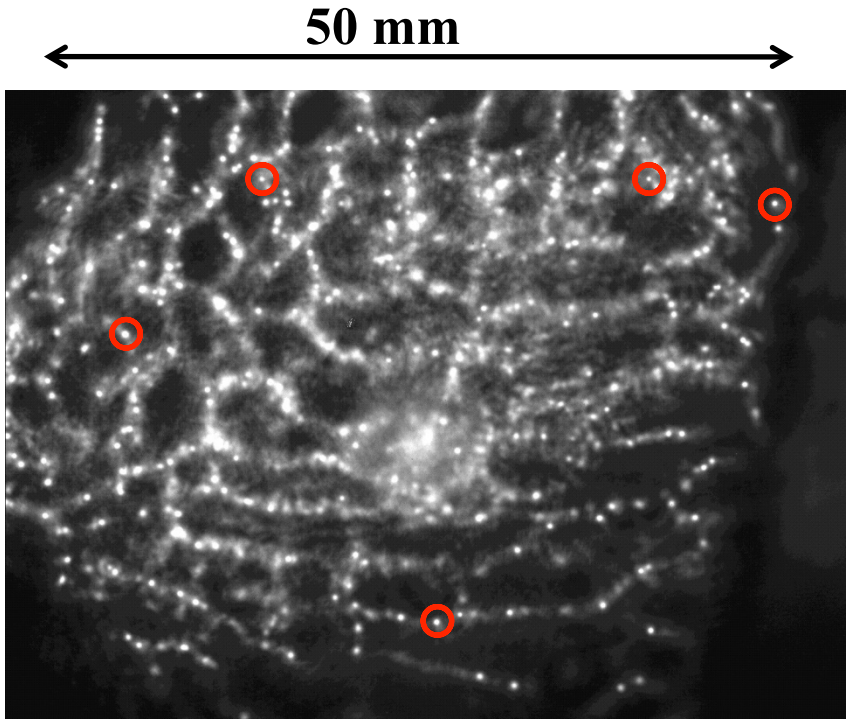


Glass fluorescence under UV irradiation was measured with Ti: Sapphire front-end. A single filament produced by 0.2 mJ, 100-fs USP has 20 cm length which is much more than diffraction (Rayleigh) length of a focused beam.

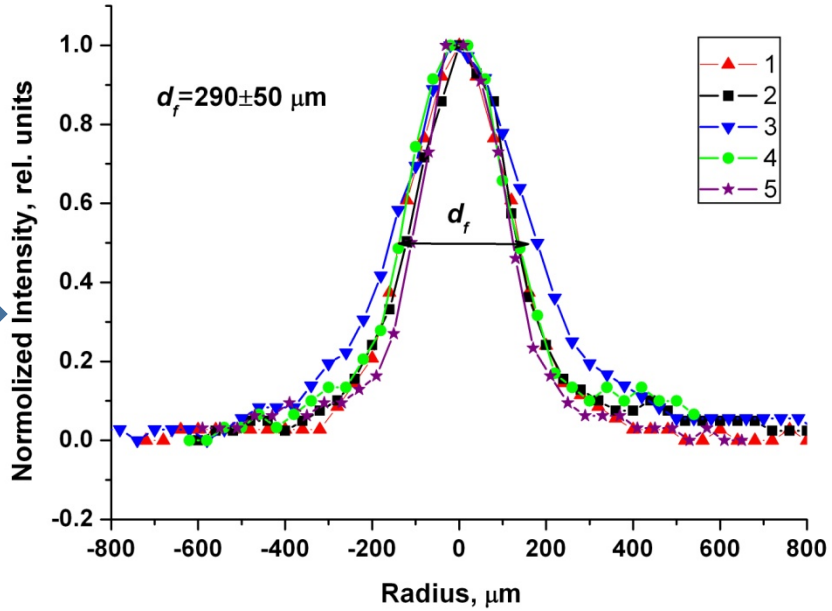




Kerr self-focusing produces multiple filamentation of a superctitical USP beam



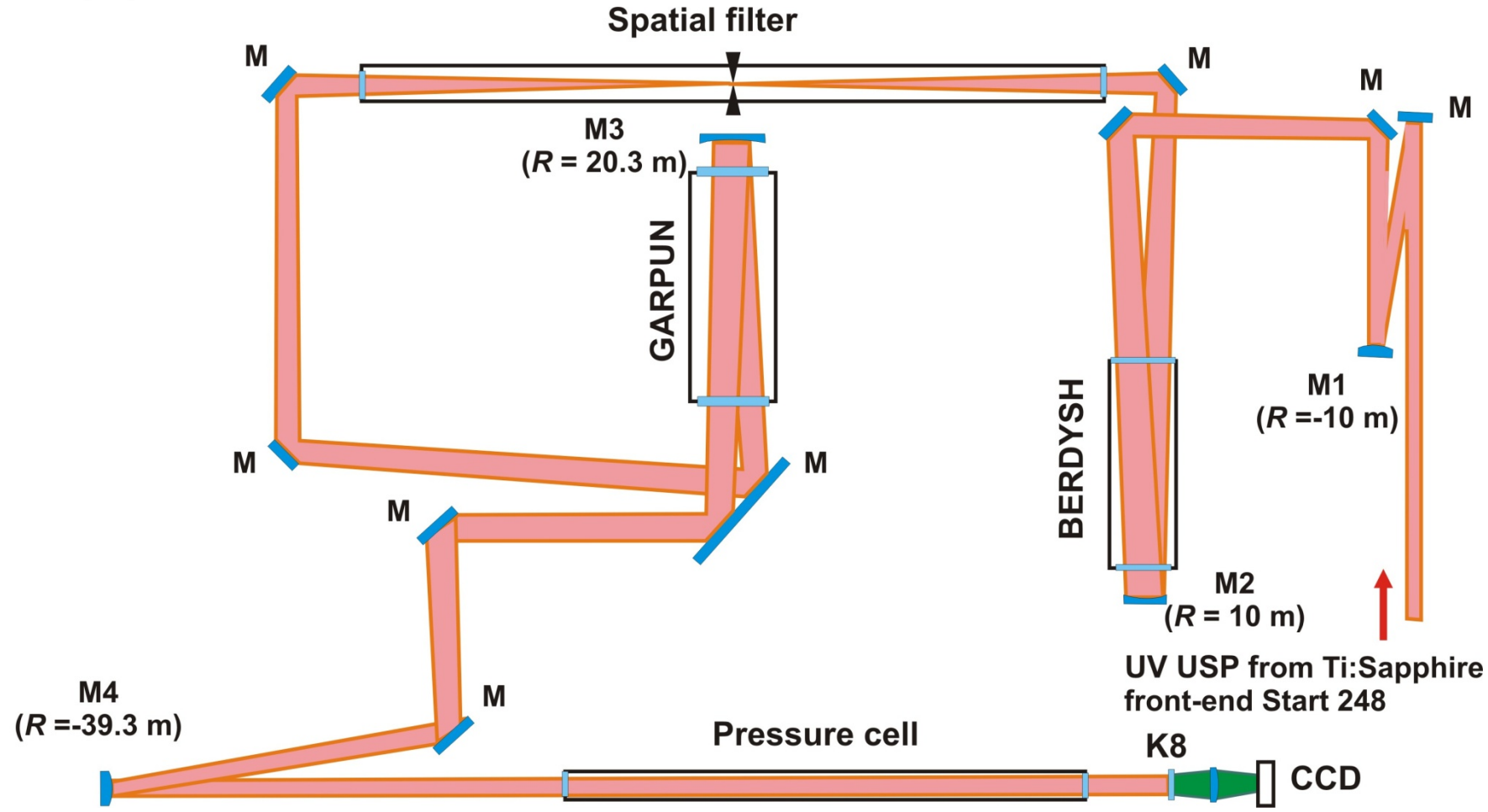
$E_1 = 0.23$ J; $P_1 \approx 2000 \times P_{cr}$



• A filamentation pattern was observed at $L \geq L_F \approx 15$ m behind the final amplifier. 300 filaments of 240–340 mm diameter contained 30% of the total USP energy. Peak intensity in filaments $I_f \sim 2 \cdot 10^{11}$ W/cm^2 and energy fluence $\varepsilon_f \sim 0.2$ J/cm^2 are in contradiction with a "standard model", and reveal the dominant role of resonance processes, i.e. (2+1) REMPI of O_2 and coherent SRS at N_2 rotational transitions (Zvorykin et al., *Appl. Optics*, 2014, 53, I31; Smetanin et al., NIMB, 2016, 369, 87).

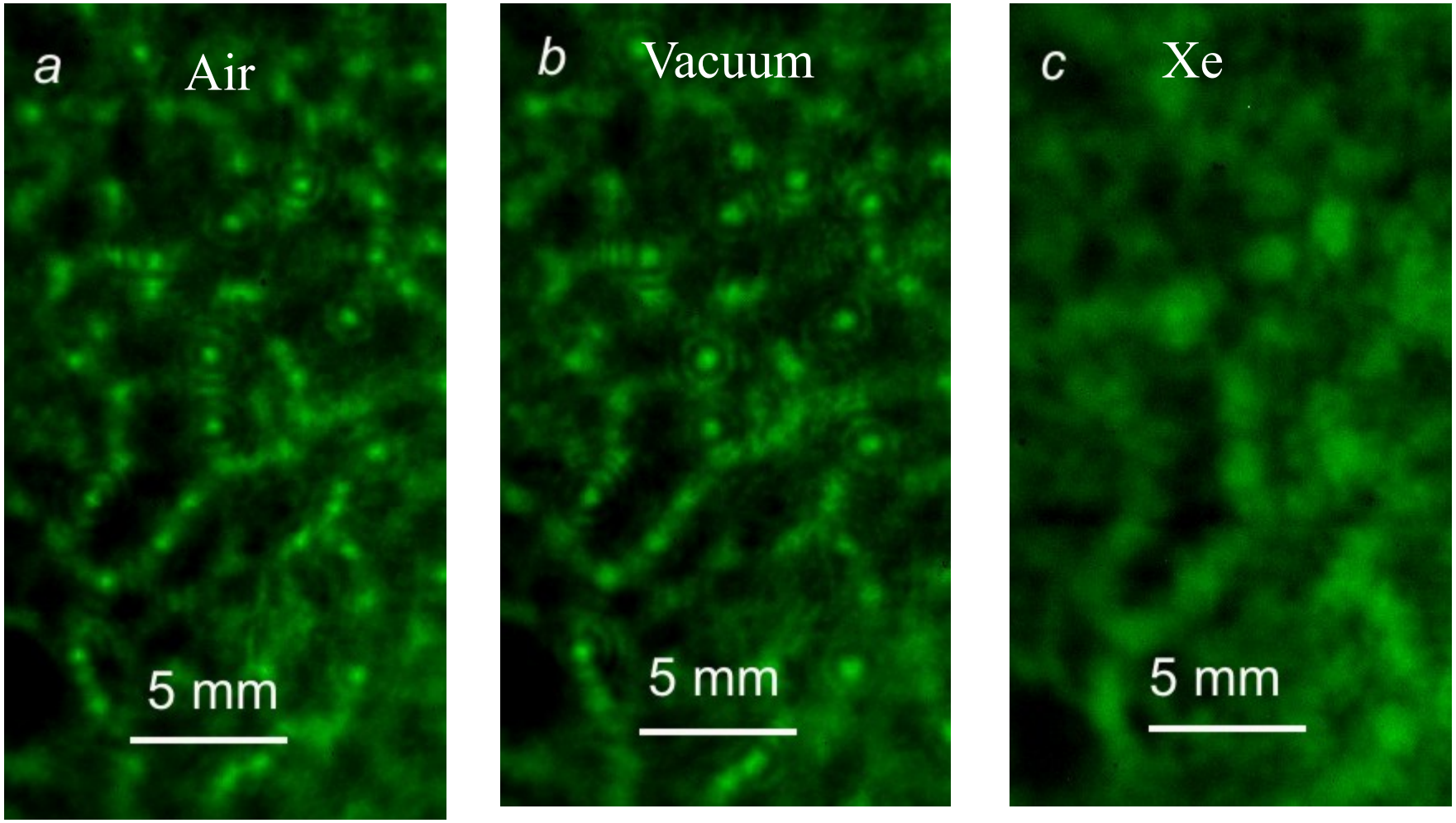
• Suppression of filamens is required to reduce losses in KrF gain medium and improve laser beam focusing.

Suppression of the USP filamentation in Xe



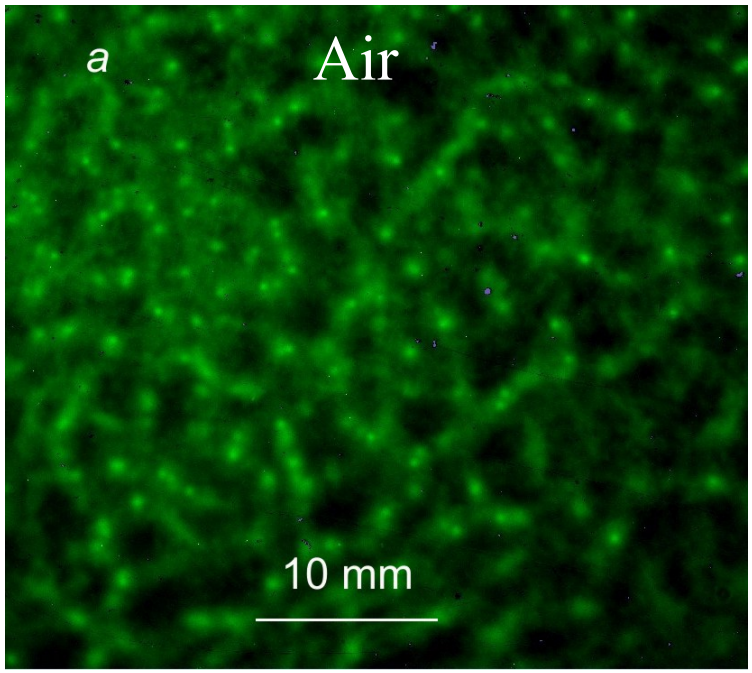
- 2.5-m length pressure cell was pumped out, filled with atmosphere air or Xe at ≤ 1 atm.
- 2-photon resonance of $6p[1/2]_0$ Xe state with KrF laser light produces a large resonantly-enhanced *negative* nonlinear refraction index (Lehmberg et al, Opt. Commun, 1995, 121, 78) − a unique feature for self- defocusing of filaments.

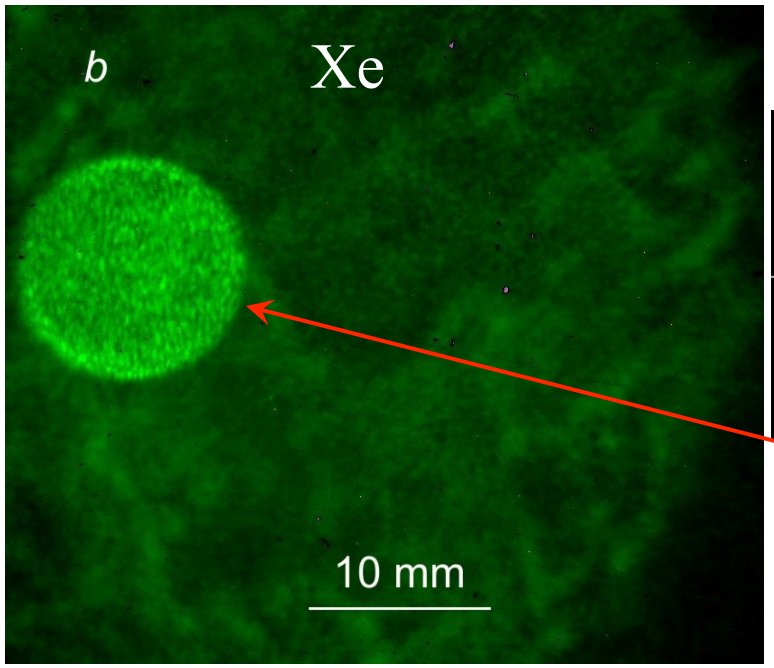
Self-defocusing of multiple filaments in Xe ($L_c > L_F$)



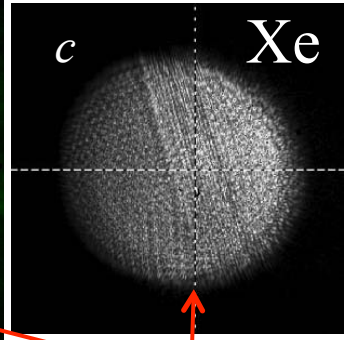
- Filaments are formed behind an air-filled cell set at $L_c > L_F$ (20 m).
- Filaments are twice increased behind the vacuum cell.
- Filaments are fully defocused behind Xe-filled cell!

Xe prevents filamentation of a supercritical beam ($L_c < L_F$)





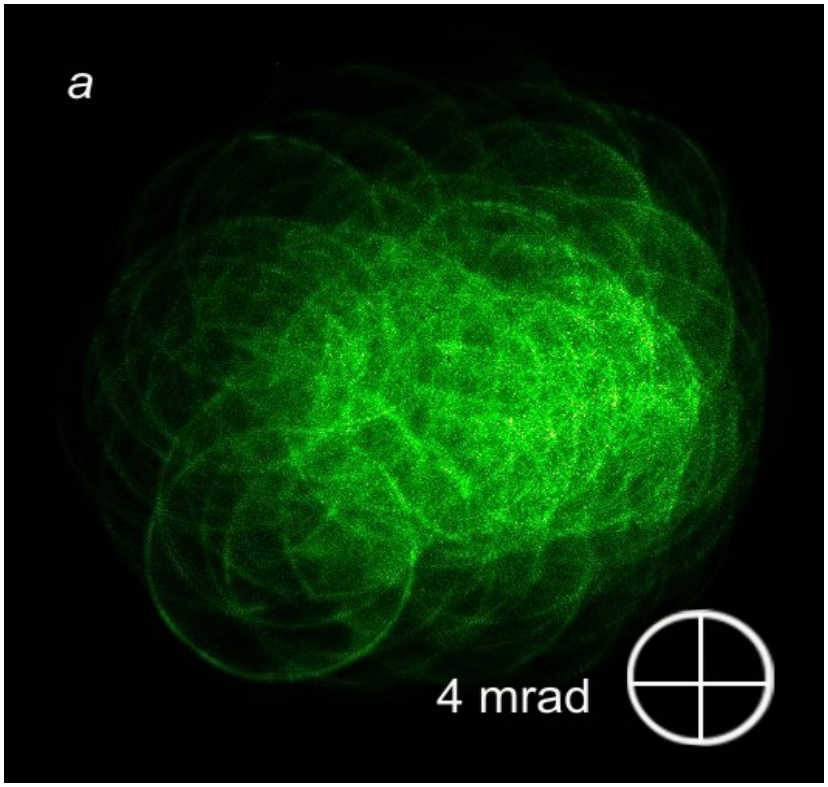
Near-field

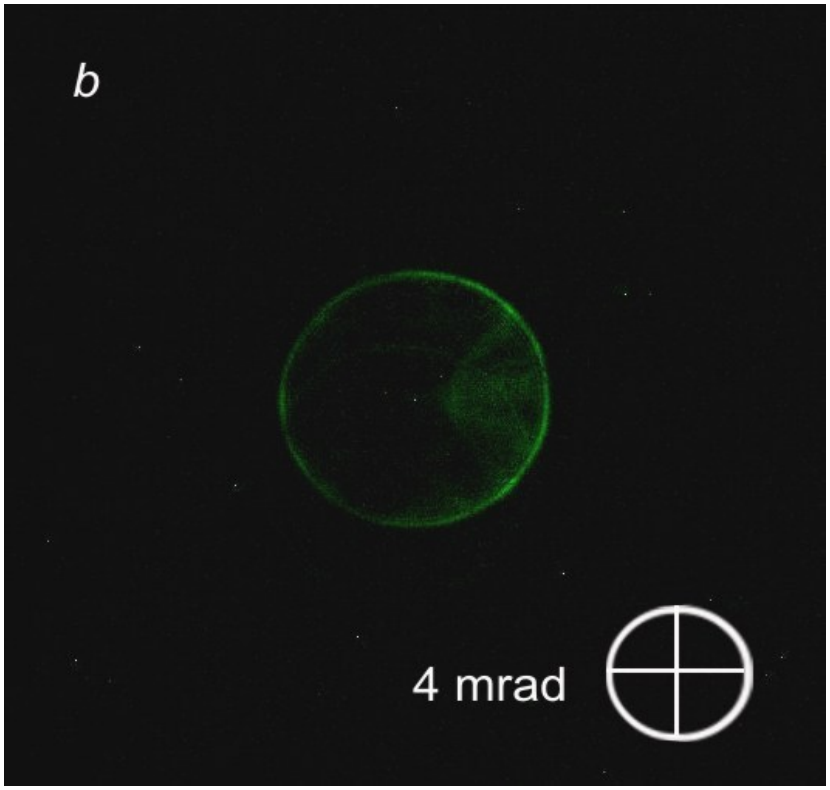


Coherent emission at $\lambda = 828$ nm

- Xe-filled cell set at $L_c < L_F$ distance prevents formation of filaments in a supercritical UV USP laser beam at $L > L_F$.
- Monochromatic IR emission at 828-nm wavelength produced buy UV filaments corresponds to Xe transition $6p[1/2]_0 \rightarrow 6s[3/2]_0$[1].
- An interference of IR emission proves that UV filaments are phase-matched.

Coherent IR cone emission of UV filaments

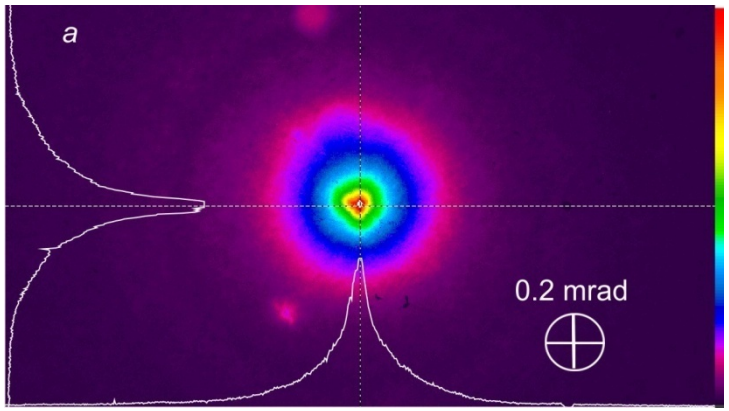


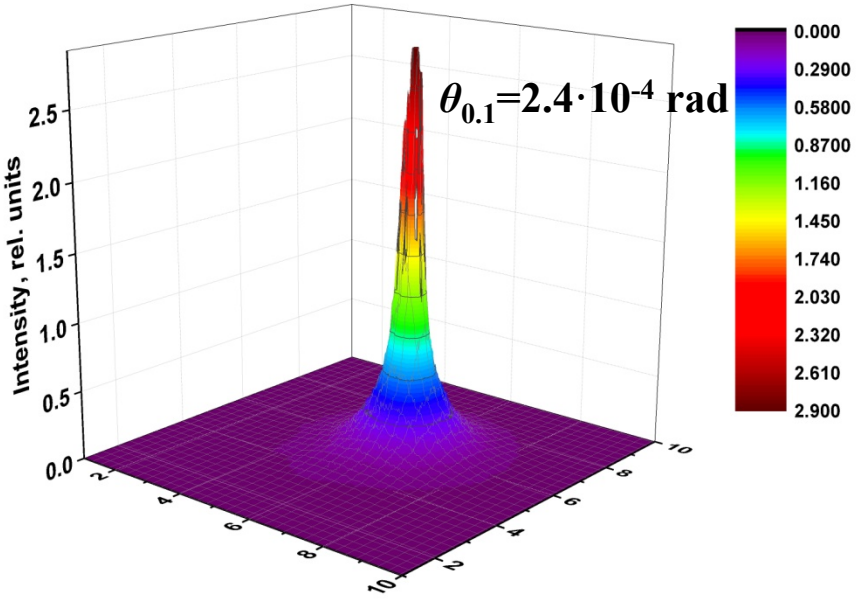


- In a far-field zone IR emission looks like narrow rings around UV filaments; number of rings increases with the USP power. Rings corresponds to the cone emission with an angle $\theta \approx 4 \cdot 10^{-3}$ rad to the axis.
- Four-wave mixing, stimulated hyper-Raman scattering and amplified spontaneous emission at the transition $6p[1/2]_0 \rightarrow 6s[3/2]_0^1$ supposedly contribute to the emission.

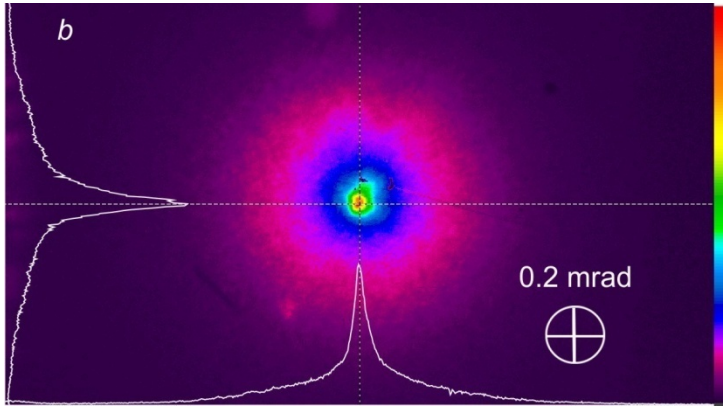
Focusing of filamented and compensated beams (*F*=2.5 m)

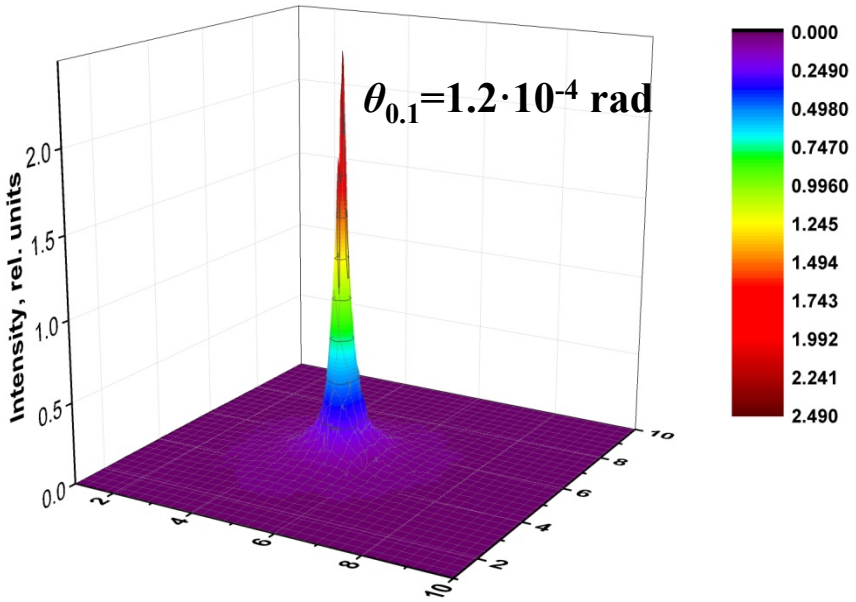
Multiple filamentation





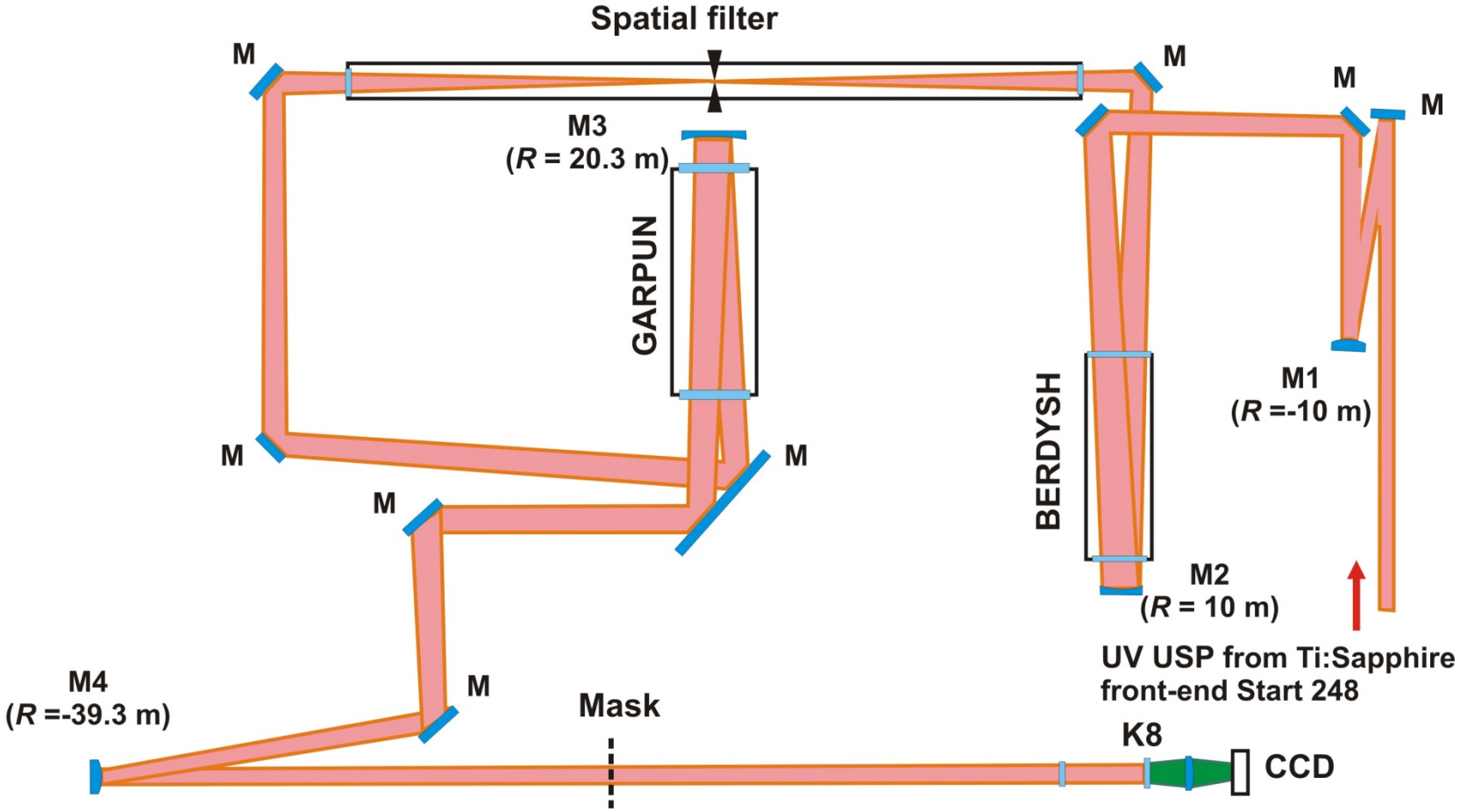
Suppressed filamentation





Laser beam with suppressed filamentation has twice less divergence

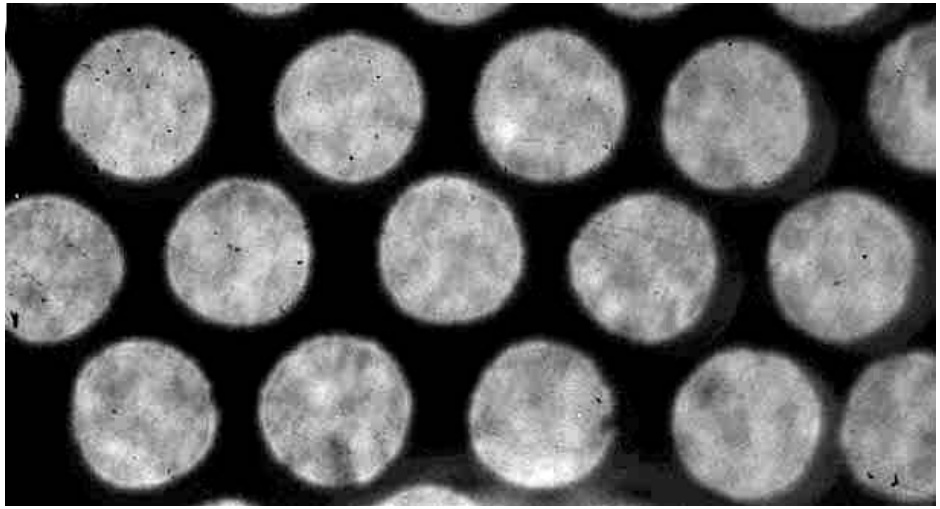
Filaments regularization



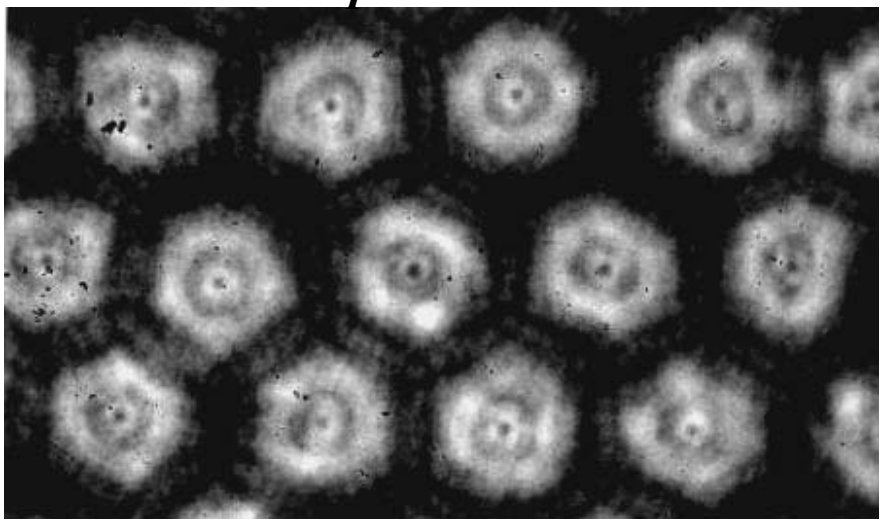
A regular filaments distribution is required to produce plasma channel arrays in air for MW waveguides and antennas (Marians et al., *Phys. Plasmas*, 2013, 20, 023301; Zvorykin et al., *Appl. Optics*, 2014, 53, I31)

Diffraction of the UV USP

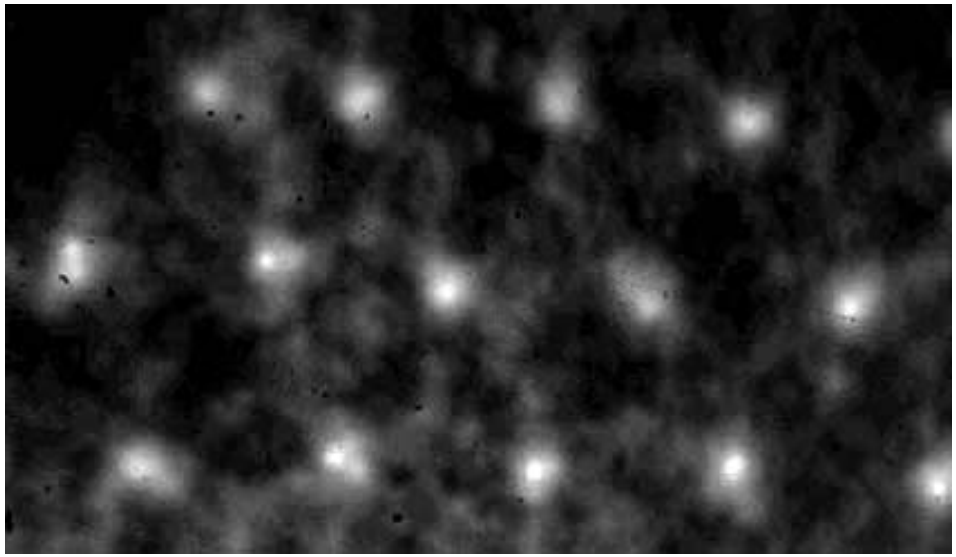
$N_F >> 1$



$N_F \sim 1$



$N_F << 1$



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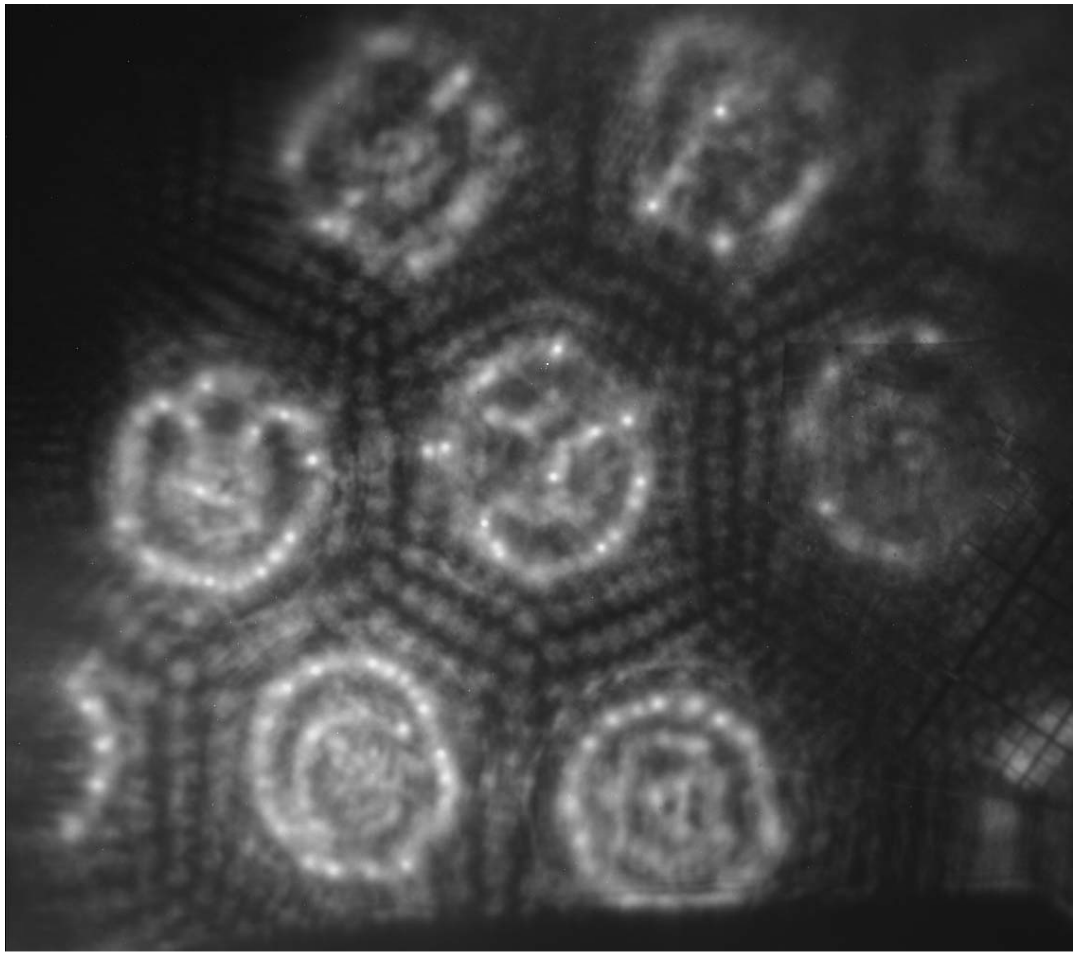
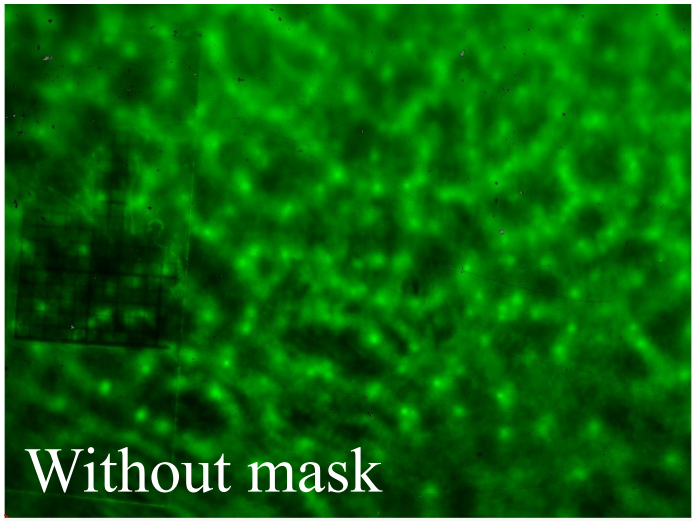
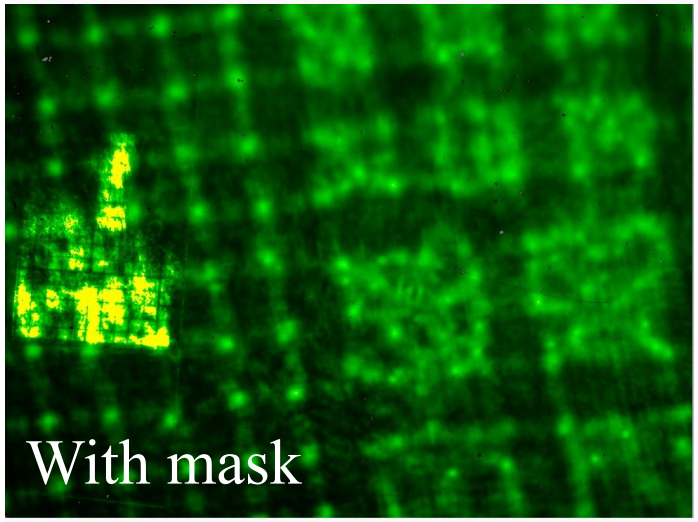
Diffraction patterns for different Fresnel number $N_F = a^2/\lambda L$

Diffraction initiates filaments

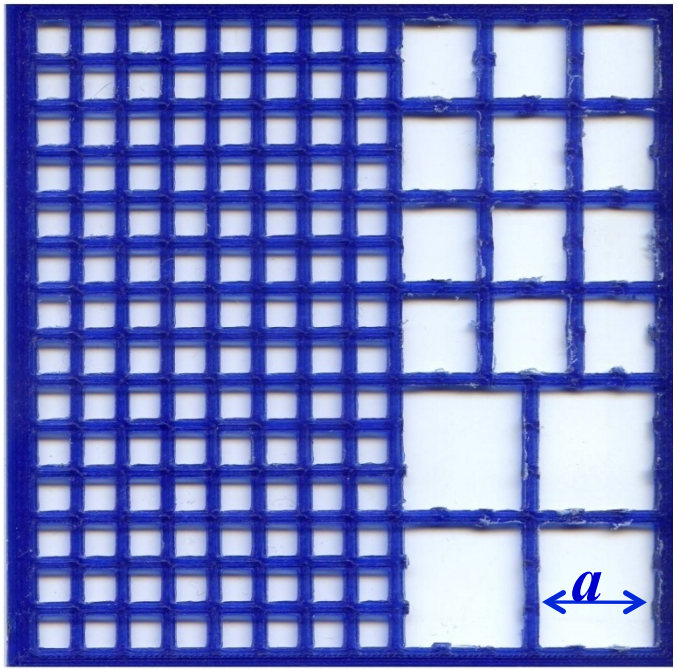


Filaments regularization





- Amplitude masks allows to regularize filaments distribution.
- The optimal mask cell should transmit beam power $P_{mask} \geq P_{cr}$
- The distance from the mask to regular filaments plane should be $L_{mask} >> a^2/\lambda$



CONCLUSIONS

- The variety of nonlinear effects were investigated at Ti:Sapphire/ KrF laser facility GARPUN-MTW in a direct amplification of sub-picosecond UV pulses up to TW peak power.
- An effective suppression of multiple filamentation of the supercritical UV laser beam was demonstrated in Xe. A two-photon resonance of laser radiation with $6p[1/2]_0$ state of Xe ensured Kerr self-defocusing of a few hundred filaments.
- UV filaments in Xe produced a narrow-angle monochromatic coherent cone emission at 828-nm wavelength via a four-waves mixing, stimulated hyper-Raman scattering and amplified spontaneous emission at the transition $6p[1/2]_0 \rightarrow 6s[3/2]_0{}^1$.
- The regular arrays of filaments were produced by means of amplitude masks.