Multiple Filamentation of UV Supercritical Laser Beam in Atmospheric Air

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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:Sapphire/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’yán (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.


• 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 $\lambda=248$ 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:Sapphire/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; $P_1:P_2:P_3...=3:5:1.5:0.5...$, $\Delta t =3–5$ ns

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

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

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


- As a refractive index in air plasma is slightly less than in air, for waveguide radius $R_{wg} \gg \lambda_{MW}$ 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**
\[ P_{cr} = 3.77 \lambda_0^2 / 8 \pi n_0 n_2 \]

The collapse is stopped when plasma defocusing balances Kerr focusing

\[ n_2 I = \frac{\rho(I)}{2 \rho_c} + \frac{(1.22 \lambda_0)^2}{8 \pi n_0 w_0^2}; \quad \rho(I) = \sigma_K I^K \rho_a t \tau_p \]

**Plasma defocusing**
\[ n \approx n_0 - \rho(r,t)/2 \rho_c, \quad \rho_c = \varepsilon_0 m_e \omega_0^2 / e^2, \]
\[ \rho = \sigma_K I^K \rho_a t \tau_p \]
\[ \sigma_{Br} = \frac{e^2}{\varepsilon_0 m_e c n_0} \left(1 + \omega^2 \tau_c^2 \right) \approx \frac{e^2}{\varepsilon_0 m_e c n_0 \tau_c \omega^2} \]

**Scaling for filament parameters**:
\[ I \sim \left( \frac{0.76 n_2 \rho_c}{\sigma_K \rho_a t \tau_p} \right)^{1/(K-1)} (0.76 n_2 \rho_c)^{K-1} \]
\[ w_0 \sim \left( \frac{2 P_{cr}}{\pi} \right)^{1/2} \left( \frac{0.76 n_2 \rho_c}{\sigma_K \rho_a t \tau_p} \right)^{-1/(2(K-1))} \]

<table>
<thead>
<tr>
<th>Wavelength $\lambda$, nm</th>
<th>800</th>
<th>248</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_2$, cm$^2$·W$^{-1}$</td>
<td>$(2.8\text{–}3.0)\cdot10^{-19}$</td>
<td>$(8\text{–}10)\cdot10^{-19}$</td>
</tr>
<tr>
<td>$P_{cr}$, GW</td>
<td>3.4–3.6</td>
<td>0.1–0.12</td>
</tr>
<tr>
<td>$O_2$ ($W_i$=12.06 eV): $K$; $\sigma_K$, s$^{-1}$·(cm$^2$·W$^{-1}$)$^{K}$</td>
<td>8; 2.8·10$^{-96}$</td>
<td>3; 1.4·10$^{-28}$</td>
</tr>
<tr>
<td>$N_2$ ($W_i$=15.58 eV): $K$; $\sigma_K$, s$^{-1}$·(cm$^2$·W$^{-1}$)$^{K}$</td>
<td>11; 6.3·10$^{-140}$</td>
<td>4; 3.2·10$^{-44}$</td>
</tr>
</tbody>
</table>
Parameters of single filaments for the IR and UV radiation (according to Couairon & Berge calculations)

- According to scaling formulas and numerical simulations (PRL, 88, 135003 (2002)) peak intensities in single filaments $I \sim 10^{13} \text{ W/cm}^2$, electron densities $\rho \sim 10^{16} \div 10^{17} \text{ cm}^{-3}$, and filament size $w_0 \sim 100 \mu\text{m}$ 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 ($\tau_{1/2} \sim 100 \text{ fs}$) of GARPUN-MTW laser facility to find critical power and diameter of filaments.

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.
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 \( d_{0.5} \approx 100 \, \mu m \) diameter was observed.

- \( E = 0.14 \) mJ
  - \( P \approx 12 \times P_{cr} \)
  - \( I = 1.1 \times 10^{13} \) W/cm²

- \( E = 0.063 \) mJ
  - \( P \approx 6 \times P_{cr} \)
  - \( I = 5.0 \times 10^{12} \) W/cm²

- \( E = 0.029 \) mJ
  - \( P \approx 2.5 \times P_{cr} \)
  - \( I = 2.3 \times 10^{12} \) W/cm²

For lower powers \( P \leq P_{cr} \) filaments were not observed while \( d_{0.5} \approx 130 \, \mu m \).

- \( E = 0.013 \) mJ
  - \( P \approx P_{cr} \)
  - \( I = 1.1 \times 10^{12} \) W/cm²

- \( E = 0.01 \) mJ
  - \( P \approx 0.8 \times P_{cr} \)
  - \( I = 7.9 \times 10^{11} \) W/cm²

- \( E = 0.0068 \) mJ
  - \( P \approx 0.6 \times P_{cr} \)
  - \( I = 5.3 \times 10^{11} \) W/cm²
Multiple filamentation of a supercritical UV laser beam

• For $P \gg P_{cr}$ 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 $\lambda \sim 800$ 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 $\lambda=248$ 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 $\sim 1$ps 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.
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 $\mu$m.
Parameters of multiple filaments of UV USP beam

Absorbed laser energy:
\[ \frac{dE}{dz} = \kappa E = 1.2 \cdot 10^{-5} \text{ J/cm} \] (for \( E = 0.2 \text{J} \))

Number of electrons per beam length:
\[ \frac{dN_e}{dz} = \frac{1}{3h\nu} \frac{dE}{dz} = 5 \cdot 10^{12} \text{ cm}^{-1} \] (for \( h\nu = 5 \text{eV} \))

Number of filaments: \( N_f \approx 500 \)

Number of electrons per filament length:
\[ \frac{dN_{ef}}{dz} = \frac{1}{N_f} \frac{dN_e}{dz} = 10^{10} \text{ cm}^{-1} \]

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:
\( P_f = 0.3P/N \approx 1.2 \cdot 10^8 \text{ W} \approx P_{cr} \)

Intensity in filaments:
\( I = P_f/S_f = (1.8 \pm 0.6) \cdot 10^{11} \text{ W/cm}^2 \)

- 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

- For USP ($\tau \sim 100$ fs),
  \[ I = 3\times10^{11} \div 1.5\times10^{13} \text{ W/cm}^2 \]
  \[ \rho \sim I^3 \cdot \tau \] 3-photon O$_2$ ionization (MPI).

- For long pulses ($\tau \sim 25$ ns),
  \[ I = 10^8 \div 10^{11} \text{ W/cm}^2 \]
  \[ \rho \sim I^2 \cdot \tau \] (2+1) resonance enhanced multiphoton O$_2$ ionization (REMPI).

- For $I = 5\times10^6 \div 5\times10^8$ W/cm$^2$
  \[ \rho \sim I \cdot \tau \] photoionization of impurities or photoemission of aerosol particles.

Electron density vs. laser intensity
Focusing of a multiply-filamented USP beam ($F = 100 \text{ m}$)

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

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 ($F = 60 \text{ m}; \ z = -22.5 \text{ m}$)

$E_1=0.16 \text{ J}; \ P_1=1330 \times P_{cr}$

$E_1=0.084 \text{ J}; \ P_1=700 \times P_{cr}$

$E_1=0.048 \text{ J}; \ P_1=400 \times P_{cr}$

30 mm

- In front of the linear focus a number of filaments decreases for lower USP energy.
- At $E_1=0.004 \text{ J} (P_1 = 0.004 \text{ TW} = 33P_{cr})$ individual filaments coalesce into hot spots of bigger size ~1 mm.
Filamentation of a single USP behind the focus ($F = 60 \text{ m}$)

- The mean radius of the USP beam obeys a linear focusing with the caustic waist radius $\sim 9 \text{ mm}$ corresponding to the beam divergence $\sim 1.5 \times 10^{-4} \text{ rad}$;
- 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 $\sim 1 \text{ mm}$. 

\[ E_1 = 0.2 \text{ J}; \quad P_1 = 1660 \times P_{cr} \]
\[ E_1 = 0.12 \text{ J}; \quad P_1 = 1000 \times P_{cr} \]
\[ E_1 = 0.09 \text{ J}; \quad P_1 = 750 \times P_{cr} \]
\[ E_1 = 0.02 \text{ J}; \quad P_1 = 166 \times P_{cr} \]
Multiple filamentation of USP train \((F = 6.75 \text{ m})\)

- 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 \(~1\text{ mm}\);
- 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.

![Graph showing beam radius vs position along the beam.](image)

\[
\begin{align*}
  E_1 &= 0.19 \text{ J}; P_1 = 1600 \times P_{cr} \\
  E &= 0.43 \text{ J} \\
  z &= -3.45 \text{ m} \\
  E_1 &= 0.15 \text{ J}; P_1 = 1250 \times P_{cr} \\
  E &= 0.3 \text{ J} \\
  z &= 0 \\
  E_1 &= 0.16 \text{ J}; P_1 = 1330 \times P_{cr} \\
  E &= 0.28 \text{ J} \\
  z &= 5.25 \text{ m} \\
  20 \text{ mm} &\quad 2 \text{ mm}
\end{align*}
\]
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 ($NA=1.5\cdot10^{-2}$– $1.5\cdot10^{-3}$) 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.