Pulse self compression by filamentation

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Projet TERAMOBILE

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funded by CNRS and DFG

Filamentation

LOA '96

Laser beam filamentation

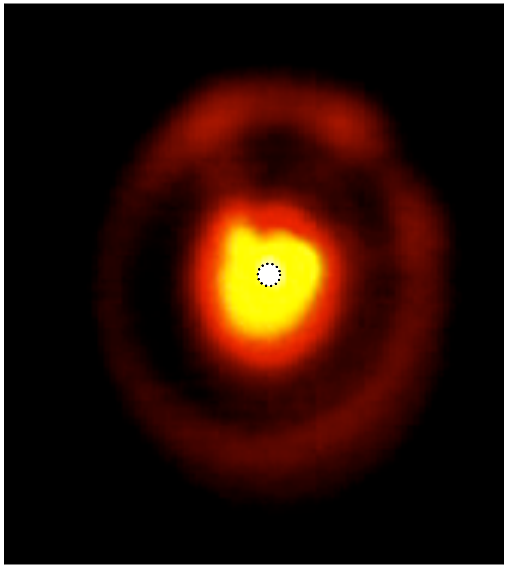
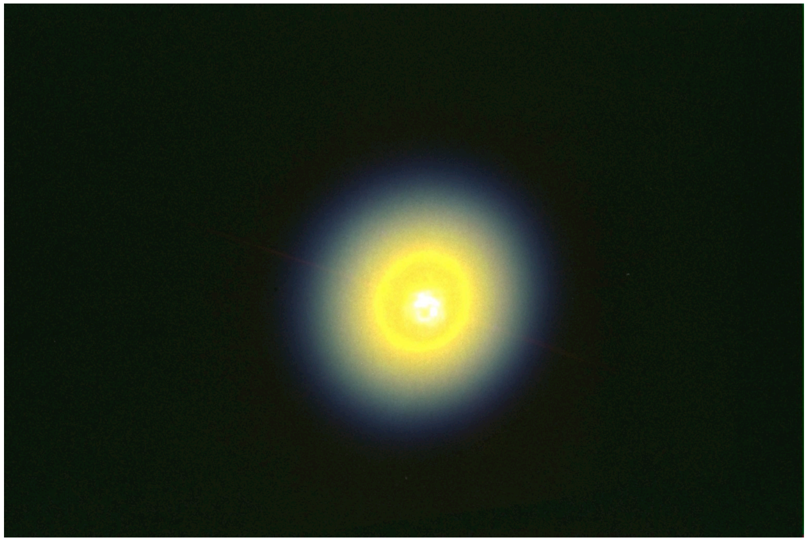


Photo at 50 m

- Dimensions ~ 100 µm
- Intensity ~ $5x10^{13}$ W/cm^2
- Ionized channels ~10^{16} e$^-$/cm^3
- White light super continuum generation

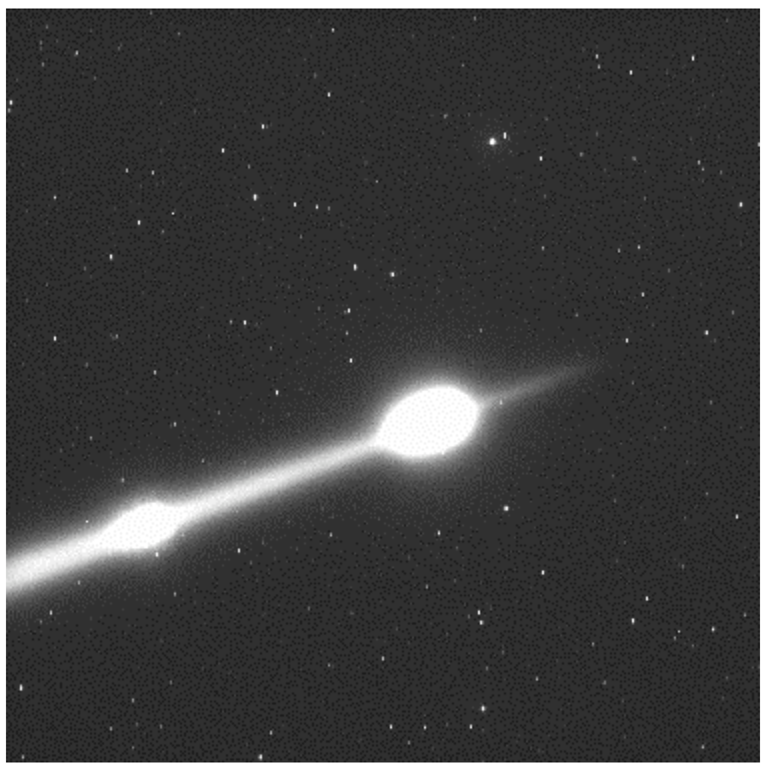
Blue Filament (400nm)

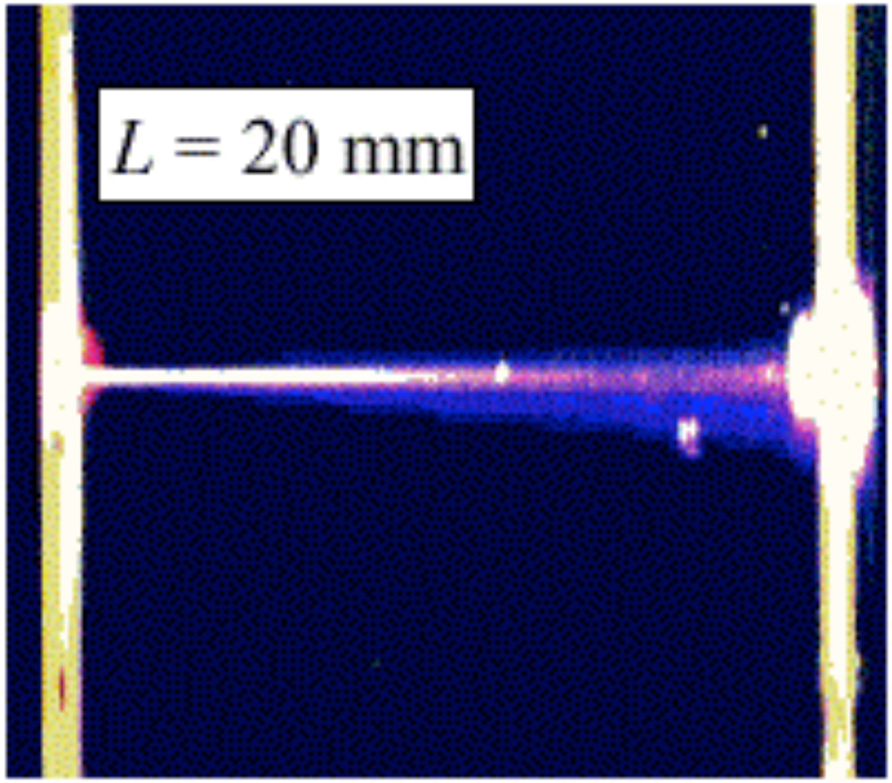
Photo at 50 m



Long range filamentary propagation of intense ultra short laser pulses in atmosphere

Teramobile Project





Filamentation in fused Silica

Phys. Rev. Lett. 87, 213902 (2001)

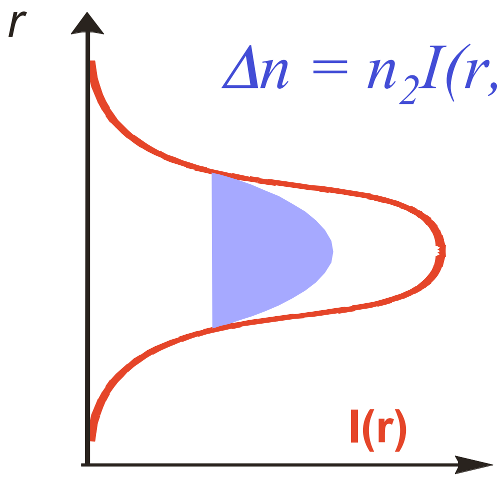
BASIC NON-LINEAR PROCESSES

(1) Self-Focusing

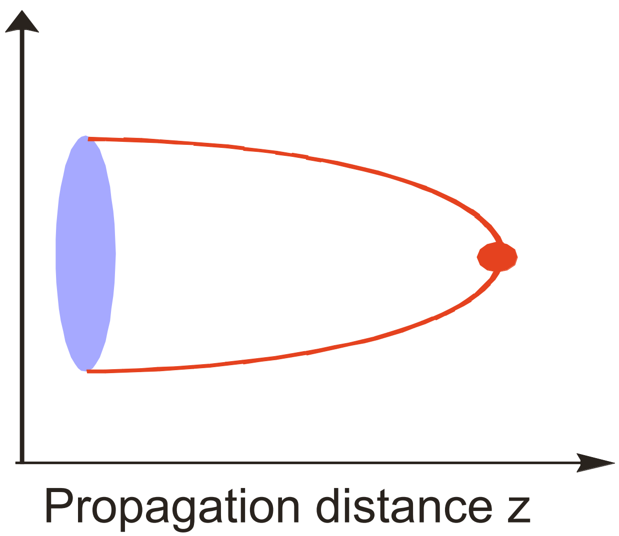
Optical Kerr Effect : $n = n_0 + n_2\, I(r,t)$

$(n_2 = 3\ 10^{-19}\ cm^2/W\ \text{in air})$

$$\Delta n = n_2 I(r,t)$$



Gaussian Profile



Catastrophic Collapse !!

BASIC NON-LINEAR PROCESSES

(2) Multi-Photon Ionization (MPI) and Plasma Defocusing

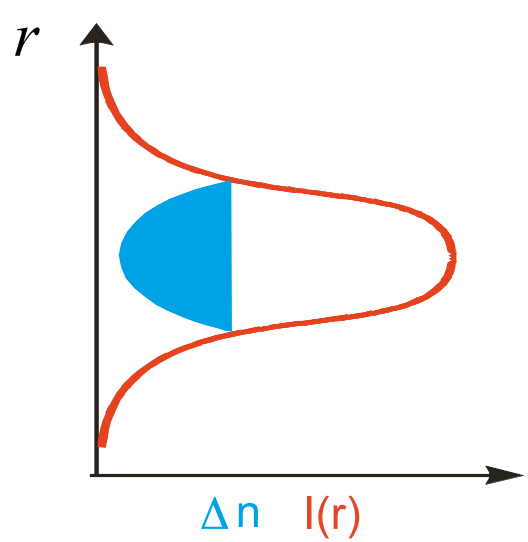
MPI → $$\Delta n = -\frac{\rho(I)}{\rho_c}$$

$\rho(I)$: electronic density ; $\rho_c = 2 * 10^{21} \text{cm}^{-3}$

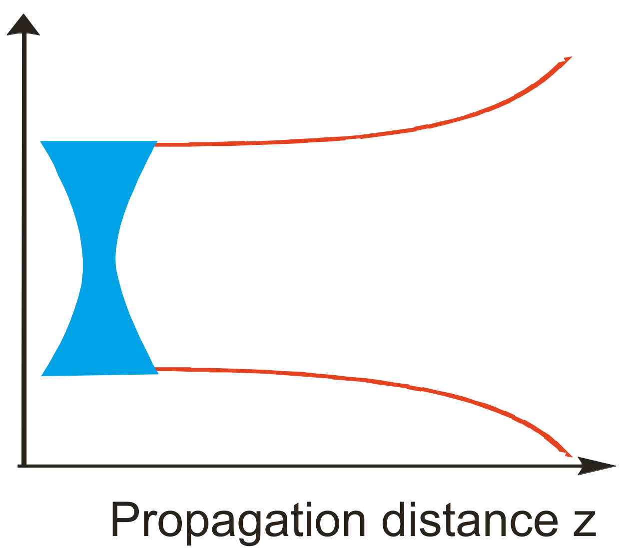
With: $$\frac{\partial \rho}{\partial t} = \sigma |E|^{2\alpha} (N - \rho)$$

N : neutral density; σ:cross-section

α : # photons for MPI of N_2/O_2 =10 (800nm)



Negative Lens



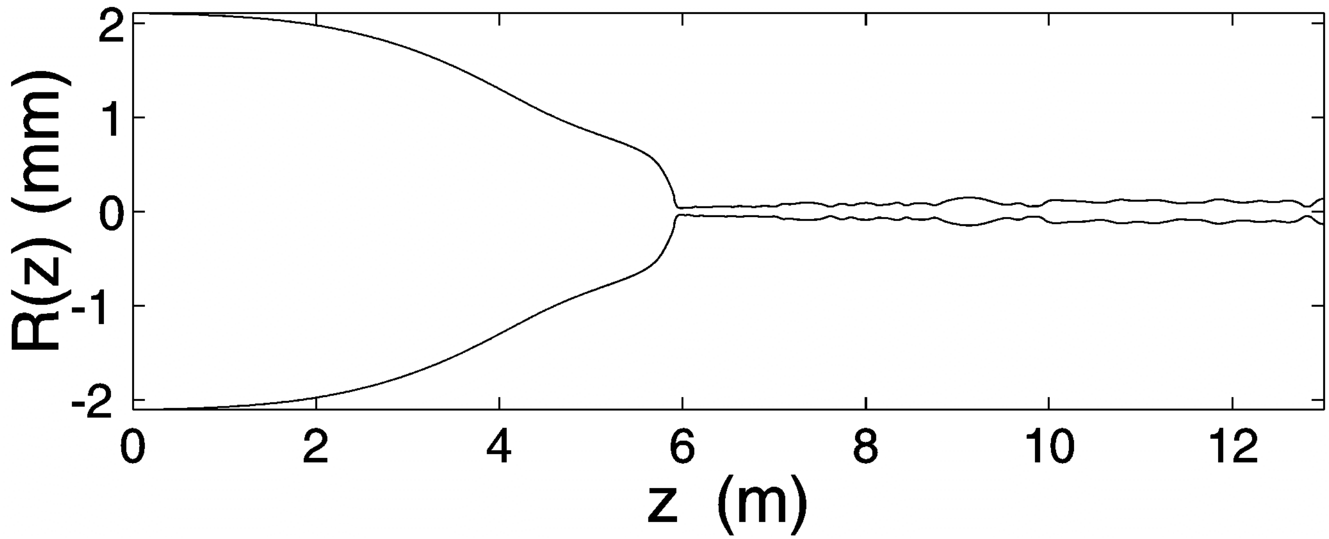
Defocusing

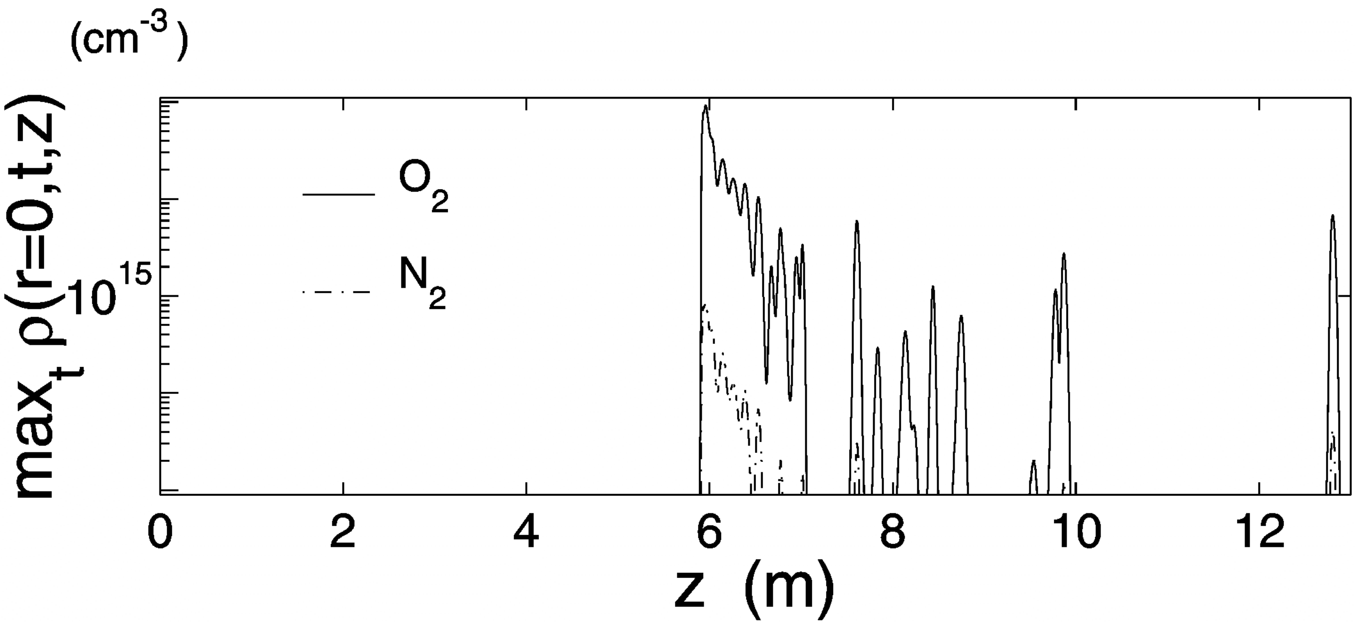
Physical mechanisms – Simulation:

- Optical Kerr effect versus Transverse Diffraction → Self-Focusing ($P_{in} > P_{cr}$)
- Multi-Photon Absorption
- Defocusing due to Multi-Photon Ionization
- Group-Velocity Dispersion
- Avalanche ionization
- Self-steepening and space-time focusing

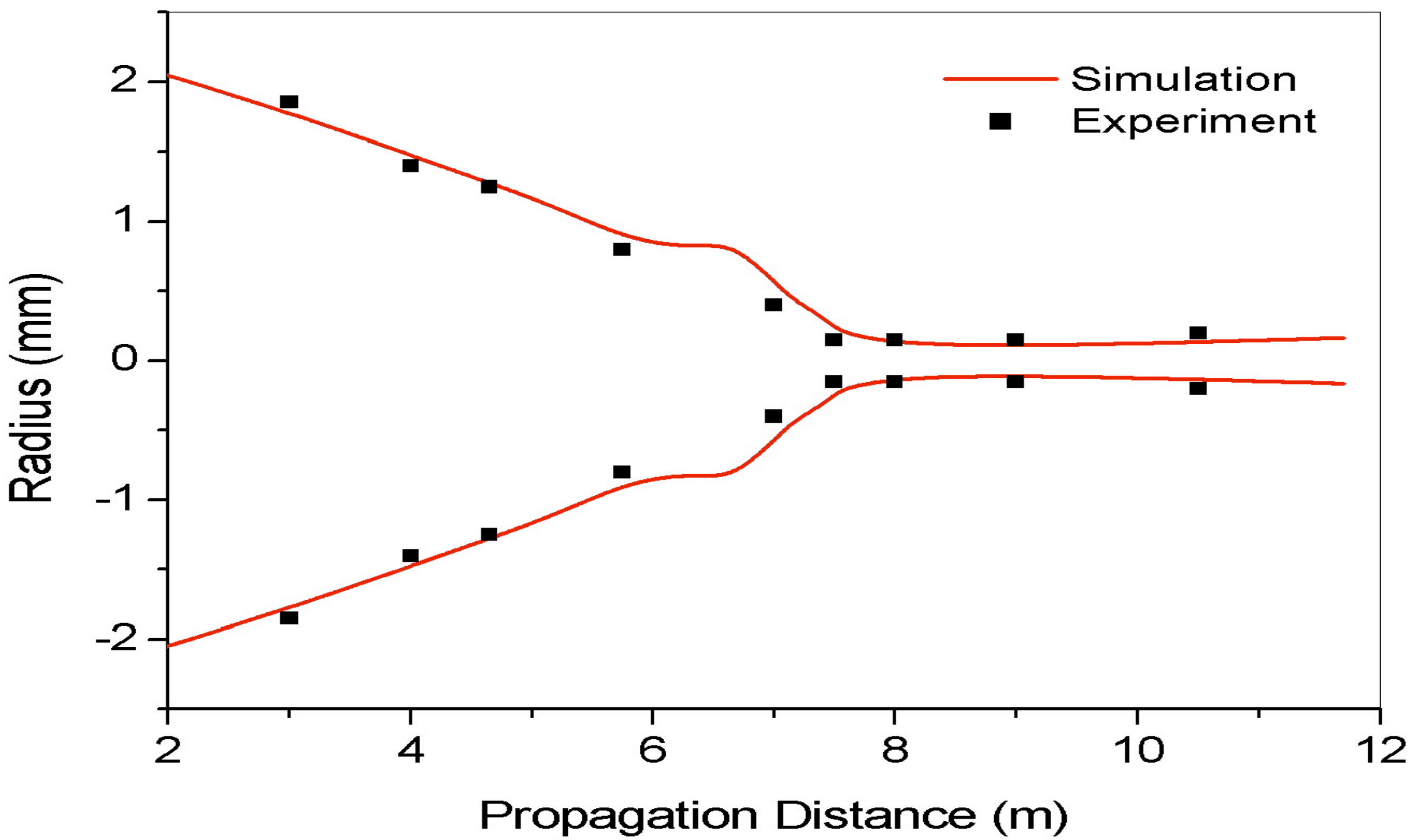
The extended nonlinear Schrödinger equation (Brabec and Krausz) coupled with the equation for the electron density ρ is solved numerically

Collimated beam propagation: simulation





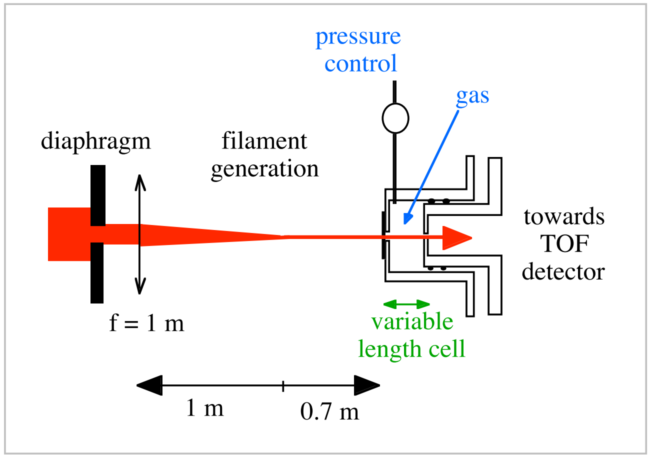
Experiment vs. simulation

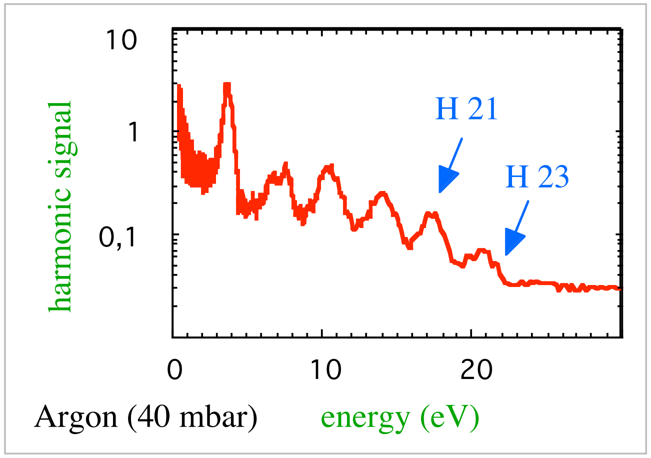


Opt. Lett. **25**, 1270 (2000) measured at FORTH, Heraklion

Measurement of the IR filament Intensity

High order harmonics generation





$h\nu = I_p + 3.2\ U_p$

I_p ionisation potential

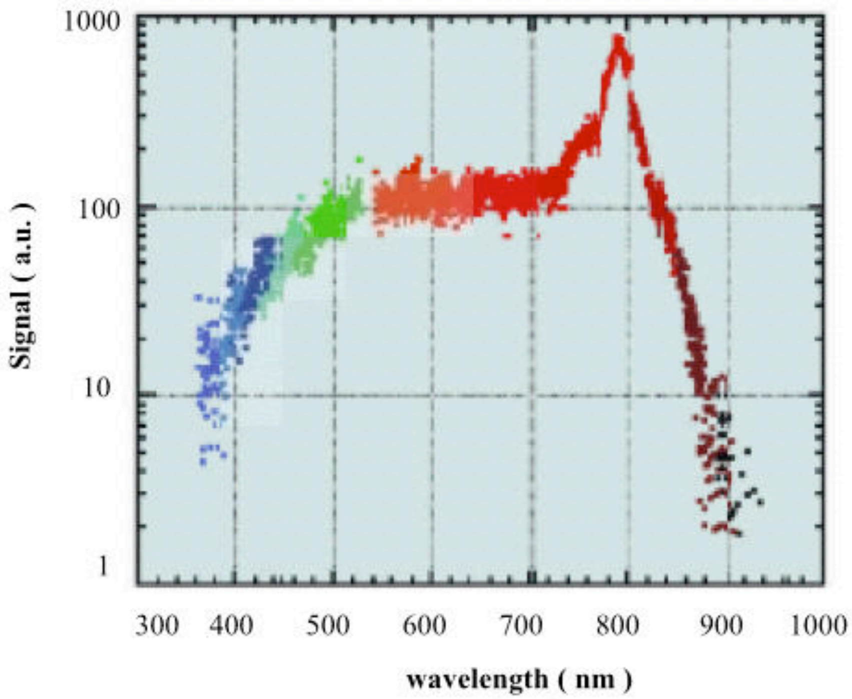
U_p ponderomotive energy

Up=9,.33 10-14 Iλ²

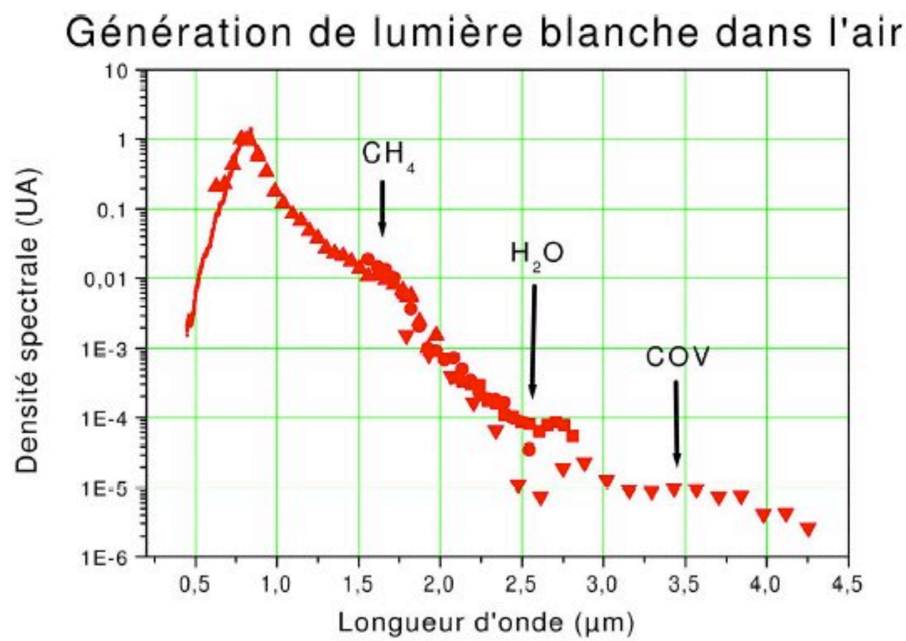
$I = 5.\ 10^{13}\ W/cm^2$

Supercontinuum generation

White Light Generation by light bullets in air



800 nm, 70 fs, 3 TW, z=10 m

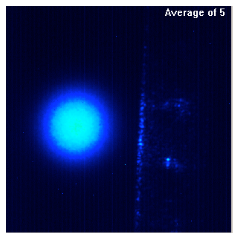


Kasparian et al. Opt. Lett 2000

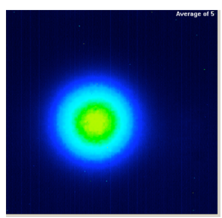
Spatial mode selfcleaning

Filament

13 m

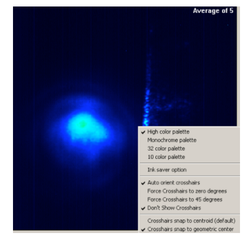


19 m

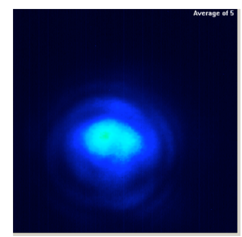


0.3 mJ

Laser



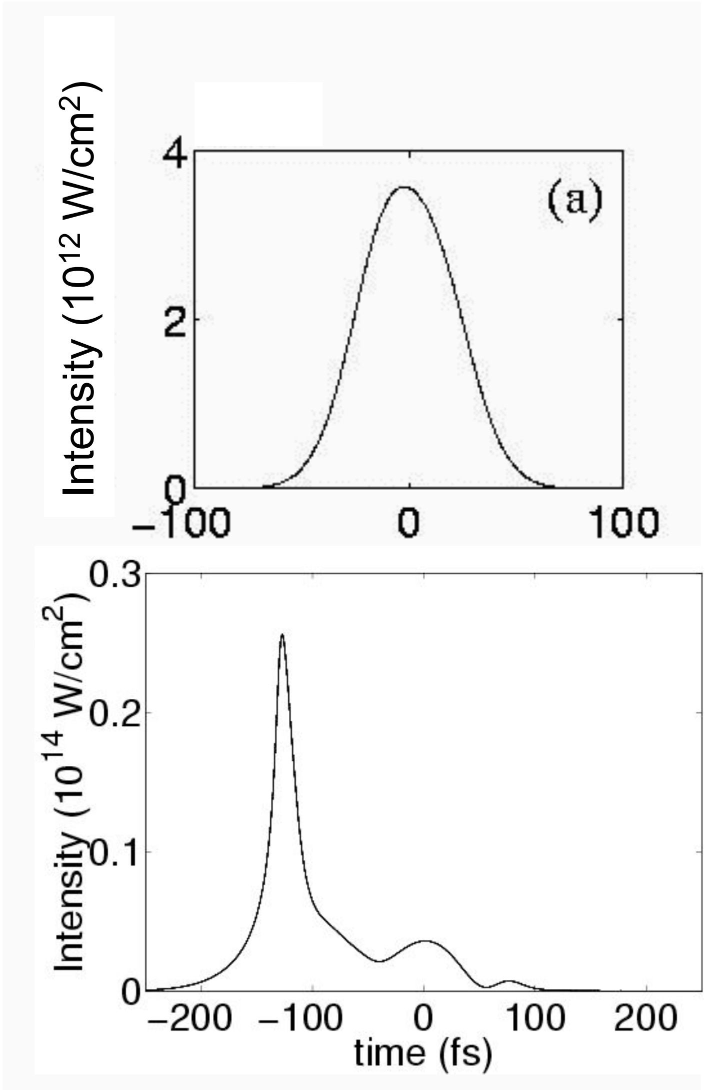
13 m



19 m

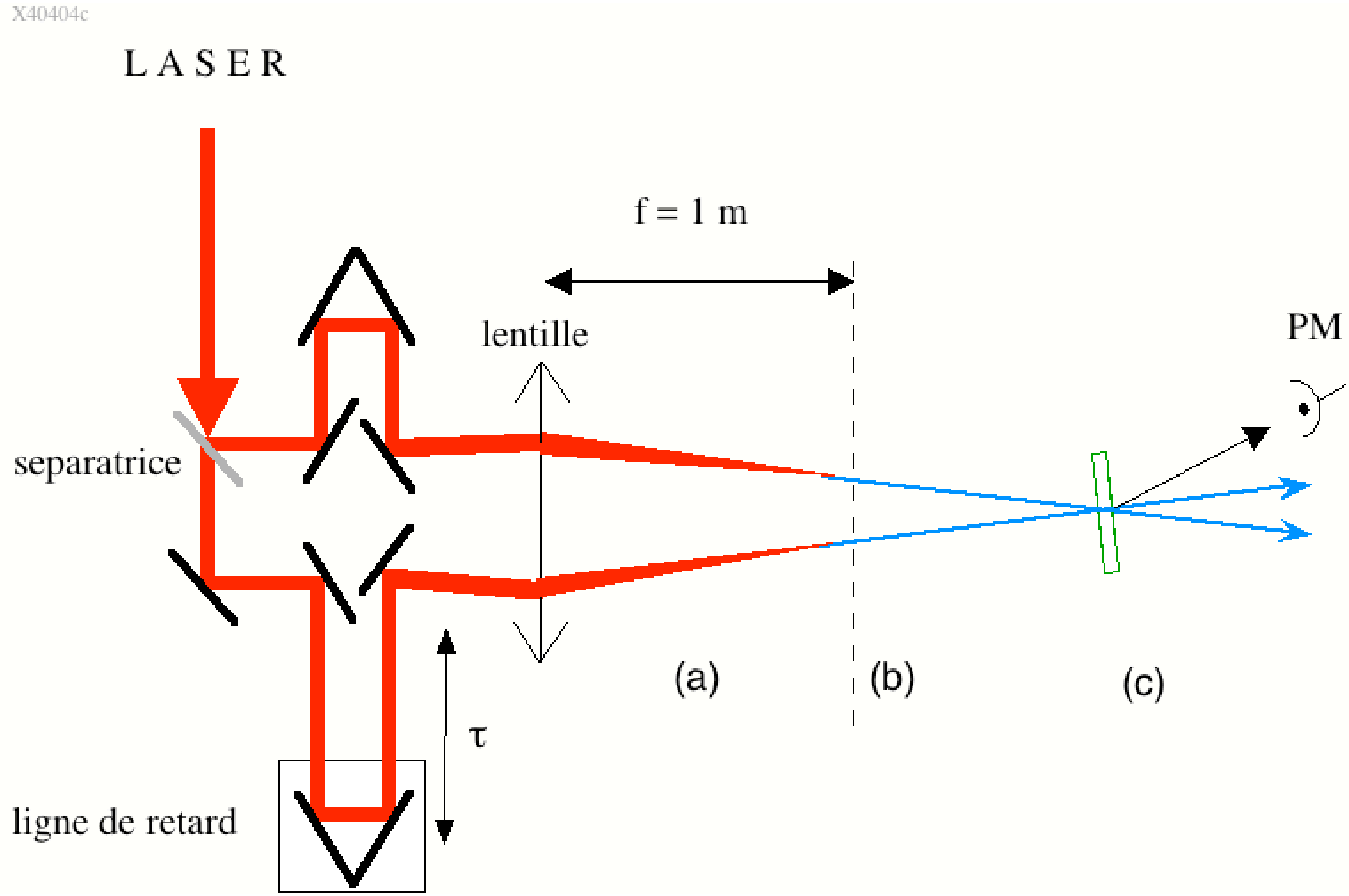
B. Prade et al., to appear in Optics Letters, Sept. 1st, 2006

Pulse Time Evolution During Propagation



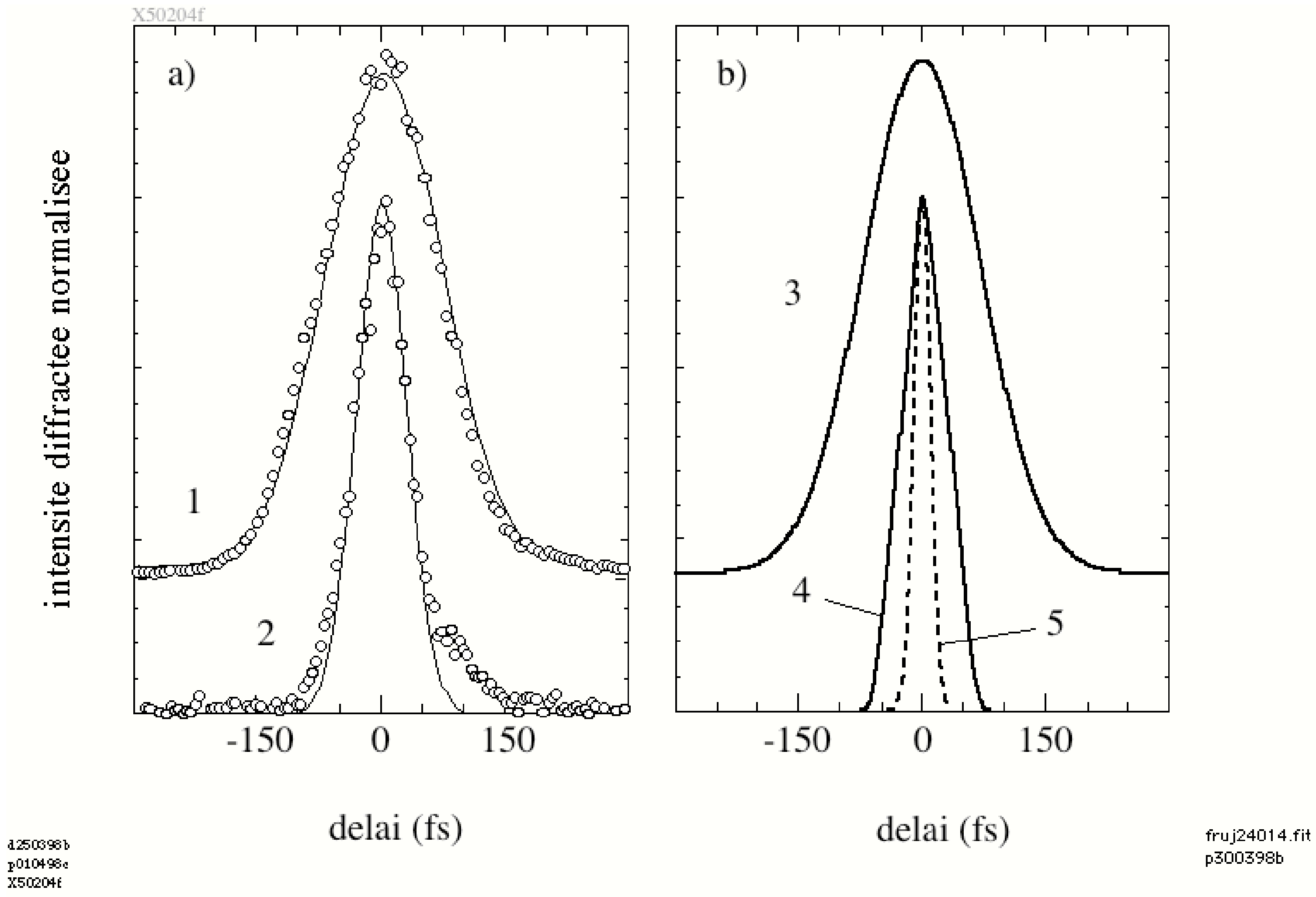
- Pulse Splitting
- Pulse Narrowing
- Advance of the pulse

Mesure de la durée de l'impulsion auto-guidée



R. Lange et al. (1998)

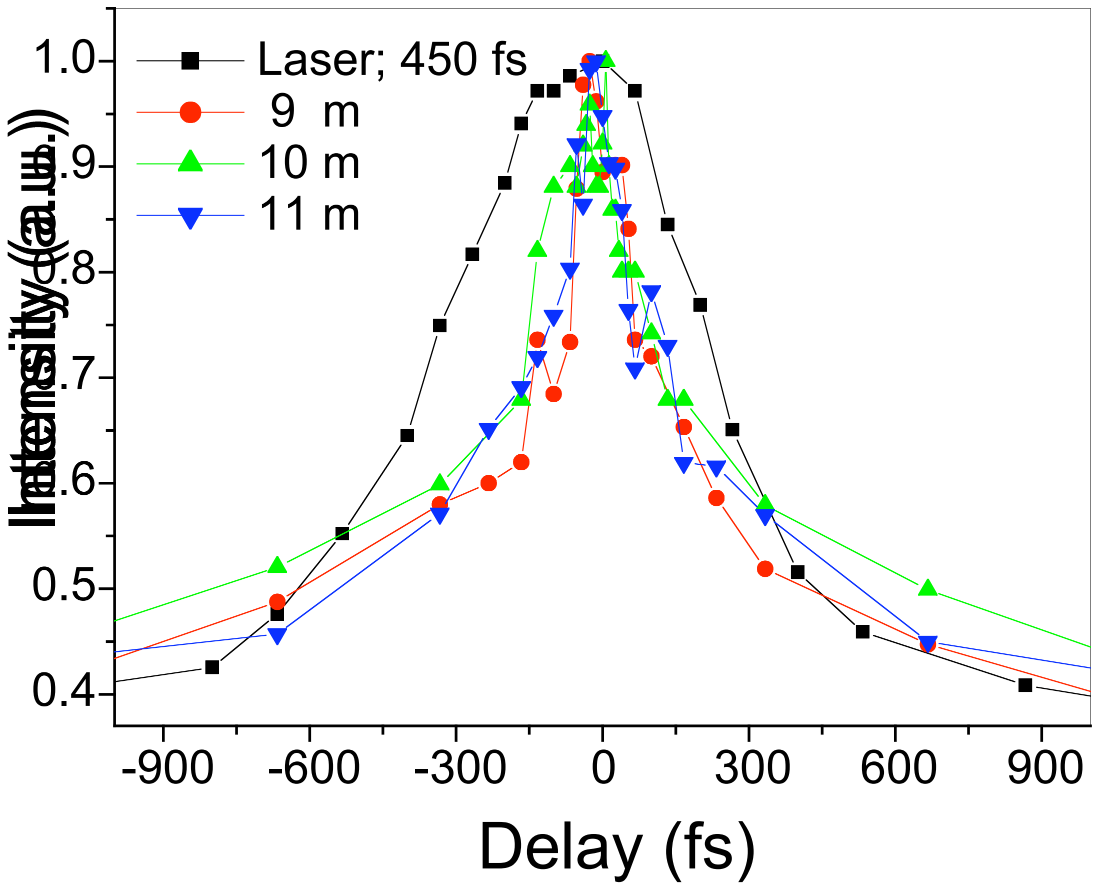
Mesure de la durée de l'impulsion auto-guidée



UV filament Pulse duration measurements

Autocorrelation using 2-photon ionization of NO molecules

measured at FORTH, Heraklion



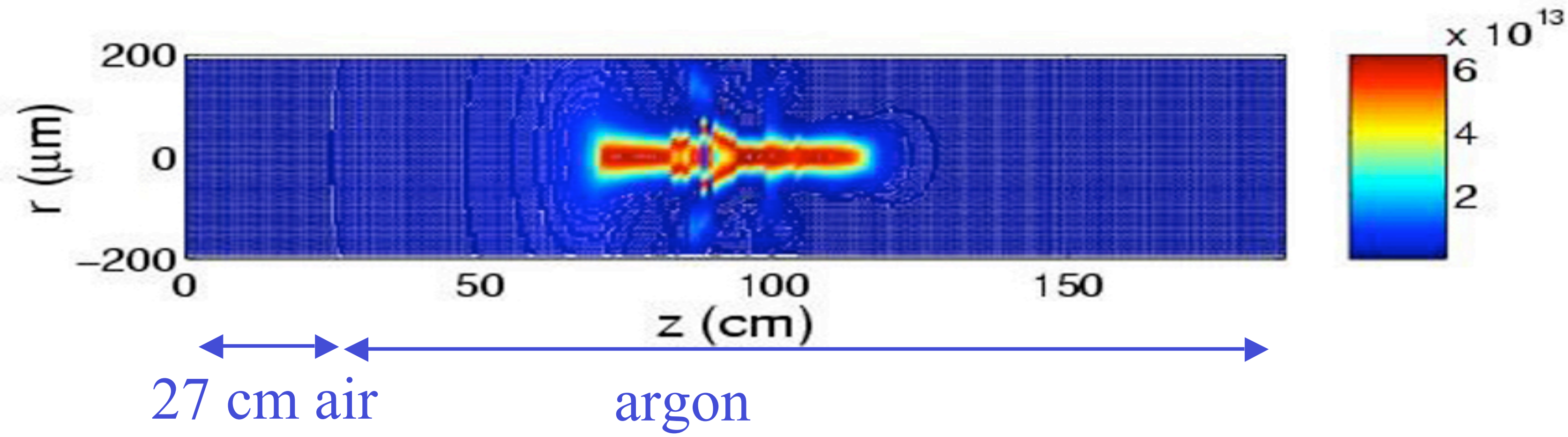
- Reduction of the pulse duration
- Stable structure for many meters of the filament propagation

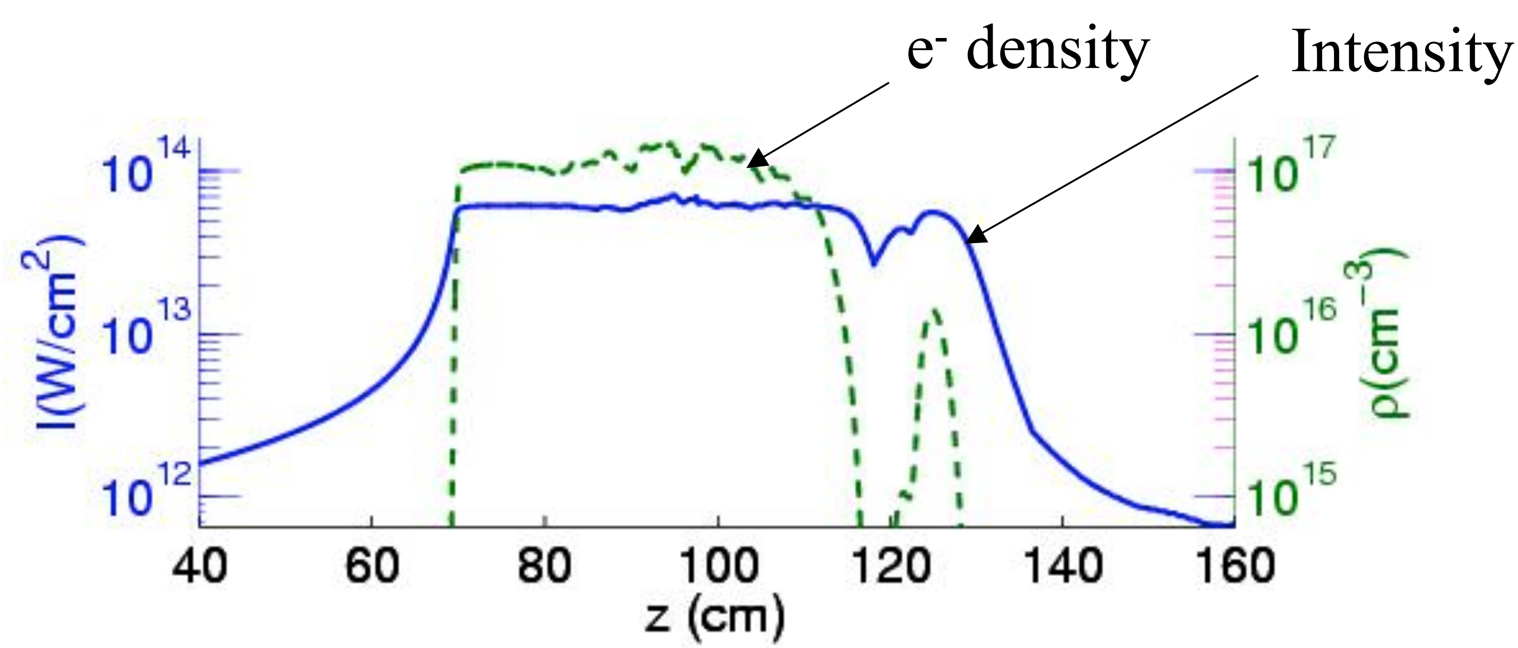
Pulse self-compression

Recent simulation suggests that nearly single cycle pulse should be obtained by self pulse compression during filamentation in Argon

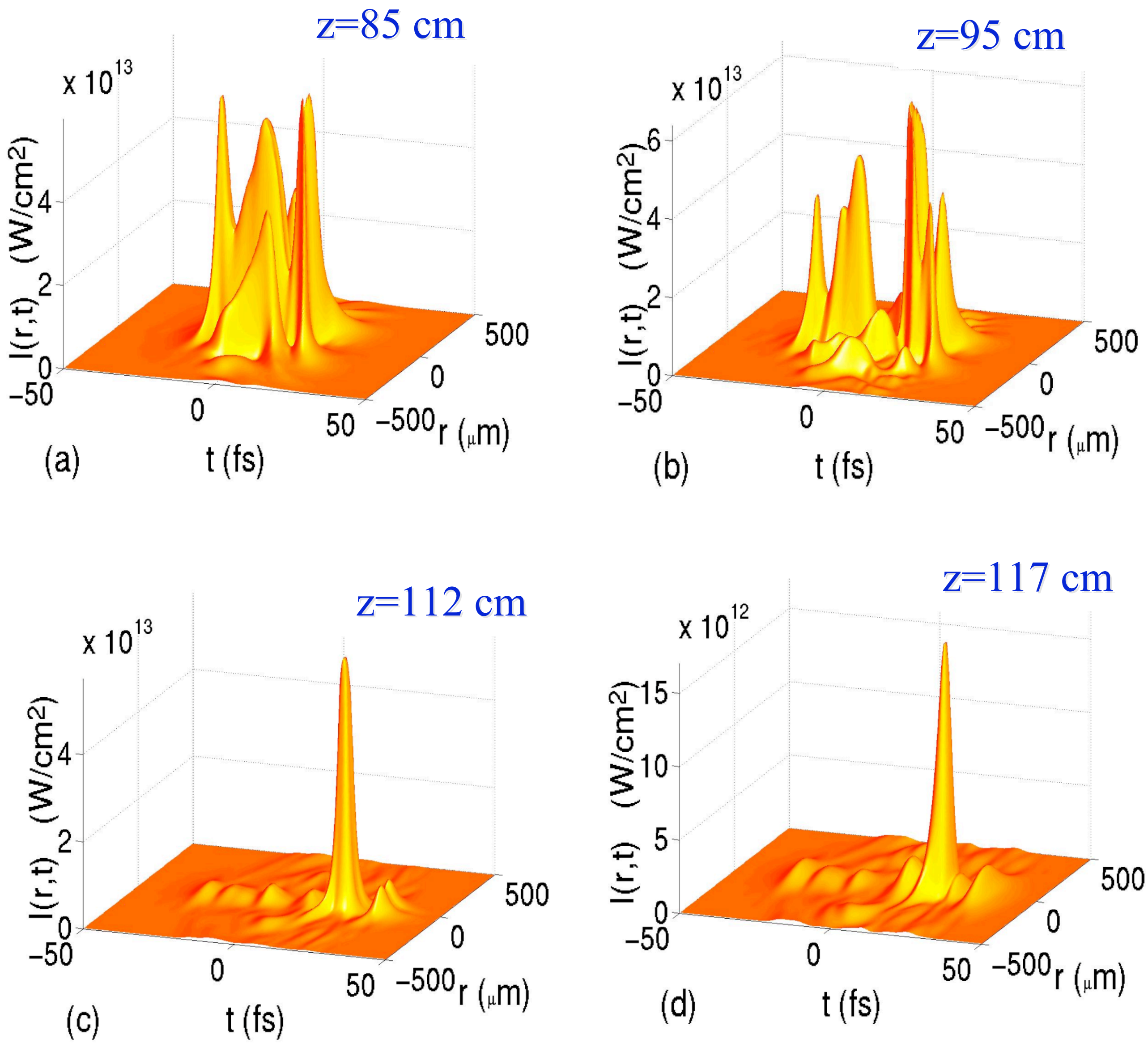
(A. Couairon et al. J. Mod. Optics **53**, 75 (2006))

Typical Intensity profiles vs z. Input pulse: 1 mJ, 25 fs, Focused in the middle of an argon cell, p=0.8 atm





Detailed space-time intensity profiles



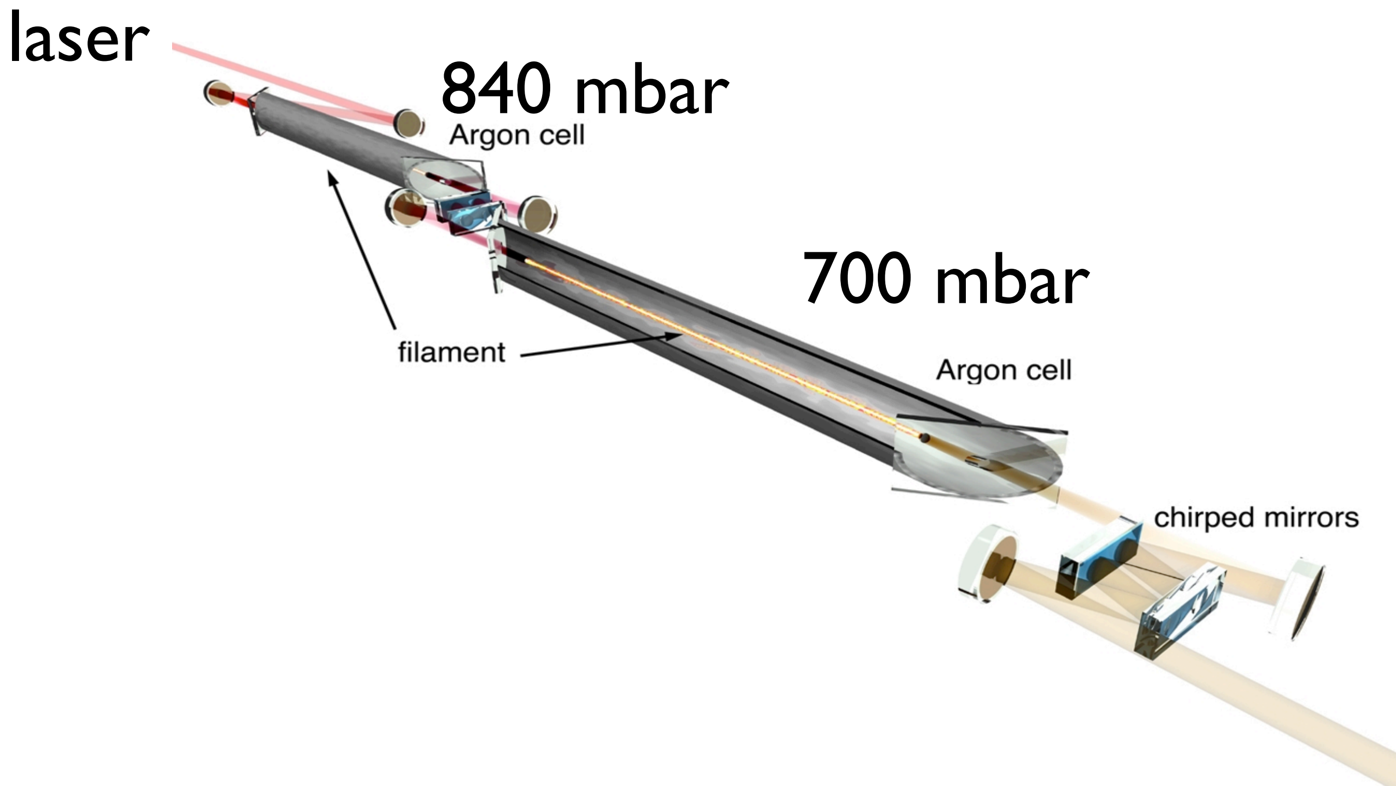
J. Mod. Optics **53**, 75 (2006)

3 fs in an isolated structure

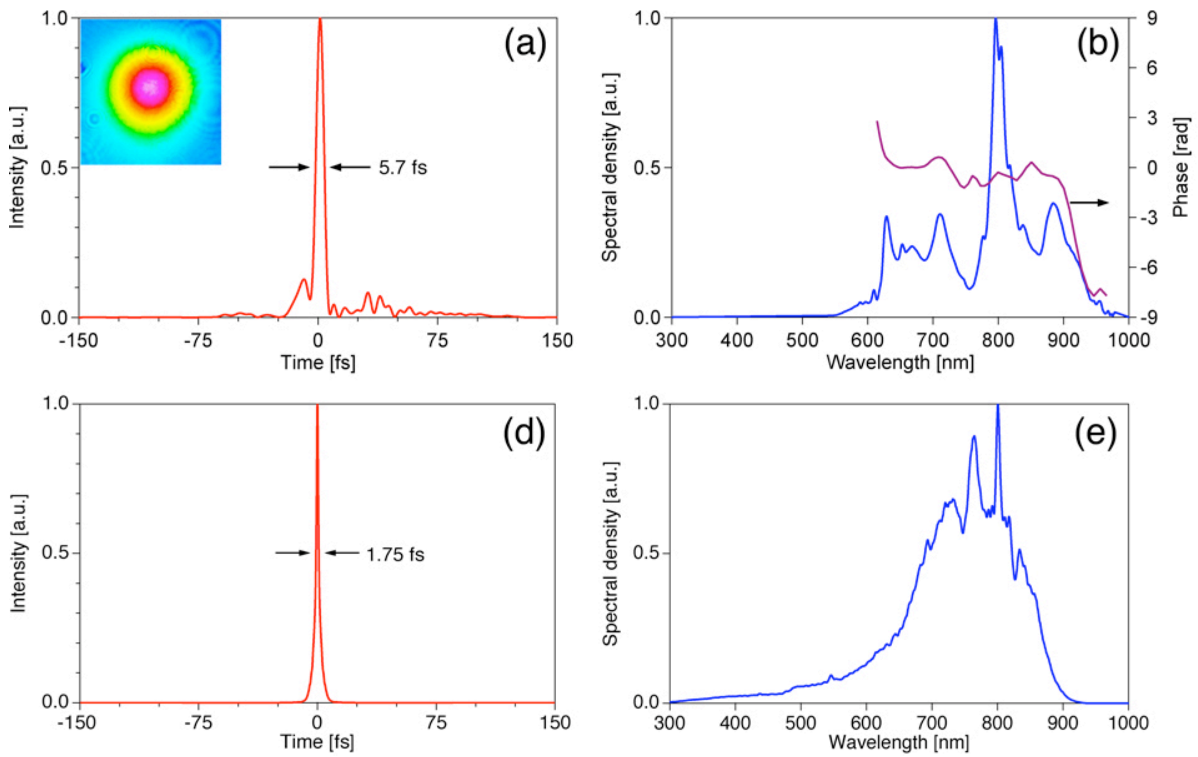
Self-compression of laser pulses by filamentation in argon gas cell at low pressure

C. Hauri, J. Biegert, A. Heinrich, F. W. Helbing, W. Kornelis
U. Keller, M. Franco, A. Couairon

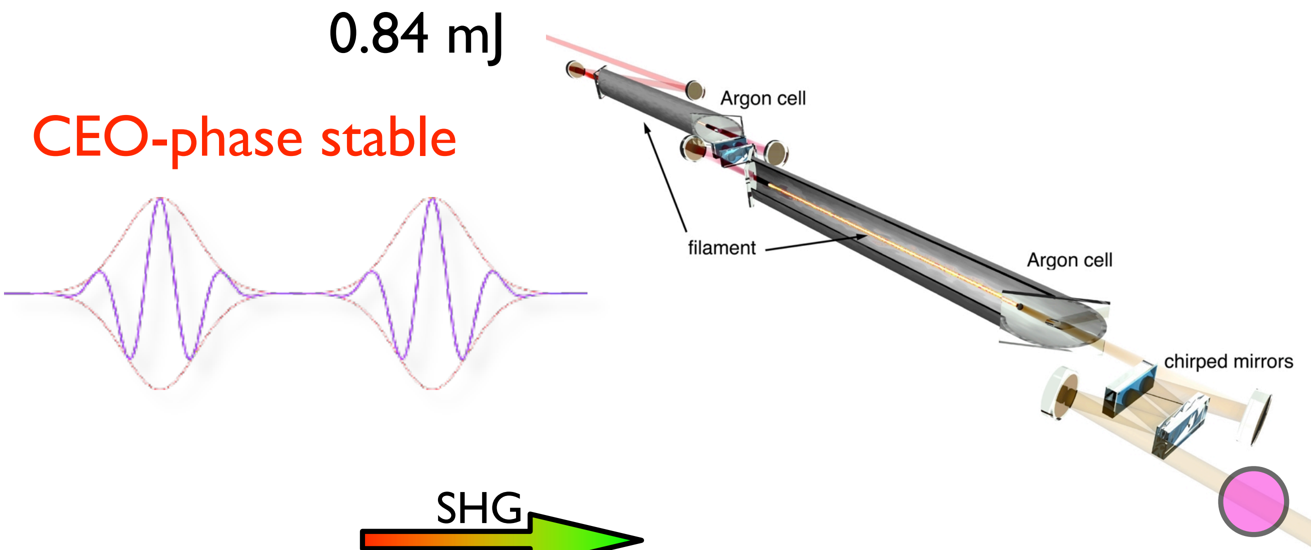
Experiments at ETH Zurich

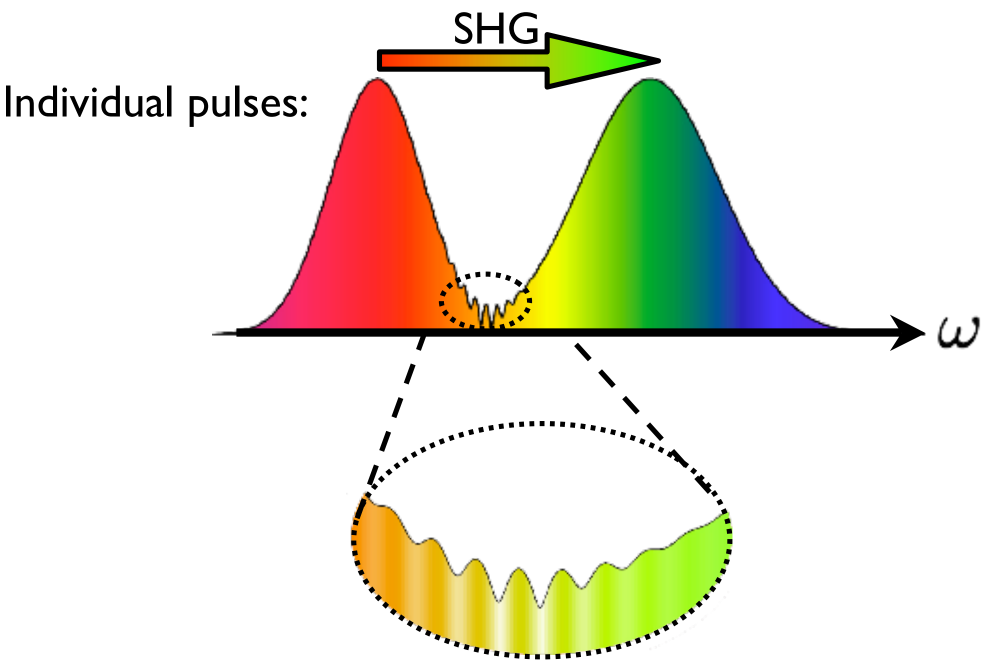


Pulse after filamentation, (H. Hauri, J. et al. ETH, Zurich, A. Couairon et al. Palaiseau Applied Physics B 2004)



Spectrum_recorded before_chirped mirrors_suggests single cycle_pulse



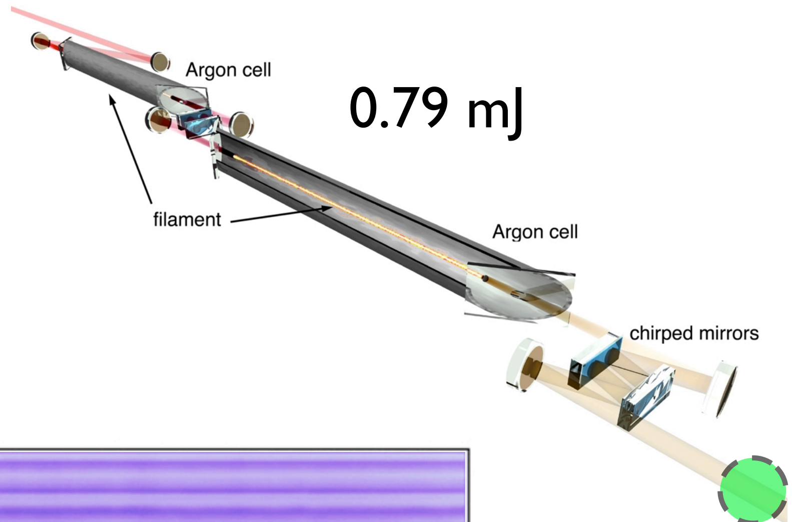


H. R. Telle et al., Appl. Phys. B *69*, 327 (1999)
D. J. Jones et al., Science *288*, 635 (2000)
A. Poppe et al., Appl. Phys. B 72, 373 (2000)
M. Mehendale et al, Opt. Lett. 25, 1672 (2000)

Input

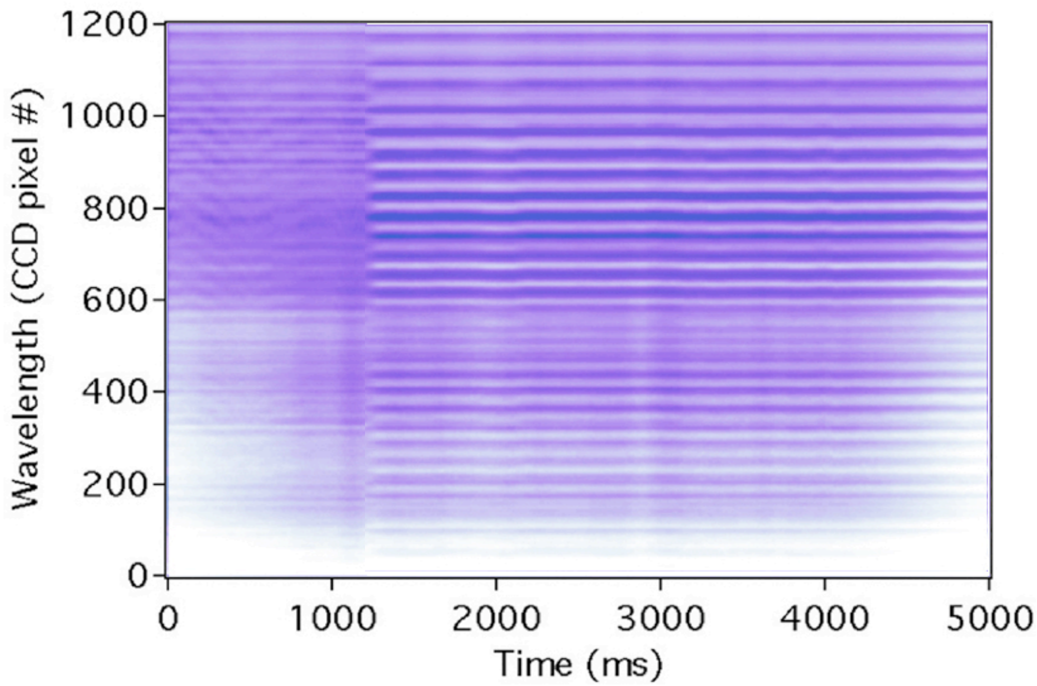
CEO-phase stable

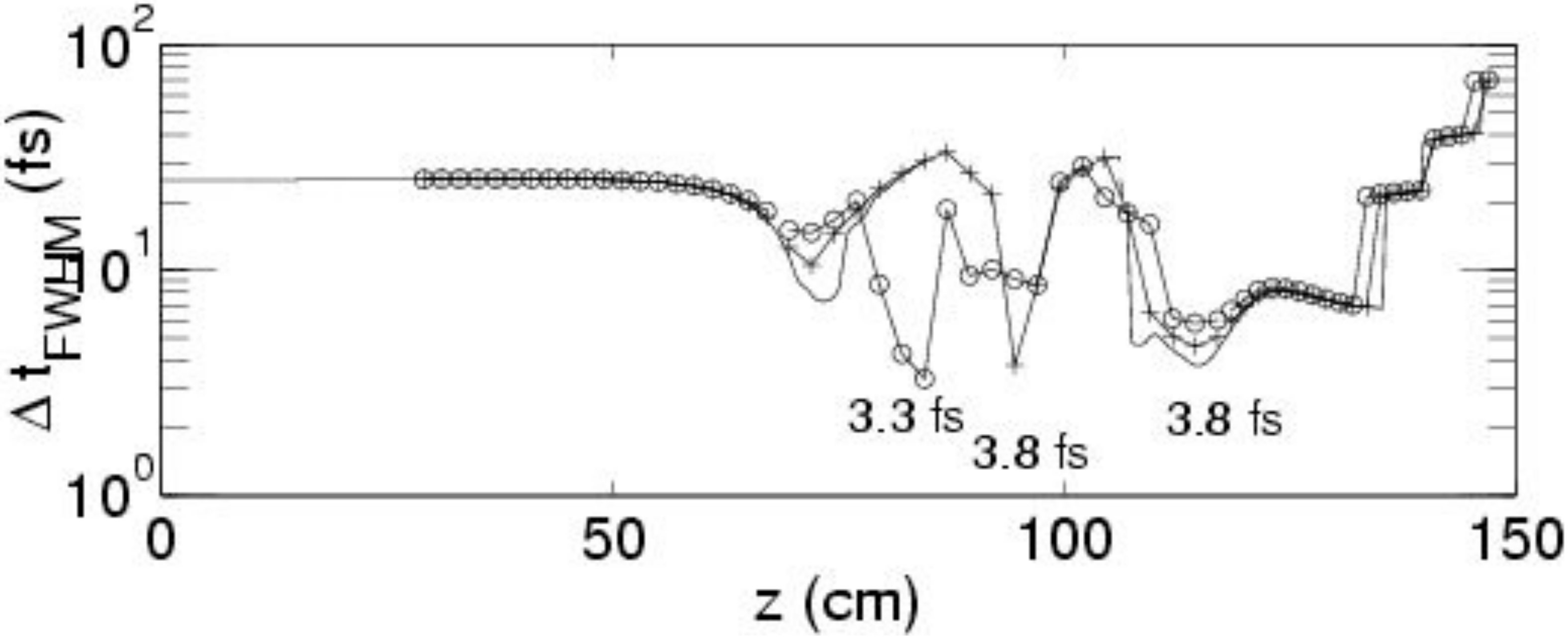
0.84 mJ



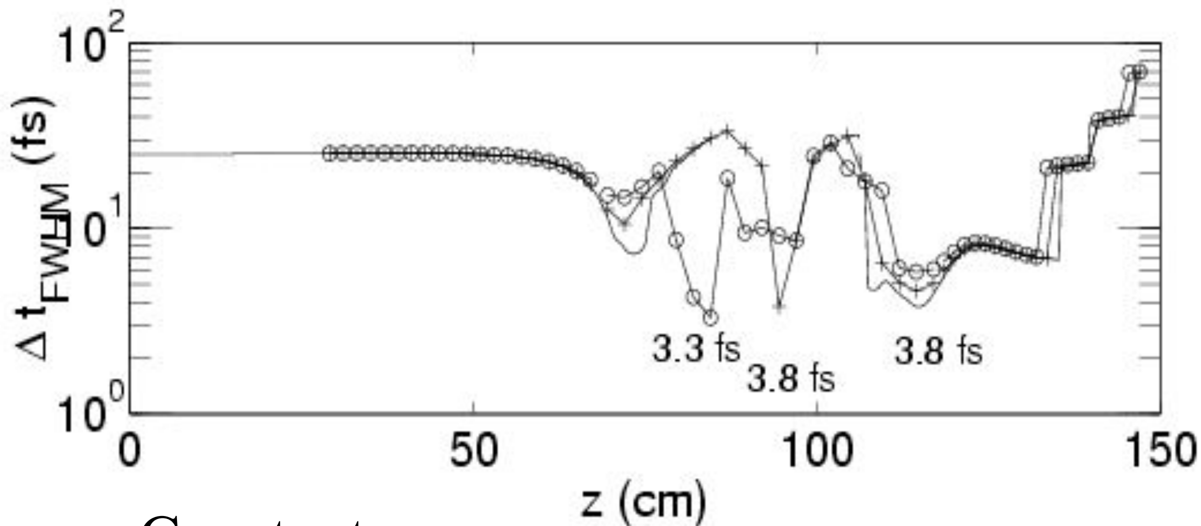
0.79 mJ

0.39 mJ

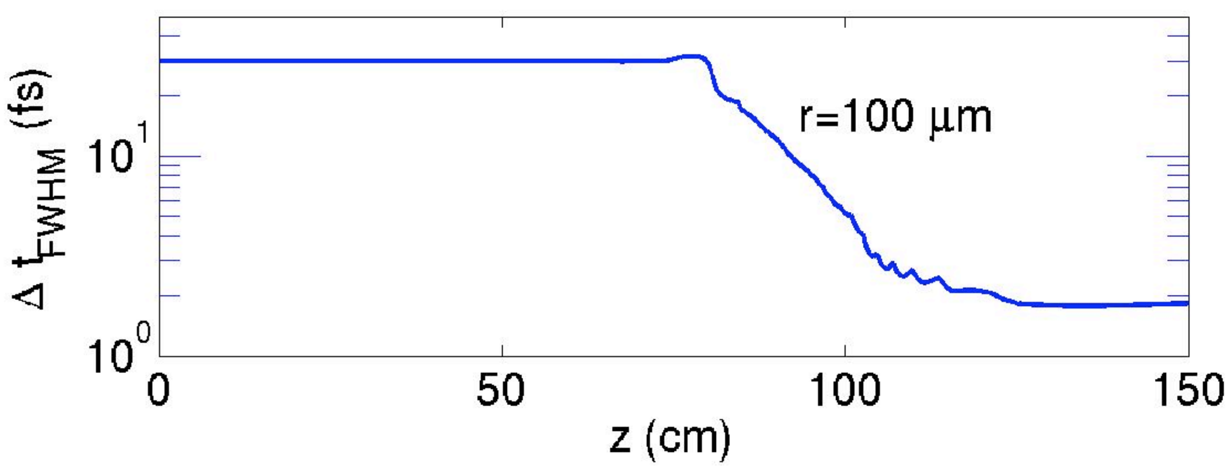




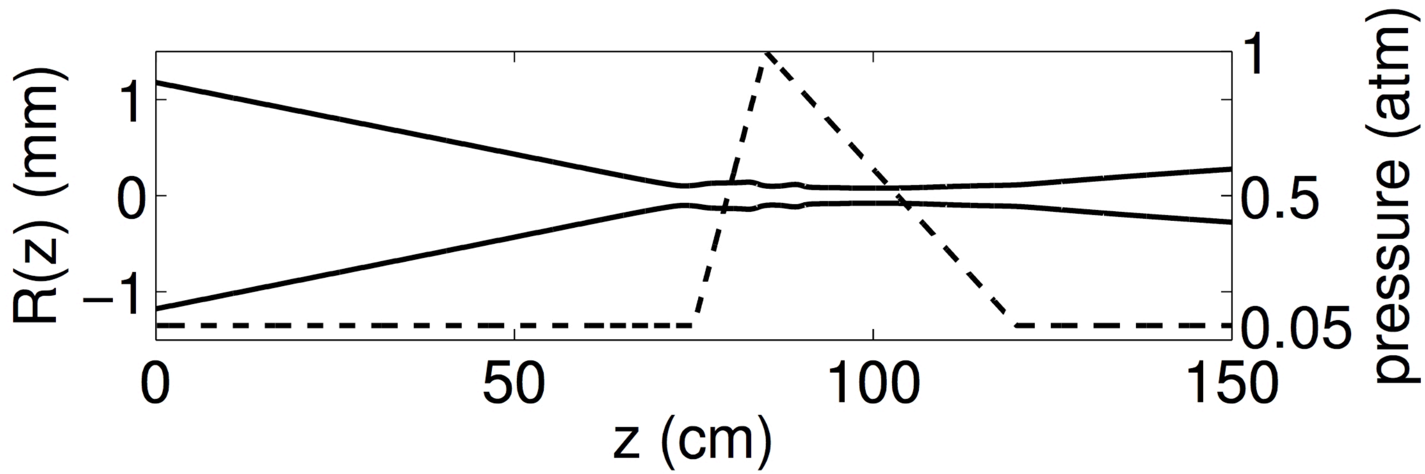
10^2
10^1
10^0
0
50
100
150
z (cm)
Δt_{FWHM} (fs)
3.3 fs
3.8 fs
3.8 fs



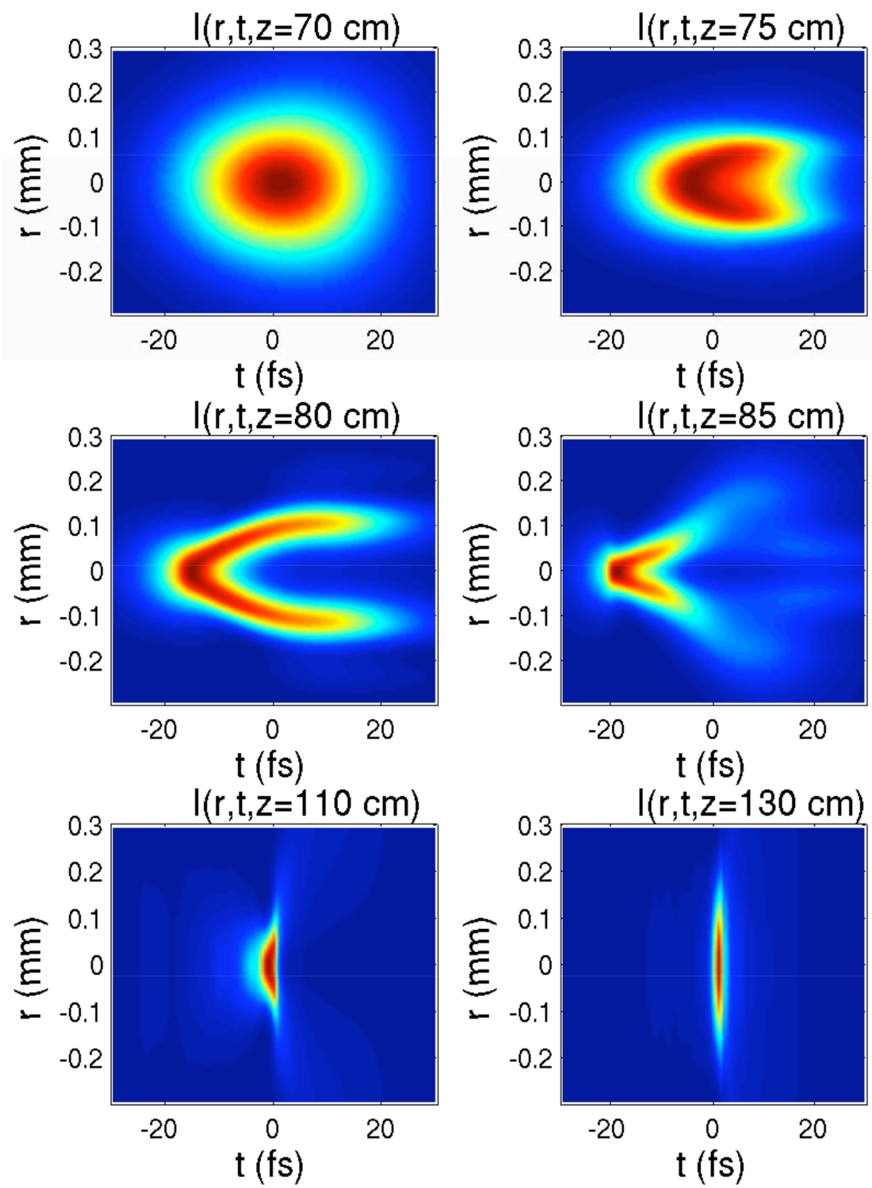
Constant pressure



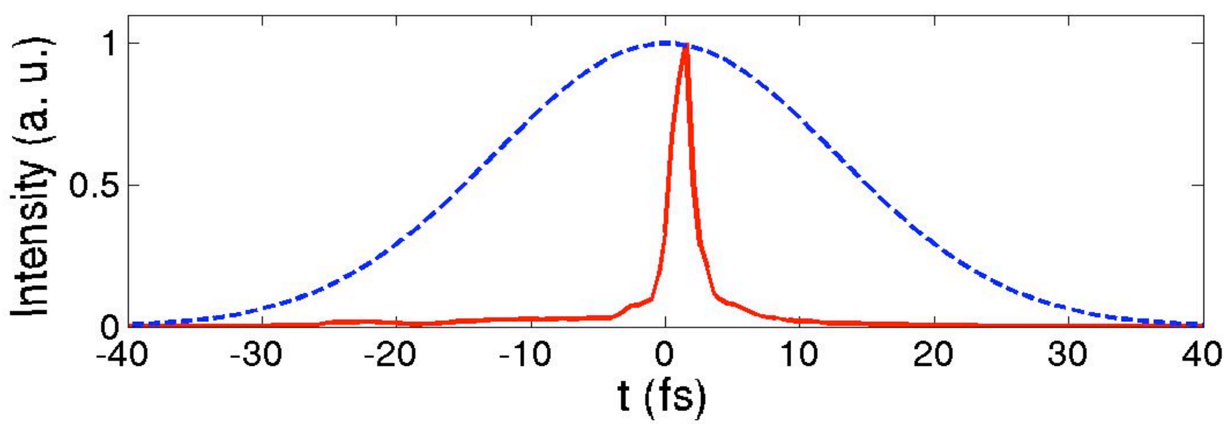
Filamentation in a Pressure gradient



A. Couairon, M. Franco et al. Optics Letters 2005

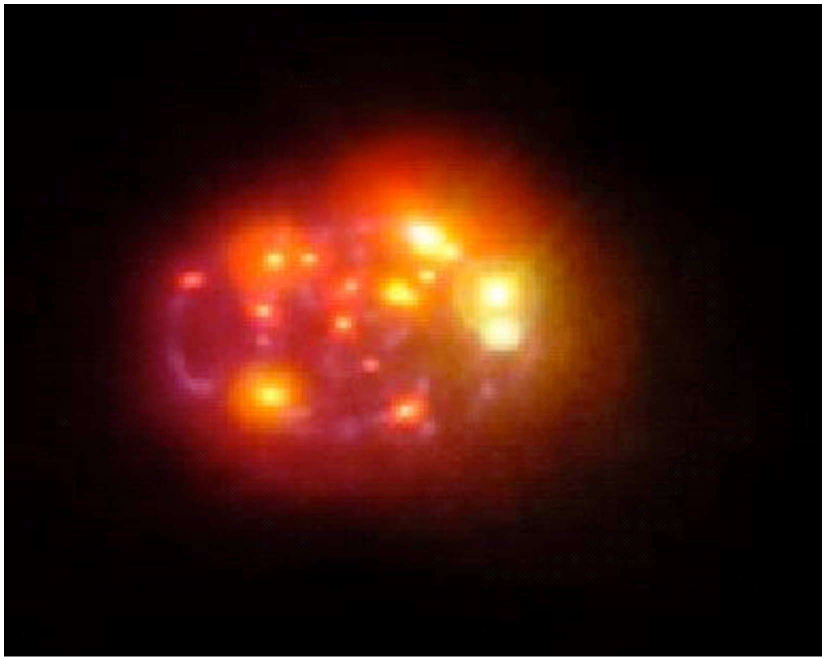


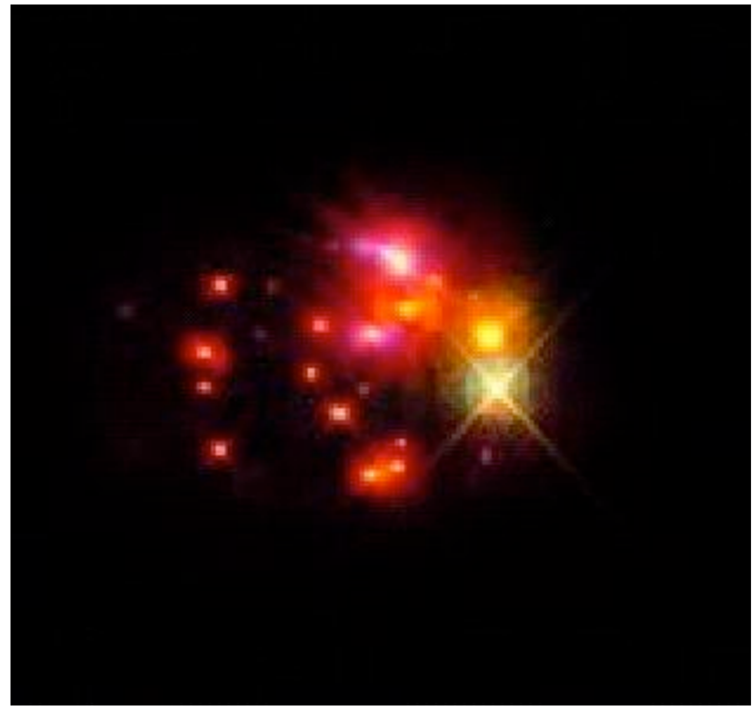
I(r,t,z=70 cm)
I(r,t,z=75 cm)
I(r,t,z=80 cm)
I(r,t,z=85 cm)
I(r,t,z=110 cm)
I(r,t,z=130 cm)
r (mm)
t (fs)
0.3
0.2
0.1
0
-0.1
-0.2
-20
0
20



Intensity (a. u.)
1
0.5
0
-40
-30
-20
-10
0
10
20
30
40
t (fs)

Multiple Filamentation $P >> P_{cr}$





A TW laser pulse leads to multiple filamentation with a seemingly random nucleation of hot spots

Interpretation : modulational instability and growth of the inhomogeneities in the input beam (Bespalov & Talanov 1966)

Organization of multiple filamentation

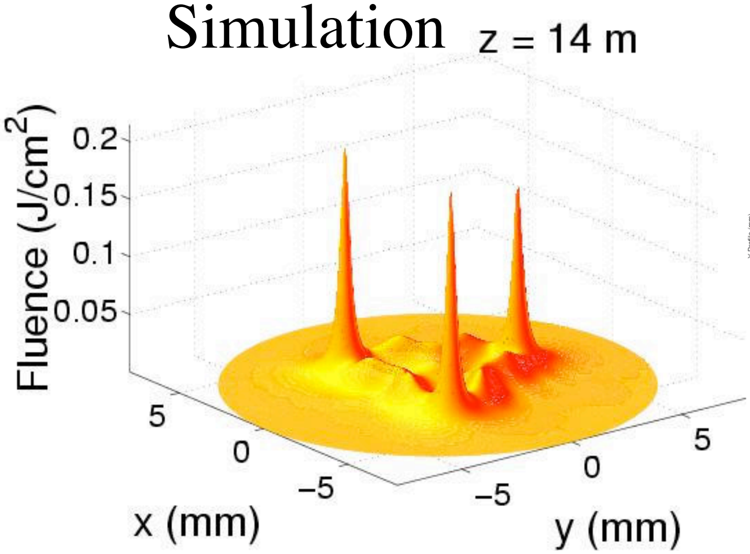
- *Organized multifilamentation using amplitude masks*
- *Spatial phase / Astigmatism*

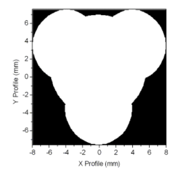
Mechain et al. PRL 2004

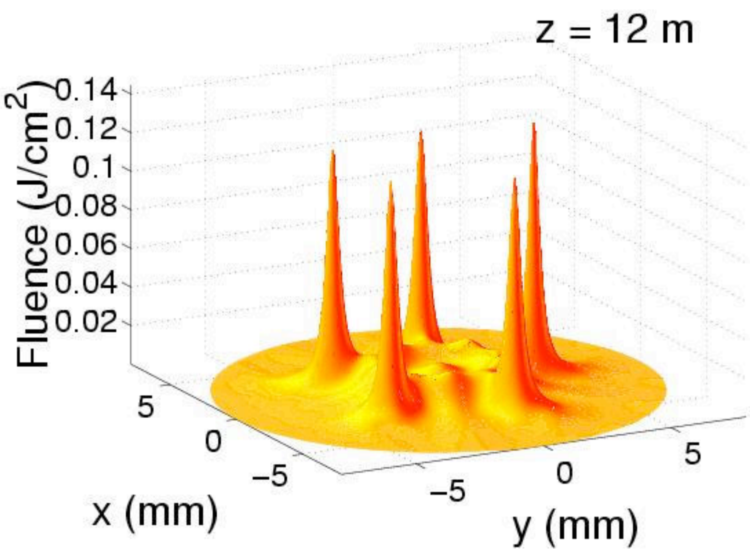
Organization of Filaments

An amplitude mask modifies the input beam (intensity) Mechain et al PRL 2004

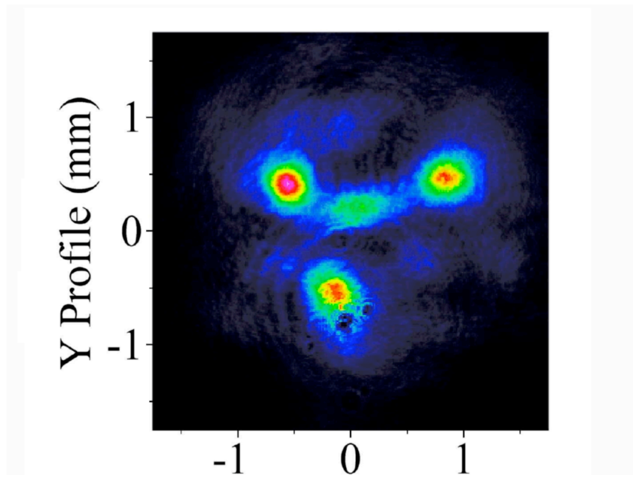
Simulation

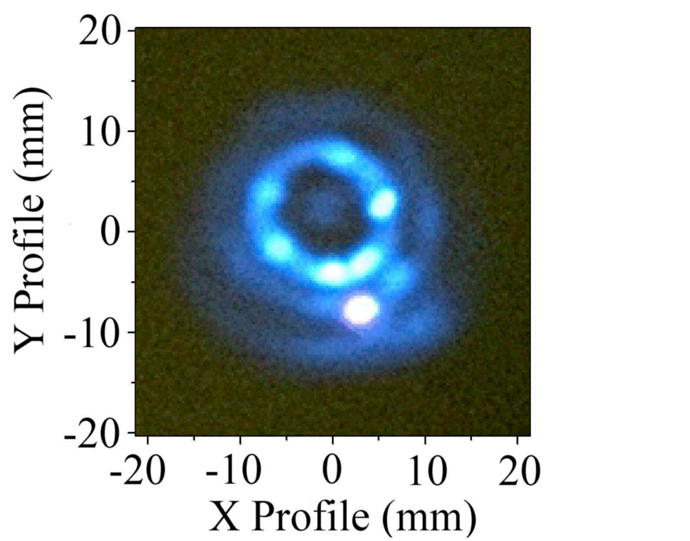






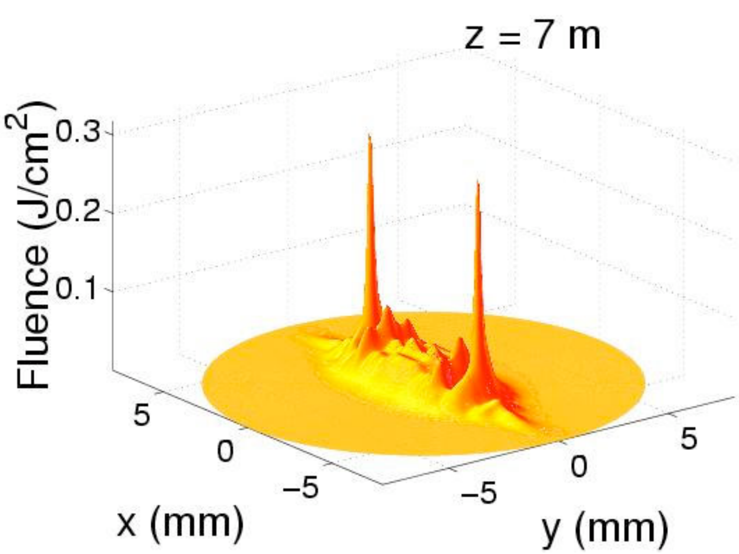
Experiments



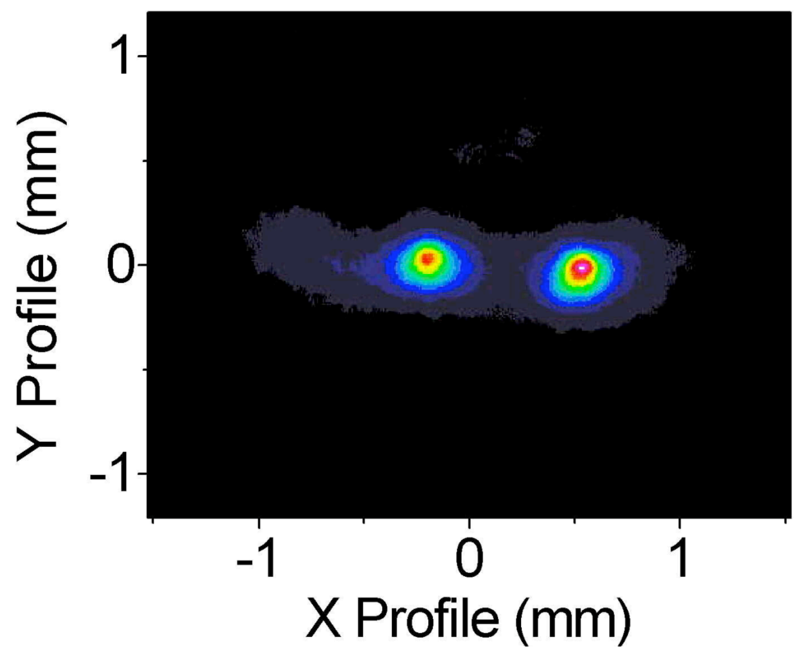


Organization of filaments

Modification of the initial phase : a focusing lens is tilted to induce astigmatism

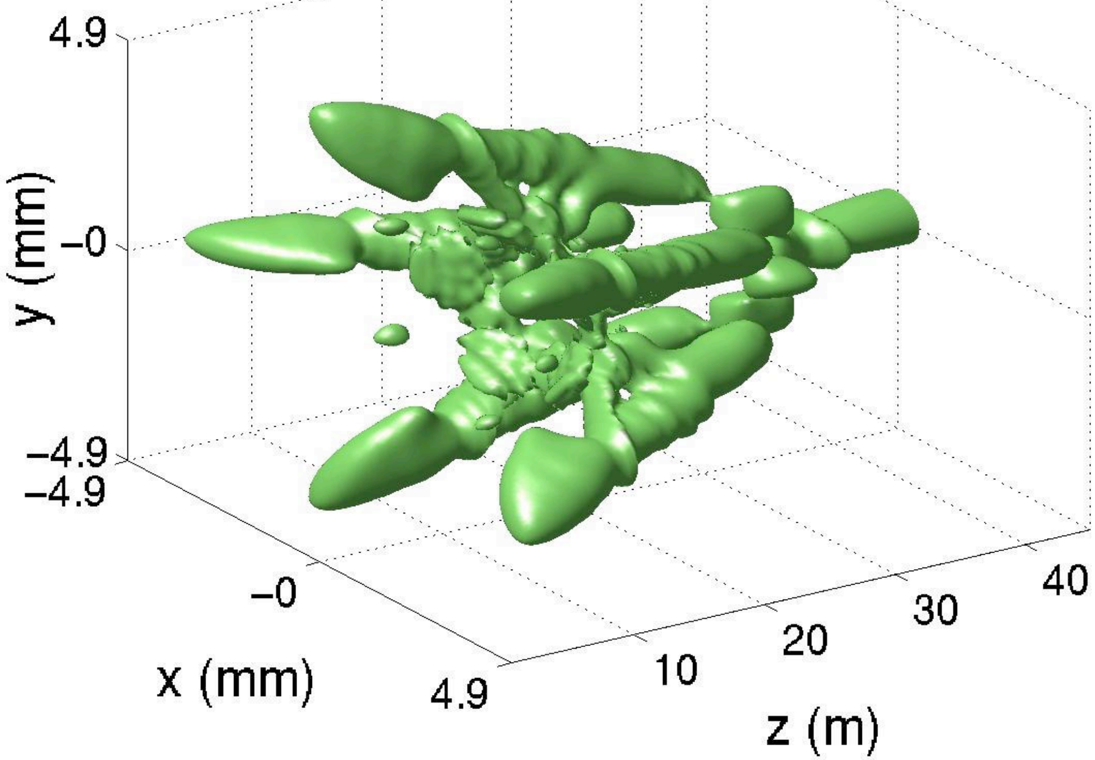


Simulation



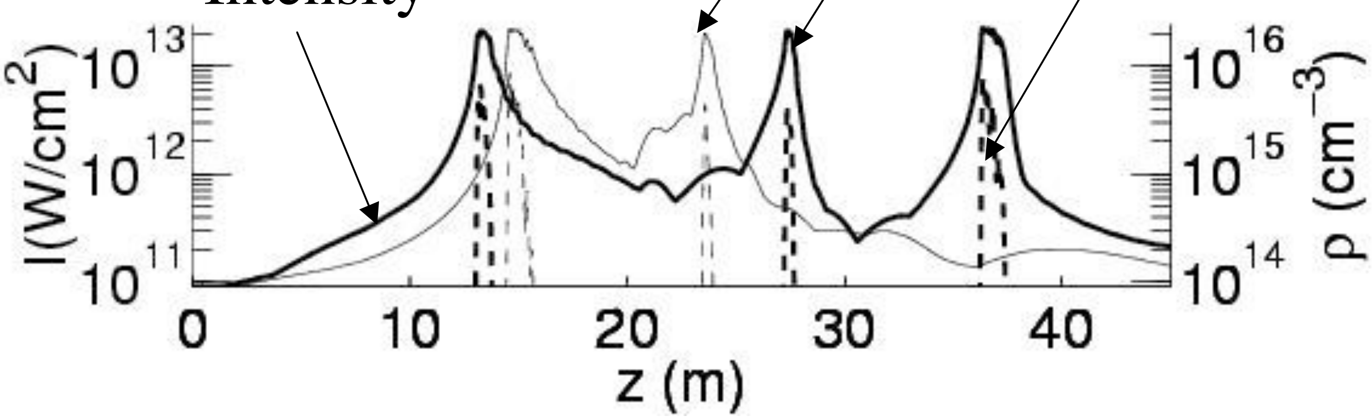
Experiments

Multiple filamentation and coalescence of filaments



Iso surface for the fluence distribution $0.02\ J/cm^2$

Phys. Rev. Lett**.** **93** 035003 (2004).



Single cycle pulse generation by filamentation - Conclusions

- *Filamentation in a low pressure argon gas cell generates single cycle pulses*
- *Energy of a few hundreds of mJ from a 1 mJ, 25 fs pulse*
- *Excellent beam quality - preserves CEO phase-locking*
- *A pressure gradient simplifies the process and avoid using chirped mirrors for recompression*
- *Efficiency as good as the hollow fiber compression technique*