Filamentation: past and present

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Early History of light filamentation

- Askar'yan (1962): Effect of Δn on beam propagation
- Hercher (1964): Laser damage tracks in solid
- Chiao et al, Talanov (1964): Self-trapping model
- Talanov, Kelley (1965): Self-focusing distance
- Wang, Garmire et al (1966): Verification of self-focusing
- Chiao et al (1966): Multiple (self-trapped) filaments
- Bespalov & Talanov (1966): Modulation instabililty
- Marburger & Wagner (1967), Lugovoi & Prokhorov (1968): Suggestion of moving focus
- Loy & Shen(1969), Zverov et al(1970), Korobkin et al(1970): Verification of moving focus
- Hellwarth (1970), Yablonovitch & Bloembergen (1972): Diameter of filaments, ionization
- Alfano & Shapiro (1970): Broadband continuum

Recent advances of fs filamentation single filaments P~Pcr

- Michigan (1995): First evidence of filamentation in air
- Jena (1997); LOA(1997): Evidence of plasma channels
- Laval (1999): Clean fluorescence
- LOA (2001): Filaments in solids
- Lithuanian (2003) : Filamentation in water
- LOA (2002, 2007) : THz emission from filaments
- Cornell (2003), LOA (2006): Townes mode profile, Selfcleaning
- Zurich (2004): Pulse compression by filamentation
- Moscow, Laval, Lyon, LOA (2002-2009) Effect of air turbulence
- Tucson (2009); Heraklion (2011): Airy beam curved filaments
- Laval, 2003; Texas, 2011: Laser in the sky

Recent advances of light filamentation (theory)

- Kandidov, Kosareva, Moscow
- Moloney, Kolesik, Tucson; multifilaments
- Brabec, Krausz: nonlinear envelope Schrodinger equation: applicable to few cycle pulses
- Couairon, Berge
- di Trapani and colleagues, Vilnius
- Akozbek , Bowden

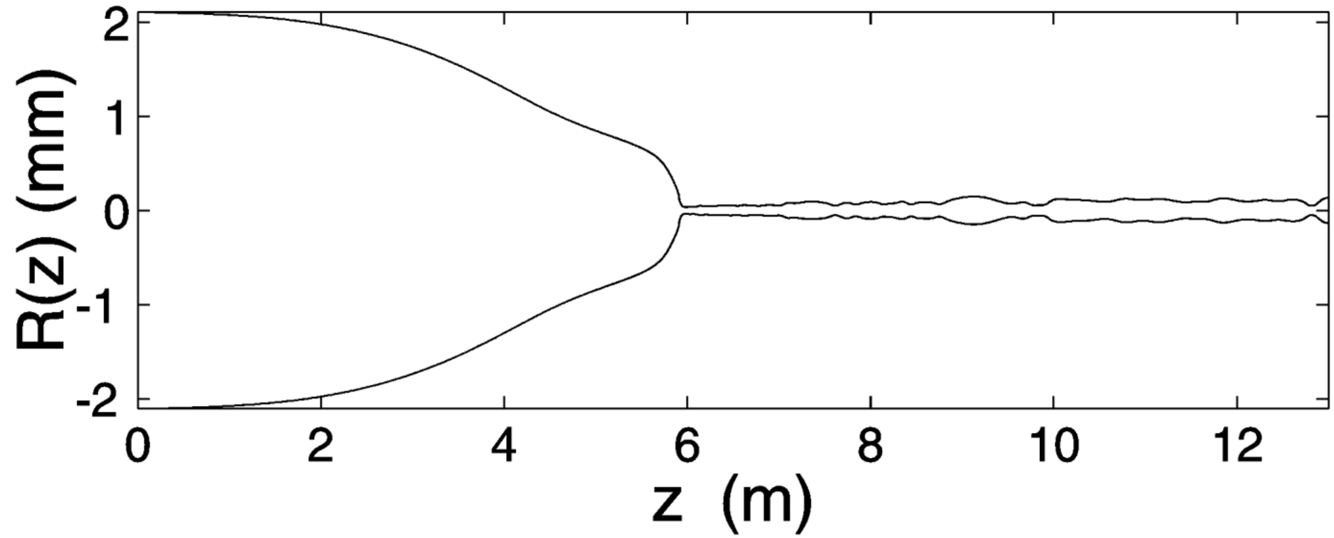
Physical mechanisms – Simulation:

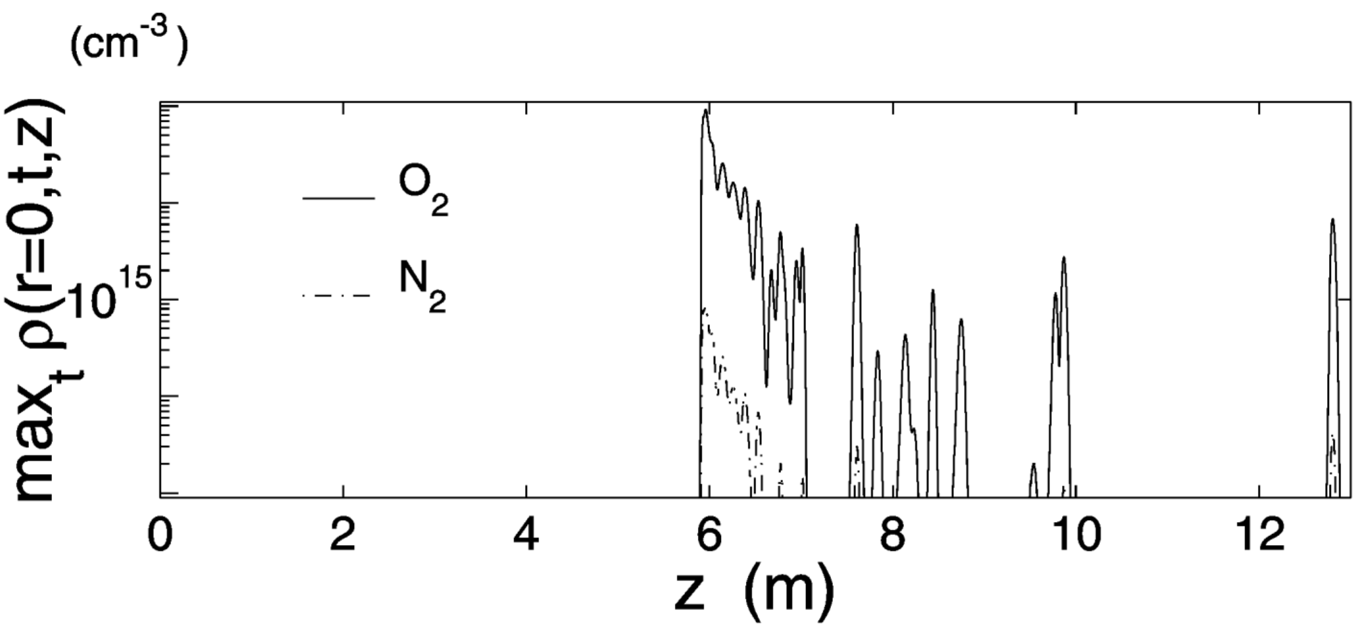
- Optical Kerr effect versus Transverse Diffraction $\rightarrow$ Self-Focusing ($P_{in} > P_{cr}$)
- Multi-Photon Absorption
- Defocusing due to Multi-Photon Ionization
- Group-Velocity Dispersion
- Avalanche ionization
- Self-steepening and space-time focusing

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

Collimated beam propagation: simulation

A. Couairon





Filamentation

LOA '96

Laser beam filamentation

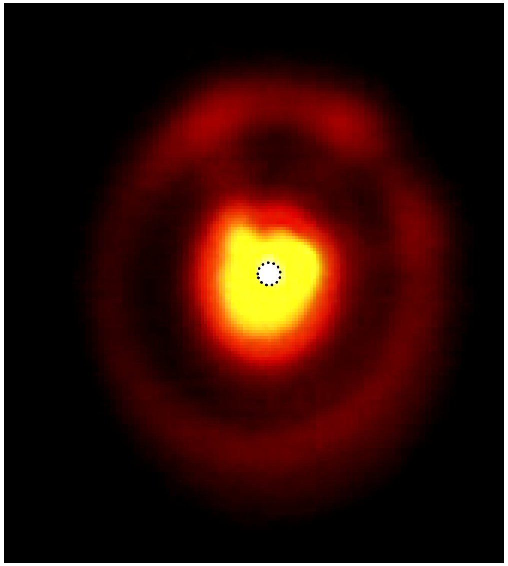


Photo at 50 m

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

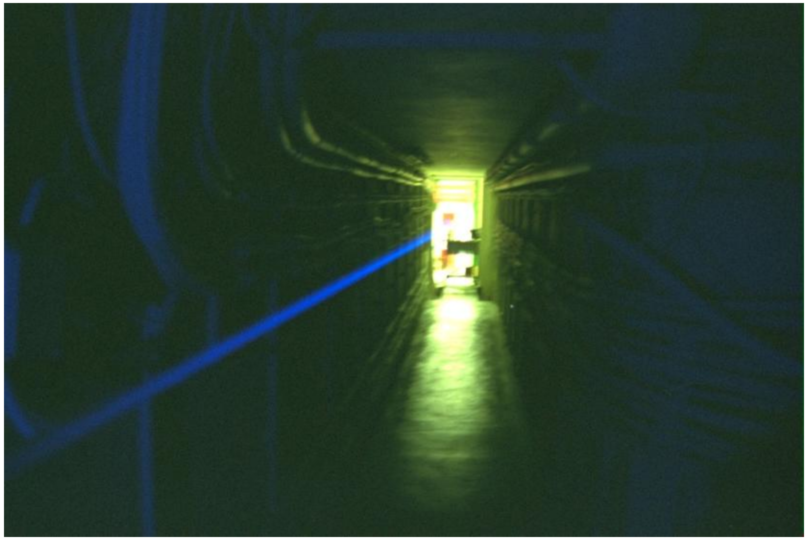
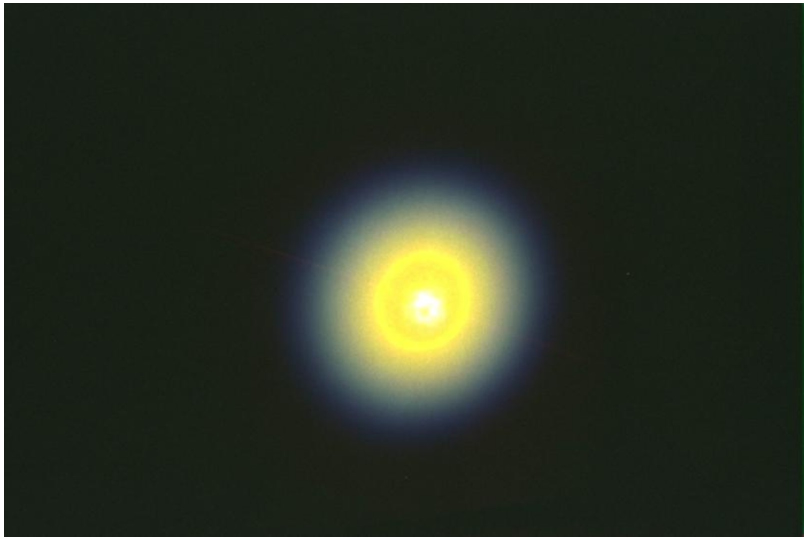
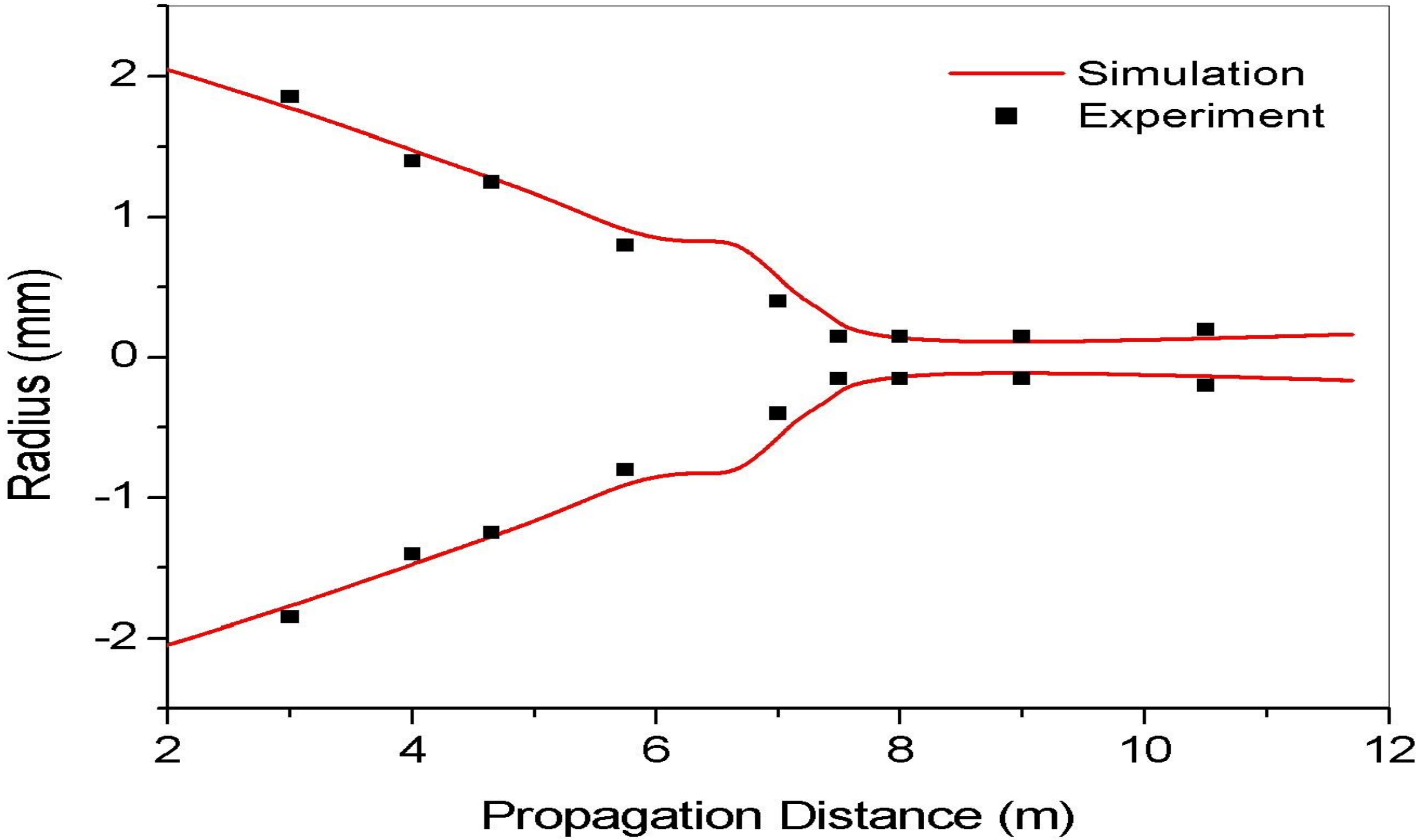


Photo at 50 m

Blue Filament (400nm)



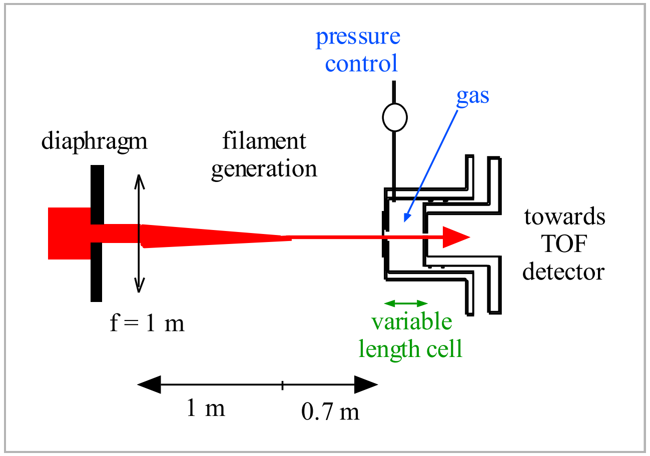
Experiment vs. simulation

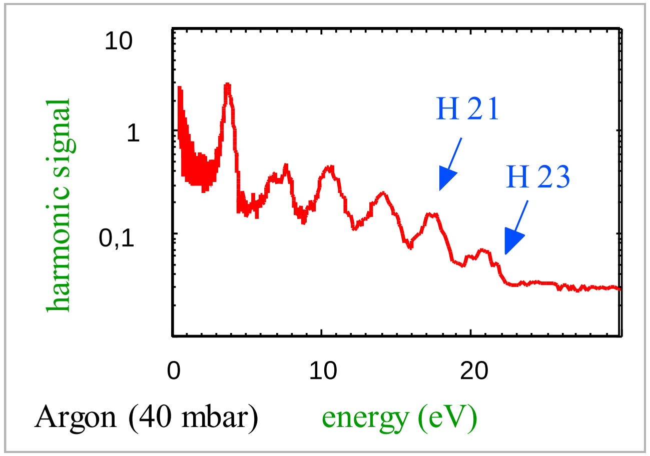


Opt. Lett. **25**, 1270 (2000) measured at FORTH, Heraklion

Measurement of the IR filament Intensity

High order harmonics generation





$h\nu = I_p + 3.2\ U_p$

I_p ionisation potential

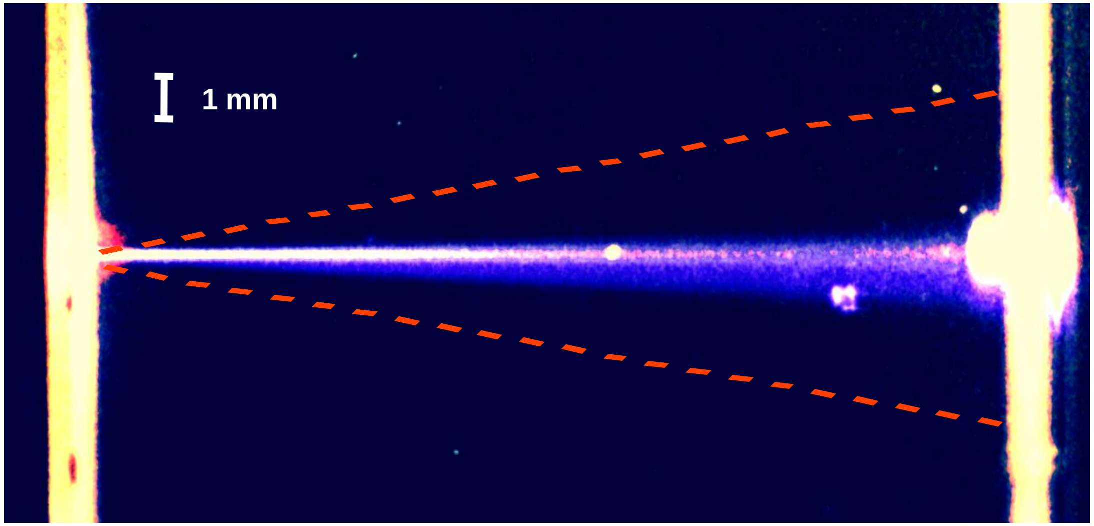
U_p ponderomotive energy

Up=9,.33 10-14 Iλ²

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

Filamentation in a transparent solid (fused silica)

filament length **100 times** **the Rayleigh distance**



λ = 800 nm

E = 1.5 μJ

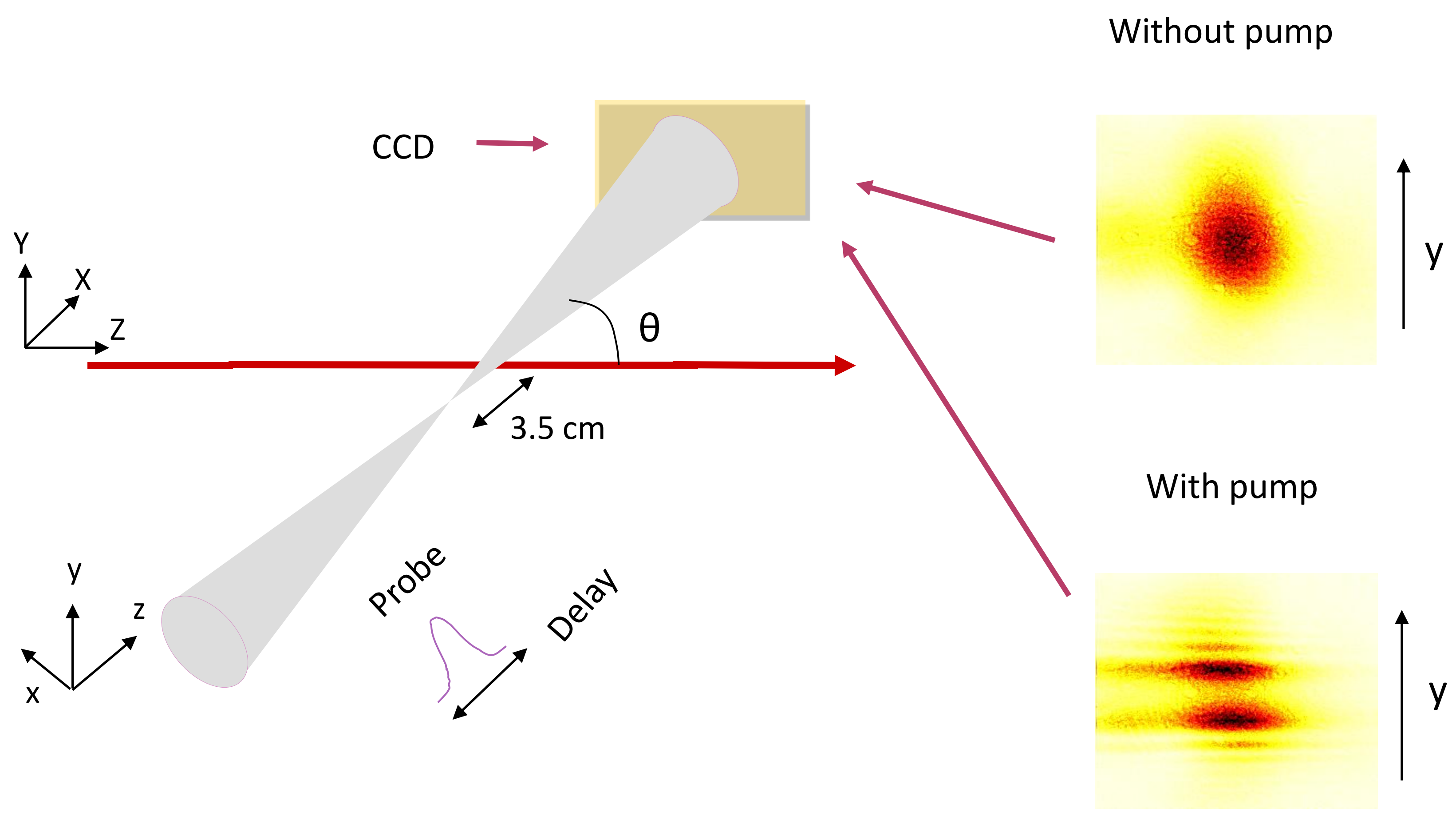
τ = 150 fs

ω_0 = 4 mm

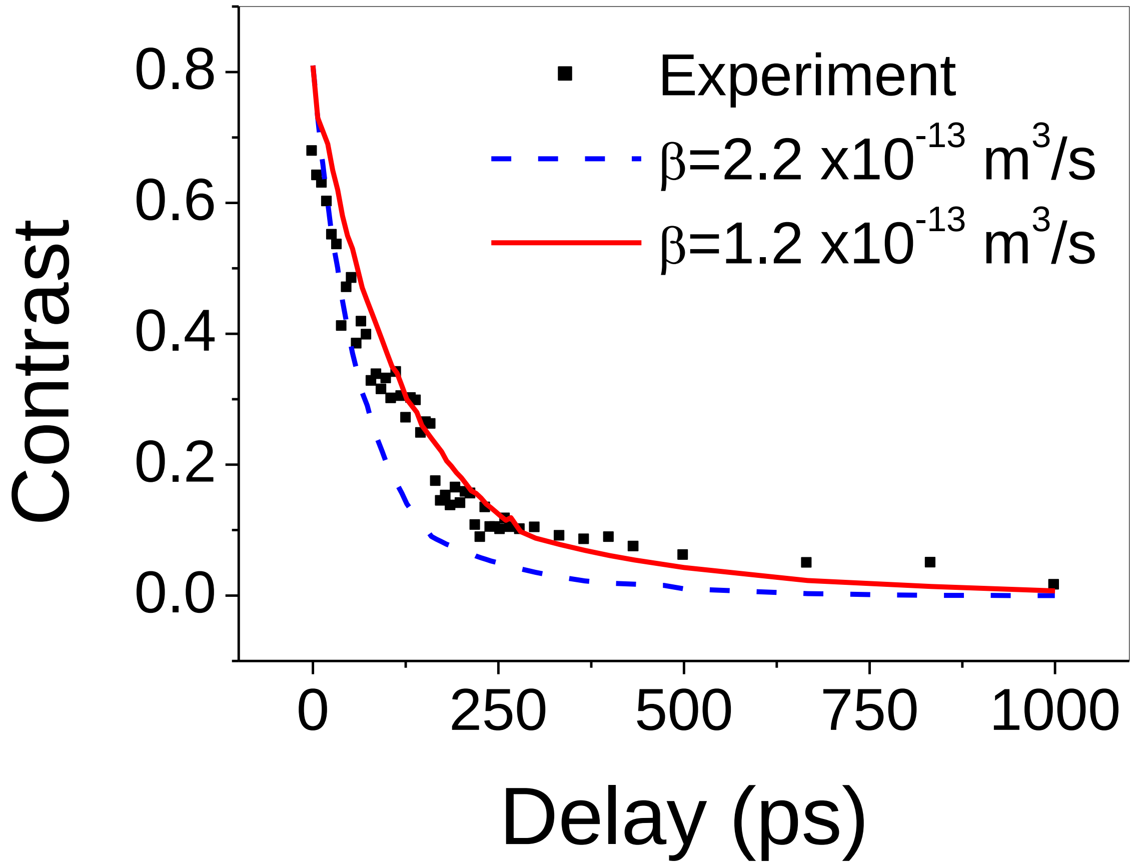
LOA - X - ENSTA

Plasma density in air filaments

Time-resolved optical diffractometry



Experiment vs. Simulation



- $n_e(t) = \frac{1}{\alpha + \beta t}$
- $n_{e0} = 2 \times 10^{17}\ \mathrm{cm}^{-3}$

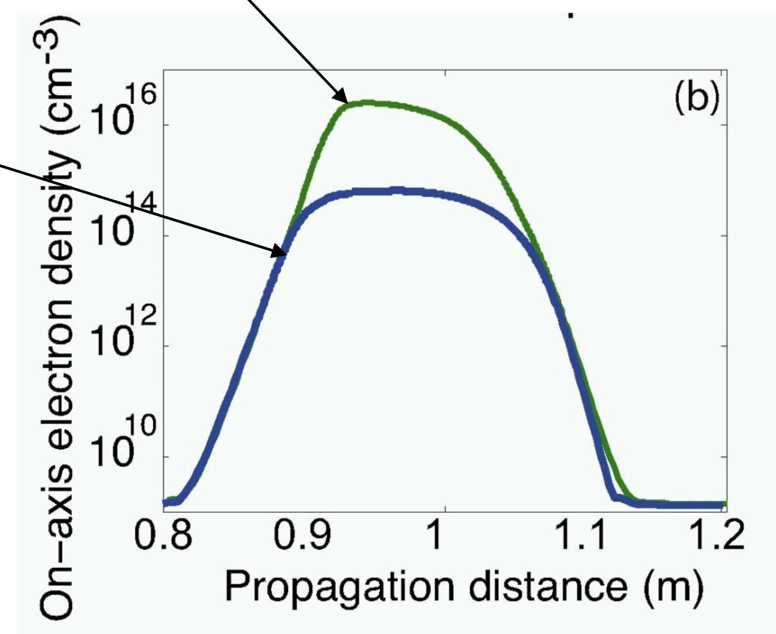
Controversy about saturation mechanism

Controversy following measurements of n2 by Loriot et al (Optics Express 17, 13429 (2009))
Cross over from positive to negative non linear index at high intensities

<0 **>0** **<0**

HOKE model with
$\Delta n_{Kerr} = n_2 I + n_4 I^2 + n_6 I^3 + n_8 I^4 + \ldots$

Plasma model

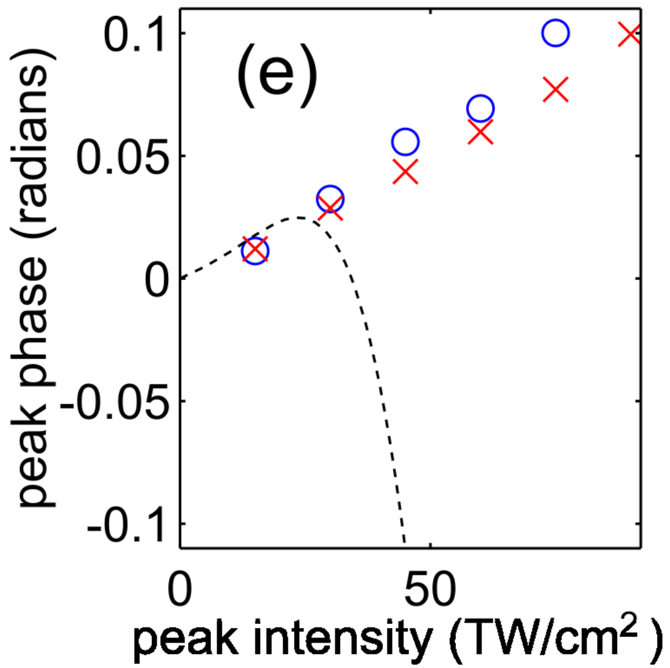


This would lead to a revision of filament picture: the saturation of n2 is the key player, plasma plays a minor role
Plasma density should be lower by factor 40

Bejot *et al.*, PRL 104 103903 (2010)

However, J. K. Wahlstrand, et al. fail to measure the saturation of n2 reported by Bejot et al.

arXiv:1105.6334v2 [physics.optics] 29 Jun 2011



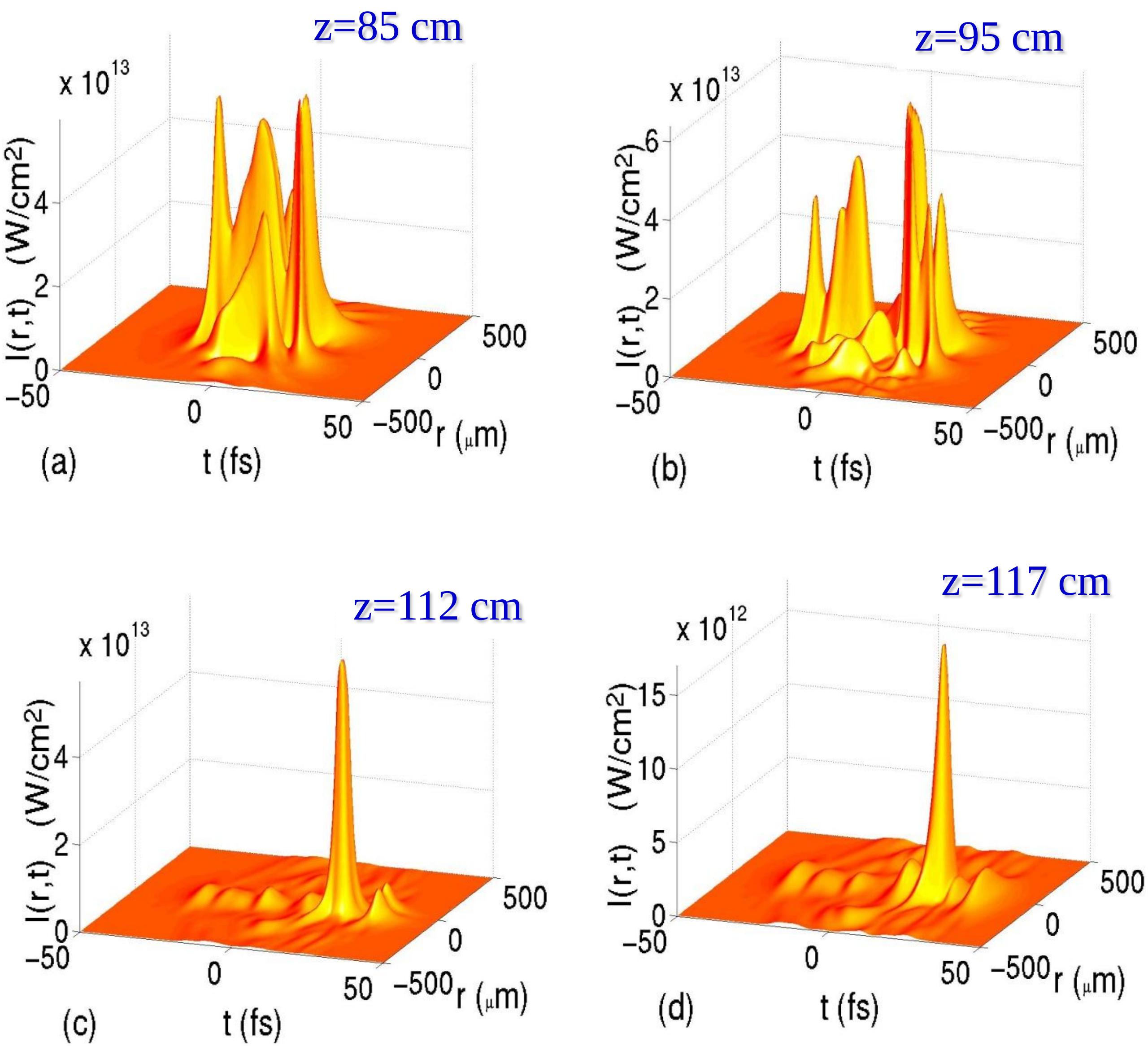
Also, recent measurements of plasma density in filaments are consistent with the traditional model

Y.-H. Chen, et al. Phys. Rev. Lett. 105, 215005 (2010)
Rodriguez et al.

Pulse self-compression

Simulations show that pulse self compression occurs during filamentation

Detailed space-time intensity profiles



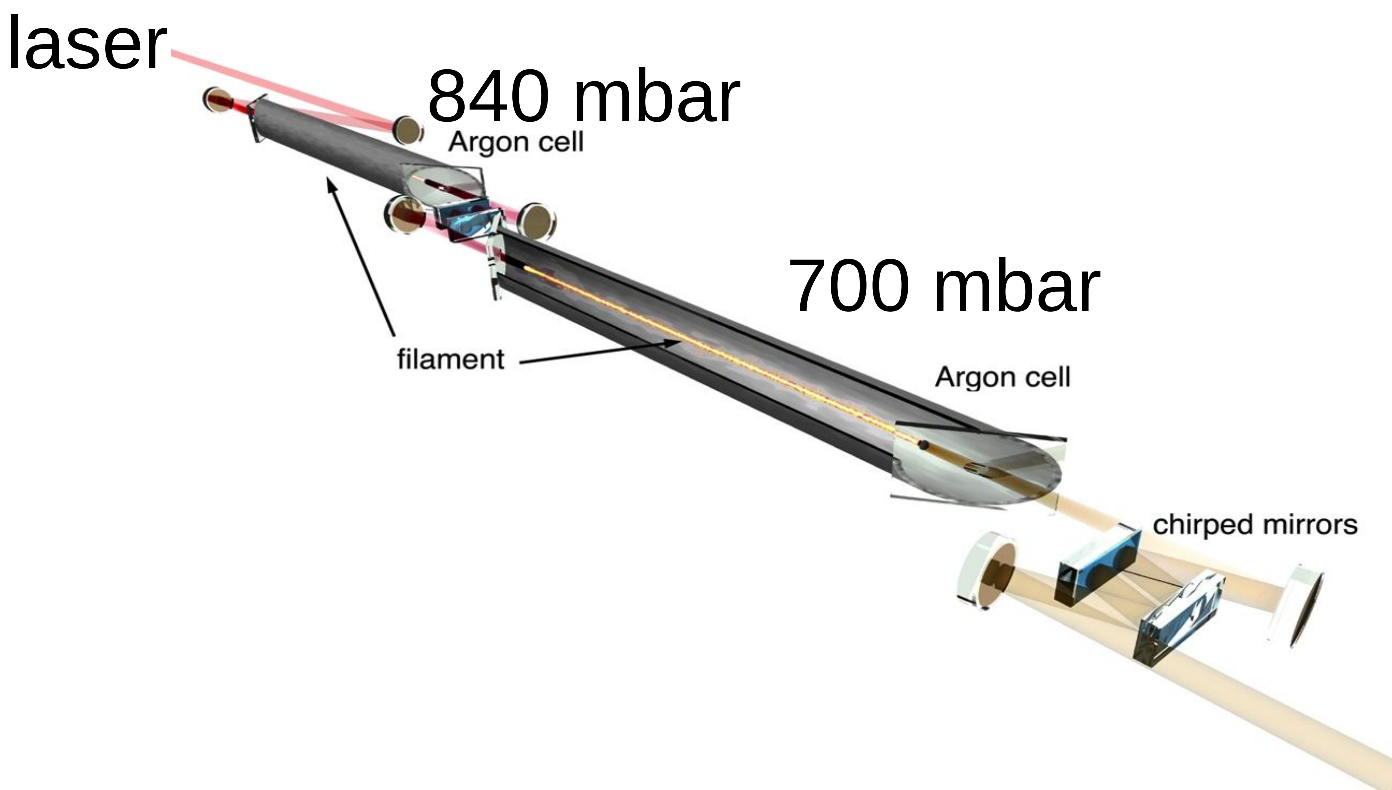
J. Mod. Optics **53**, 75 (2006)

3 fs in an isolated structure

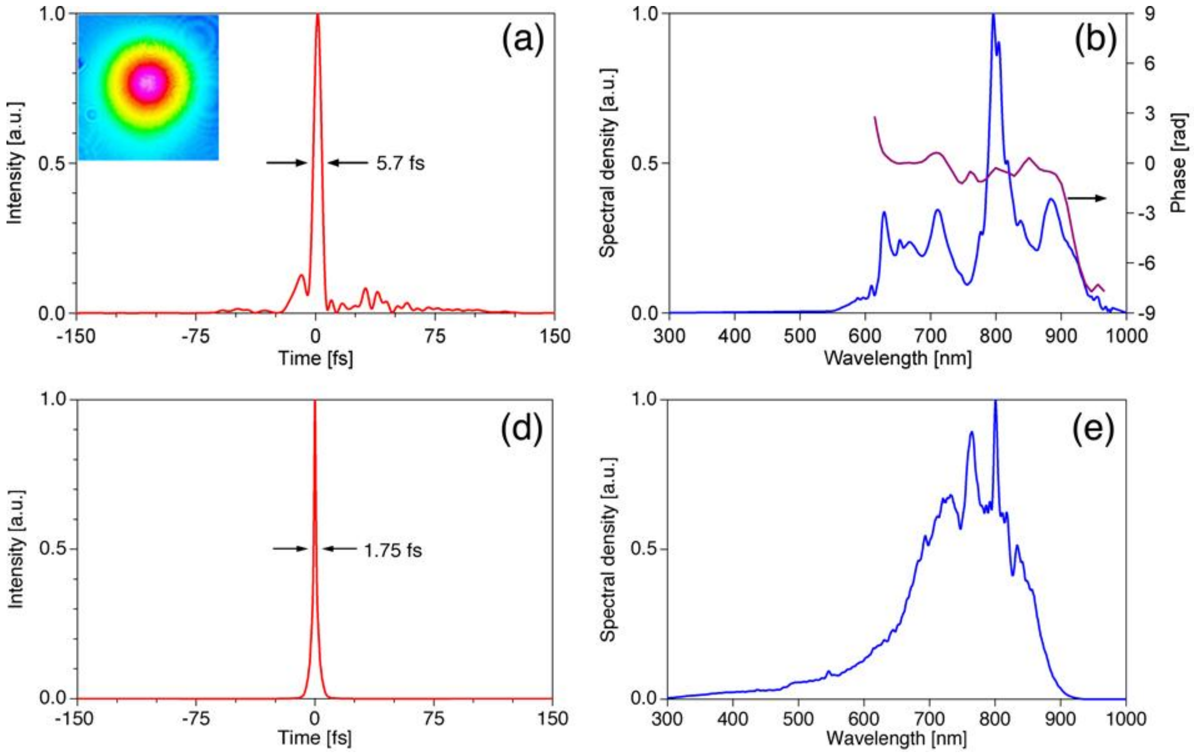
Self-compression of laser pulses by filamentation in argon gas cell at low pressure

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

Experiments at ETH Zurich



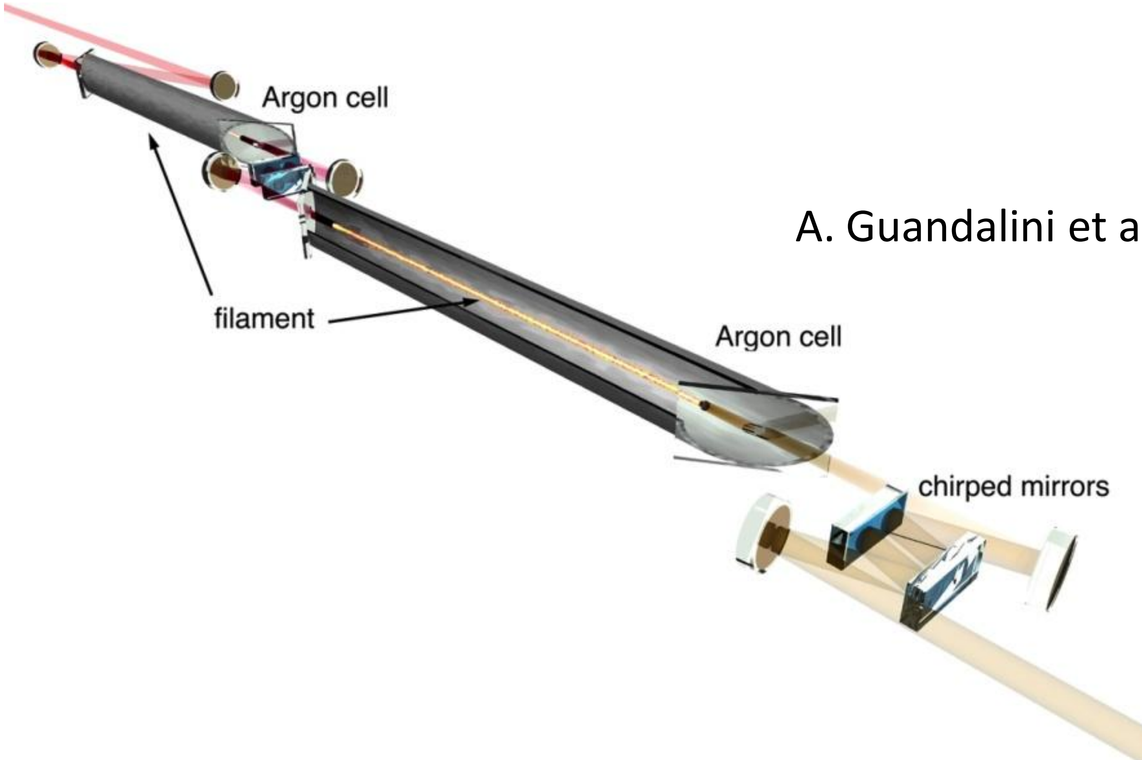
Pulse after filamentation,
(H. Hauri, J. et al. ETH, Zurich, A. Couairon et al. Palaiseau Applied Physics B 2004)



Spectrum recorded before chirped mirrors suggests single cycle pulse should be possible

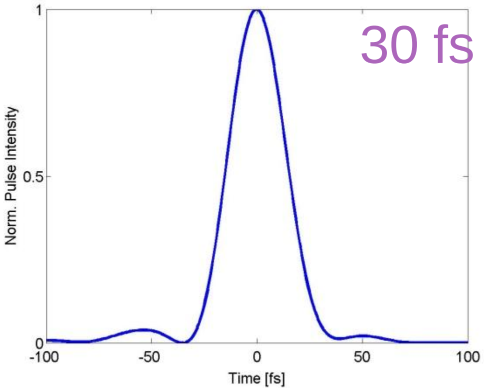
0.66 mJ

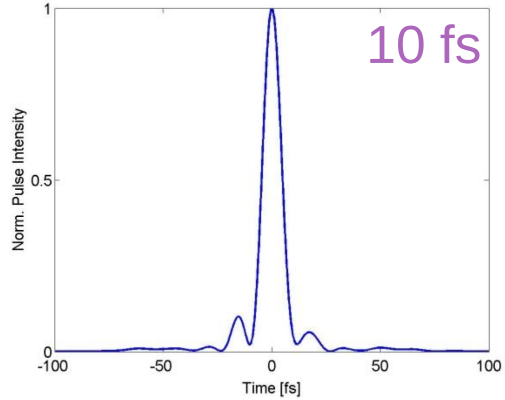
Compressed Output

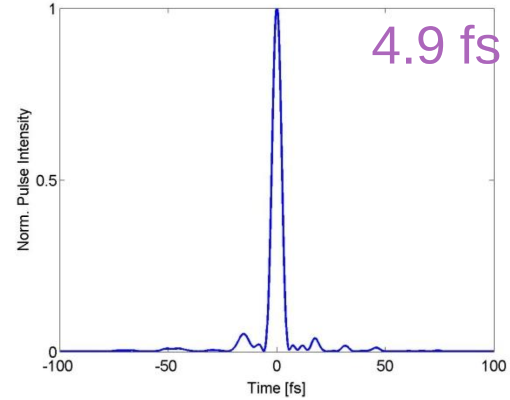


A. Guandalini et al., J. Phys. B. *39,* S257 (2006)

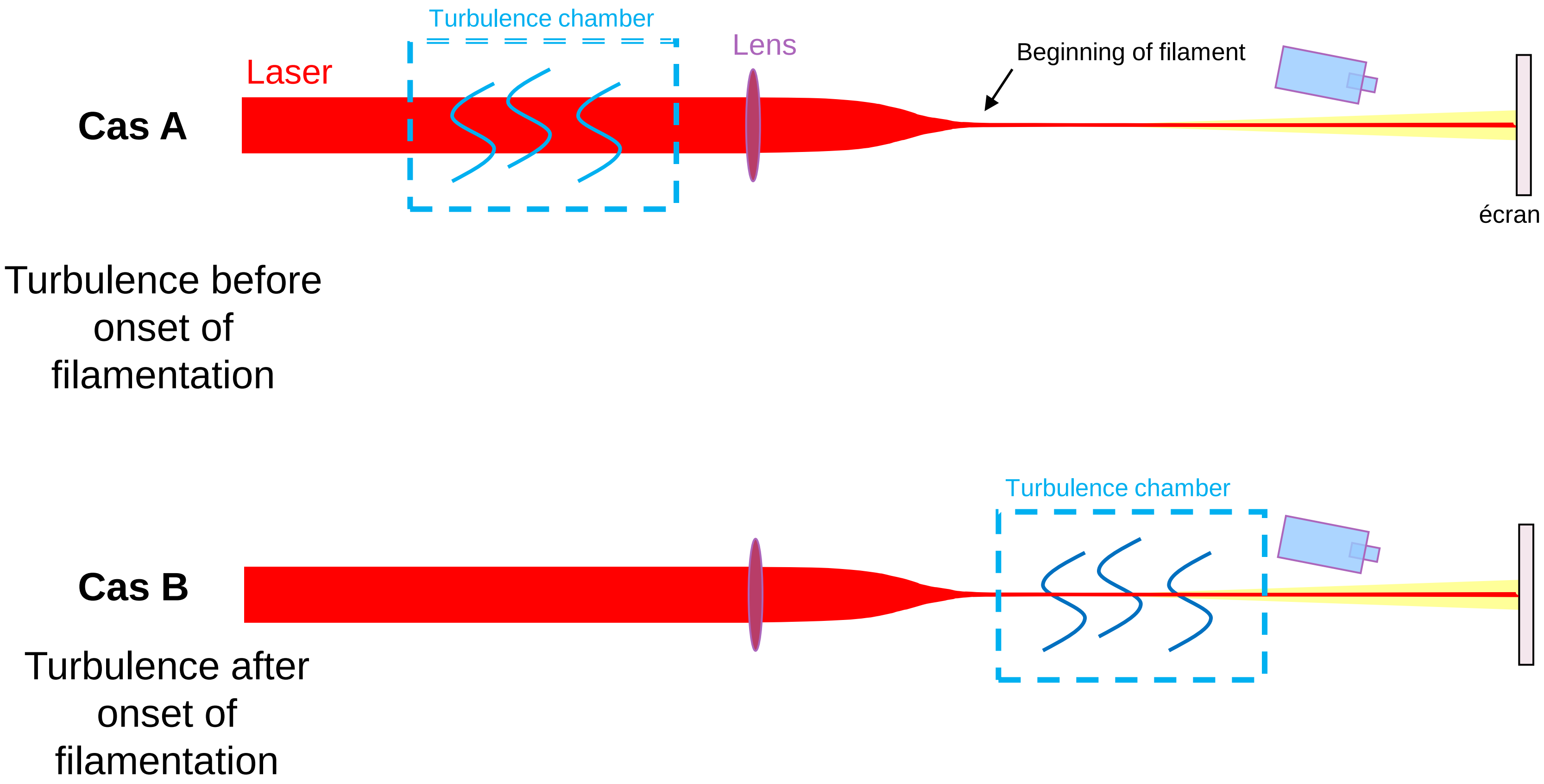
4.9 fs, 0.12 mJ (core part), 18% transmission





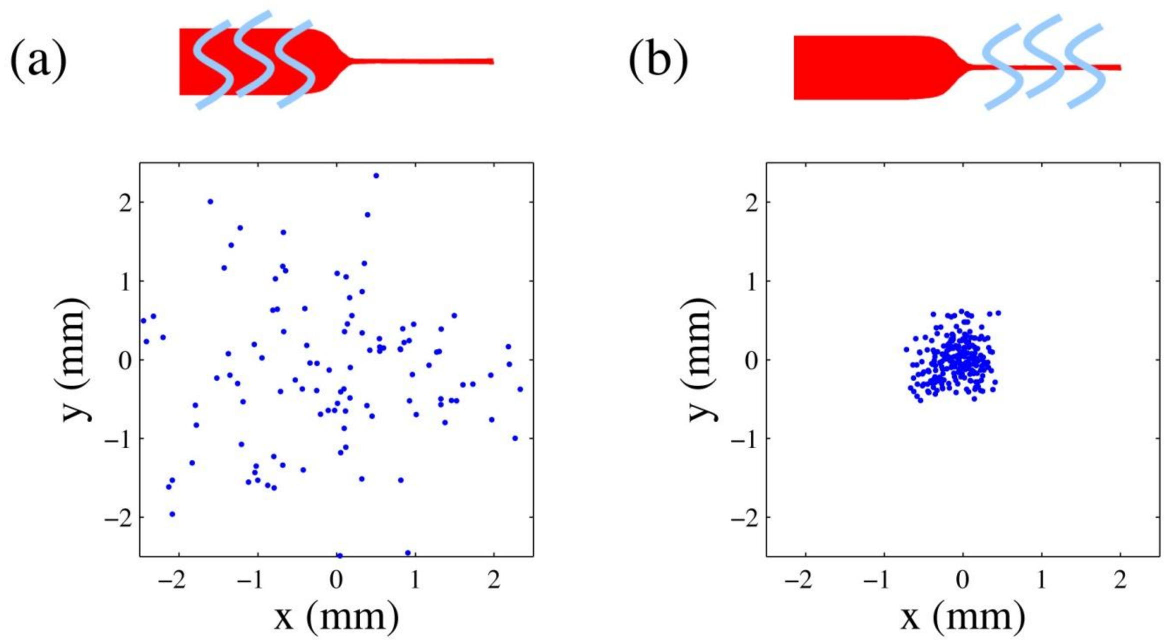


Influence of air turbulence



Effect of air turbulence on pointing stability

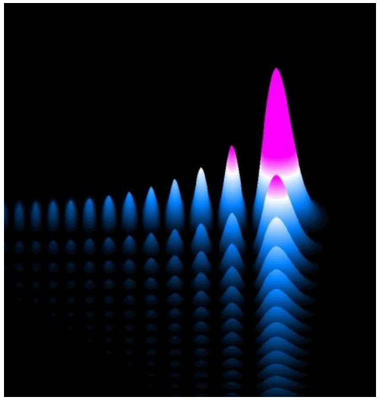
$$C_n^2 = 1.7 \times 10^{-11} m^{-2/3}$$

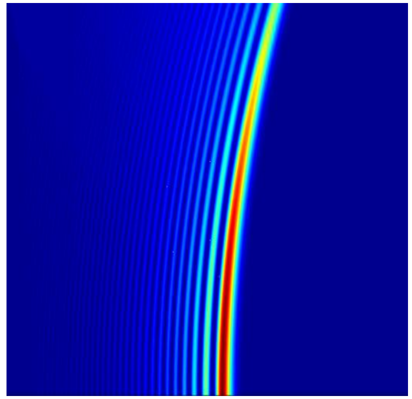


Cas A

Cas B

Airy beams resist diffraction and self-bend on propagation in free space

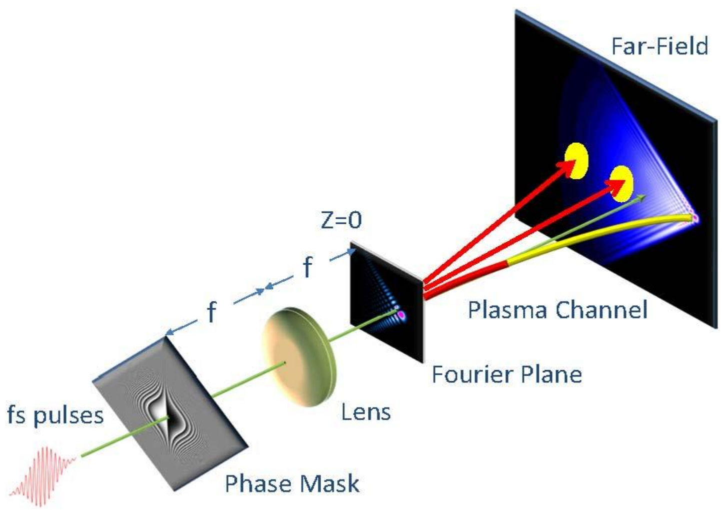




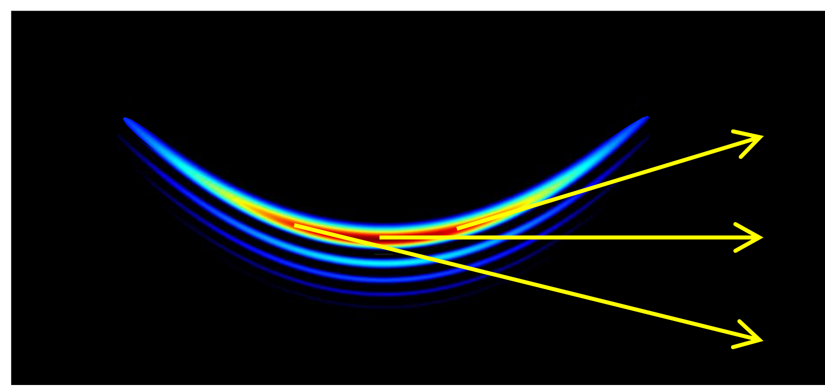
Introduced by D. Christodoulides and co-workers at the University of Central Florida in 2007:

G. Siviloglou, A. Dogariu, D. Christodoulides, PRL, vol. 99, p. 213901 (2007)

Experiments on filamentation of femtosecond Airy beams: University of Arizona, 2009



Forward white-light emission propagates along angularly resolved trajectories

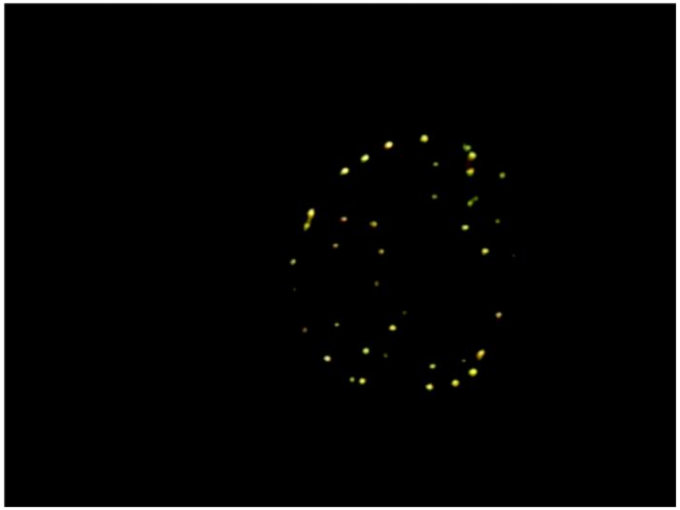


P. Polynkin, M. Kolesik, J. Moloney, G. Siviloglou, D. Christodoulides, Science, vol. 324, p. 229 (2009)

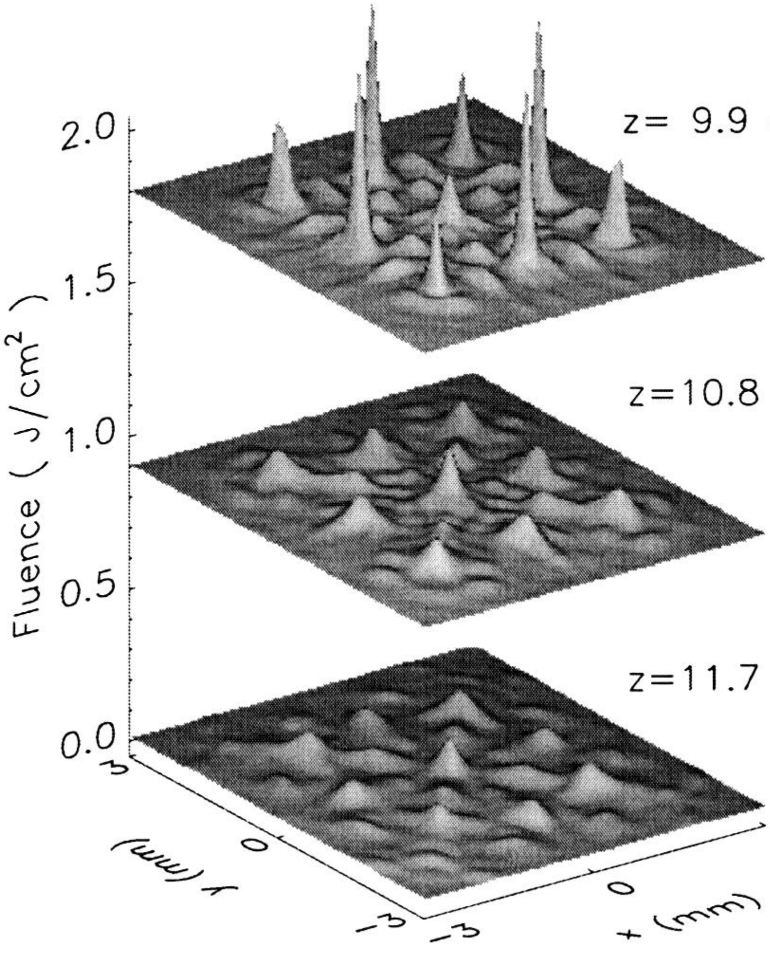
Recent advances of fs filamentation multi filaments P>>Pcr

• Tucson (1999):	Multifilaments, replenishment model
• Jena, (2000):	km long white continuum propagation
• Jerusalem (2004), LOA (2004):	km long ionization path
• LOA , Laval, Vilnius (2004):	Organization of multifilaments
• LOA (2004); Salamanca (2005):	Bright channels
• Maryland ; Milano (2008):	Attraction between filaments
•Austin (2009); LOA (2010):	Exchange of energy between filaments

Collimated beam propagation at high input powers

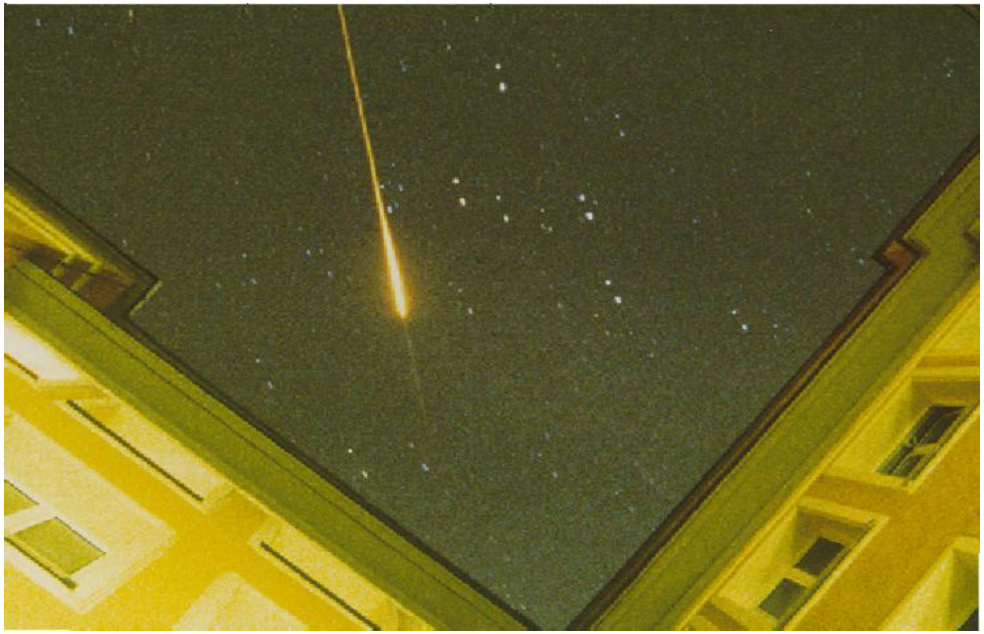


Experiment at LOA
50 fs,150 mJ, 50 M



Simulations (3D): M. Mlejnek *et al*. PRL **83**, 2938 (1999)

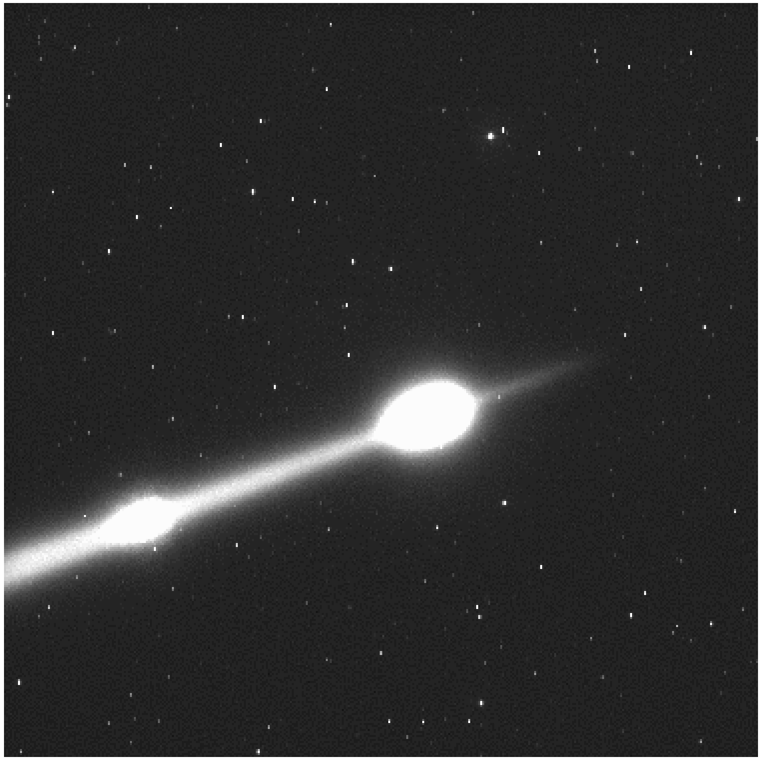
Modulational instability and growth of the inhomogeneities in the input beam (Bespalov & Talanov 1966)



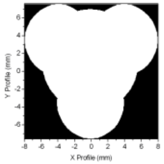
Filaments at 12 km
R. Sauerbrey, L. Woeste
(University Jena, 1997)

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

Teramobile Project

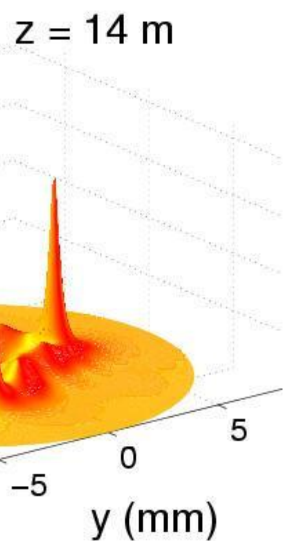


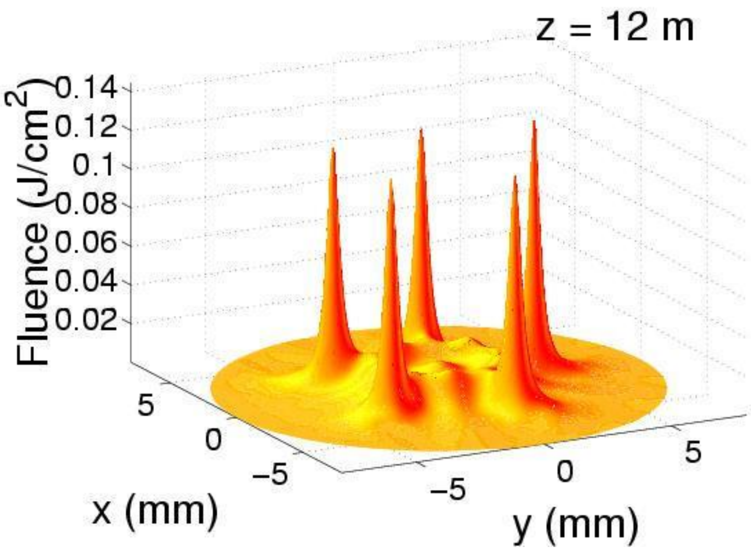
Organization of Filaments



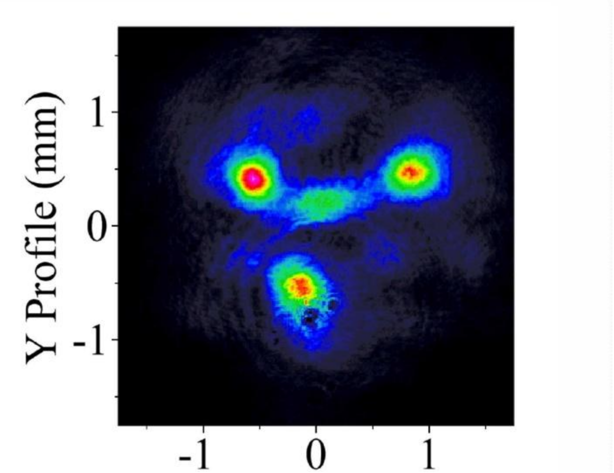
An amplitude mask modifies the input beam intensity

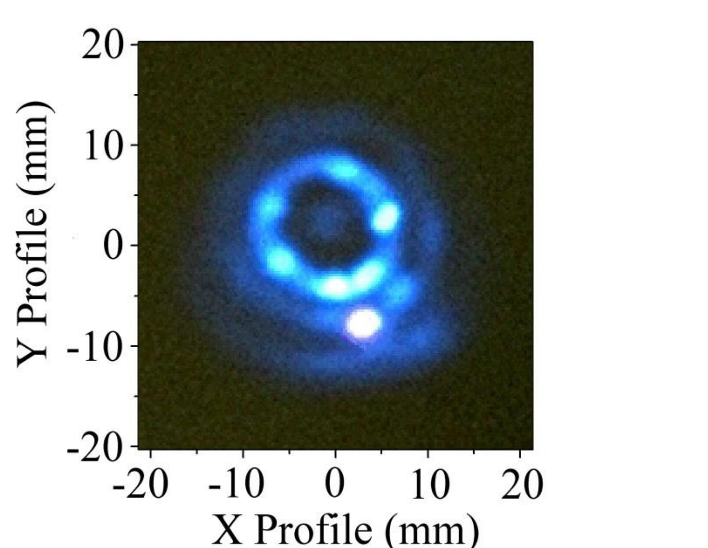
Simulation



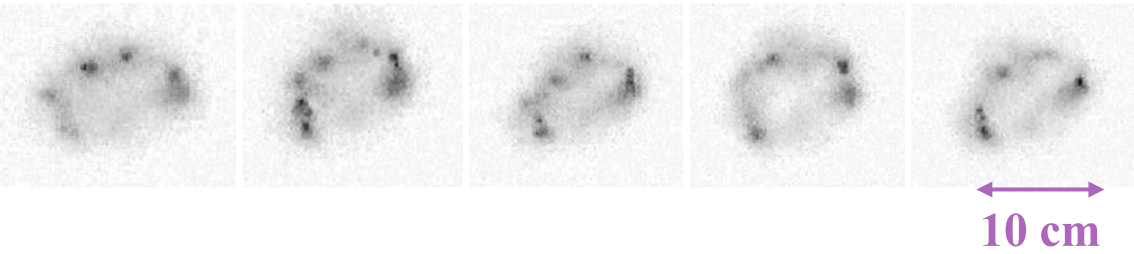


Experiments





Successive laser shots recorded after 830 m



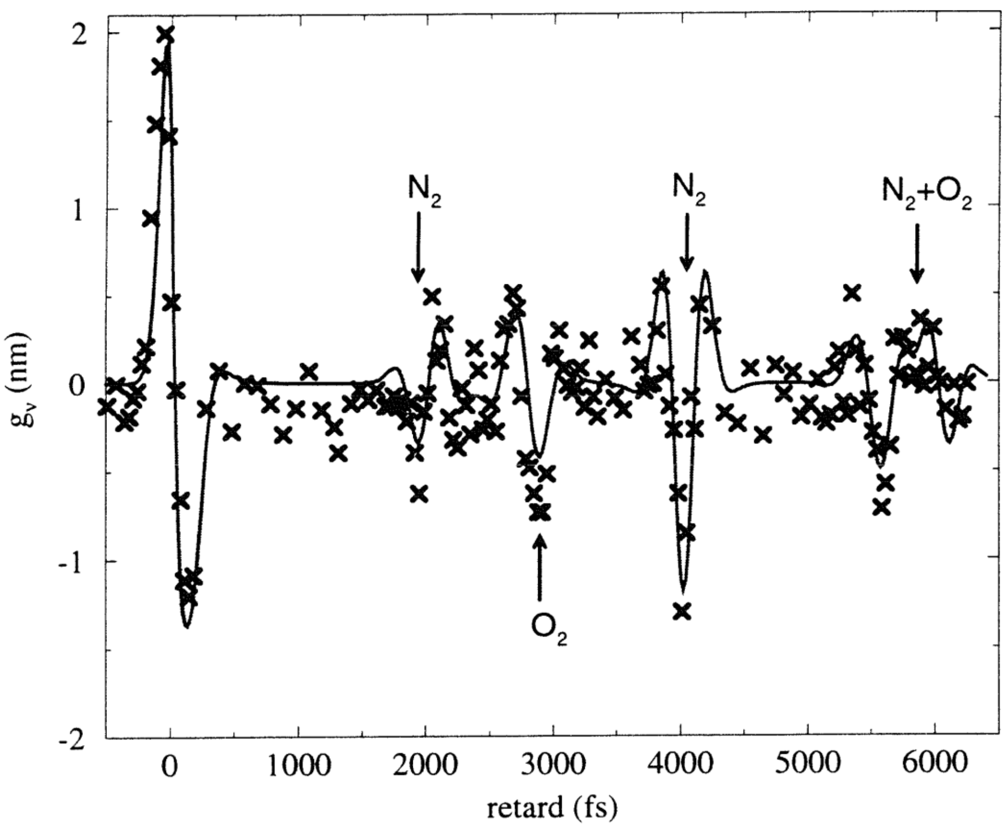
Position of high intensity spots
Reproducible from shot to shot

Supergaussian beam profile explains ring pattern

Remote steering of a filament

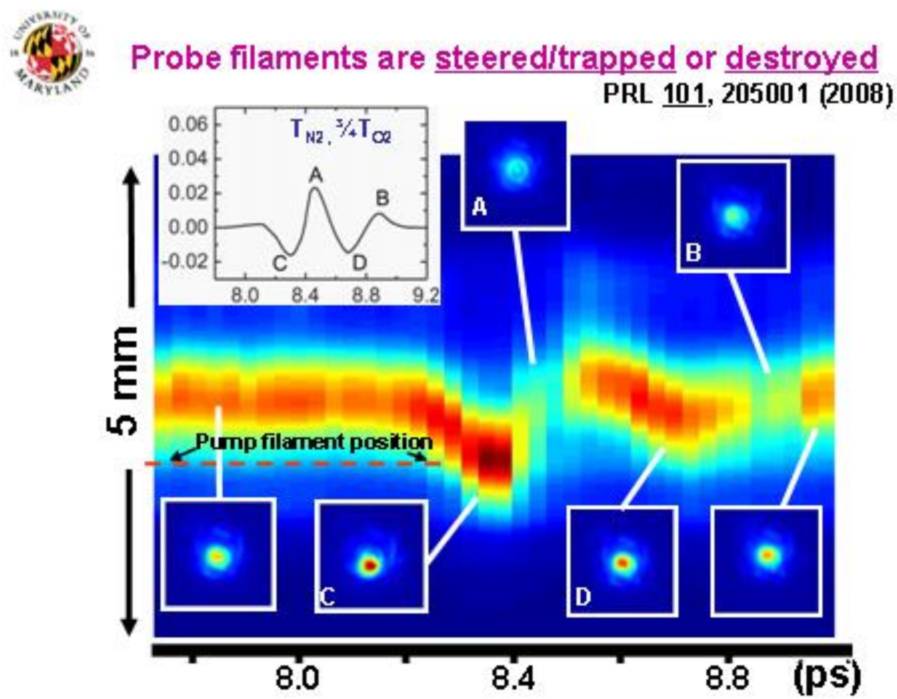
Revivals of n2 in air

Ripoche et al. Optics Comm. 1997



Rotational wave packets revivals

S. Varma, Y. H. Chen, H. M. Milchberg, PRL 101, 205001 (2008)
see also Nisoli et al. PRL (2008)

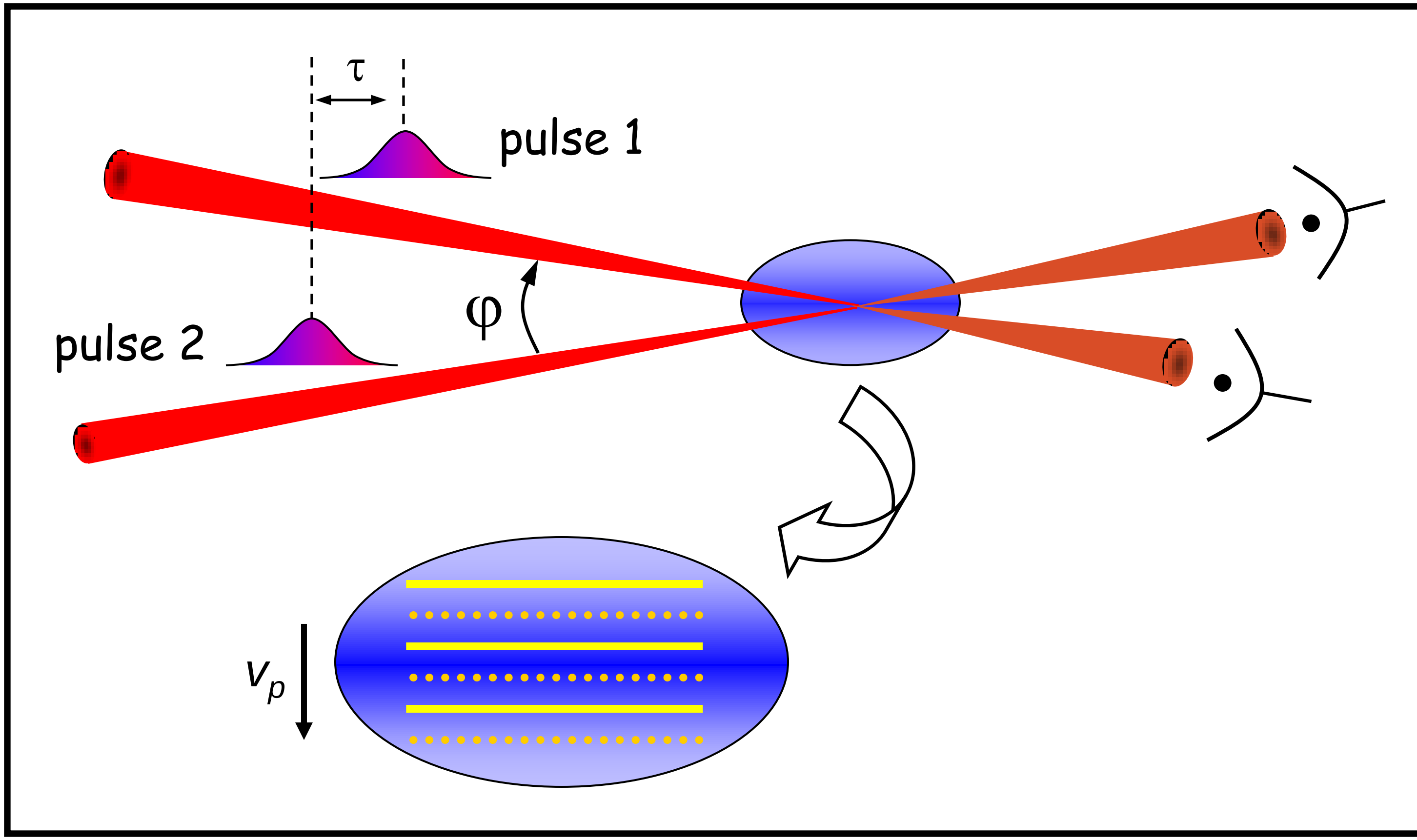


Energy exchange between filaments

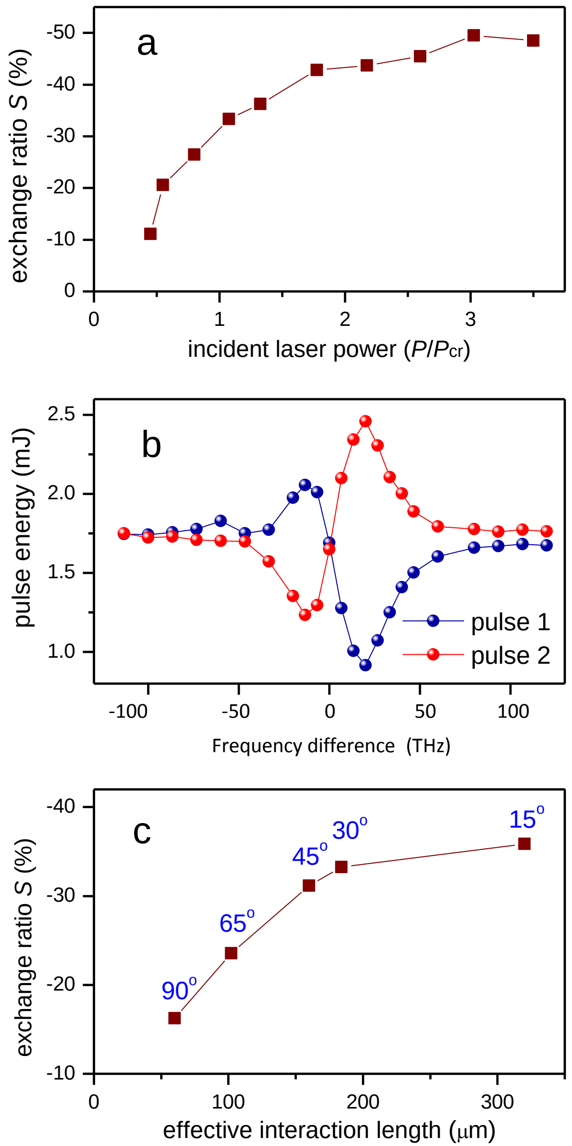
Bernstein et al. Phys. Rev. Lett. 102, 123902(2009)

Yi Liu et al. Phys. Rev. Lett (2010)

Experimental setup



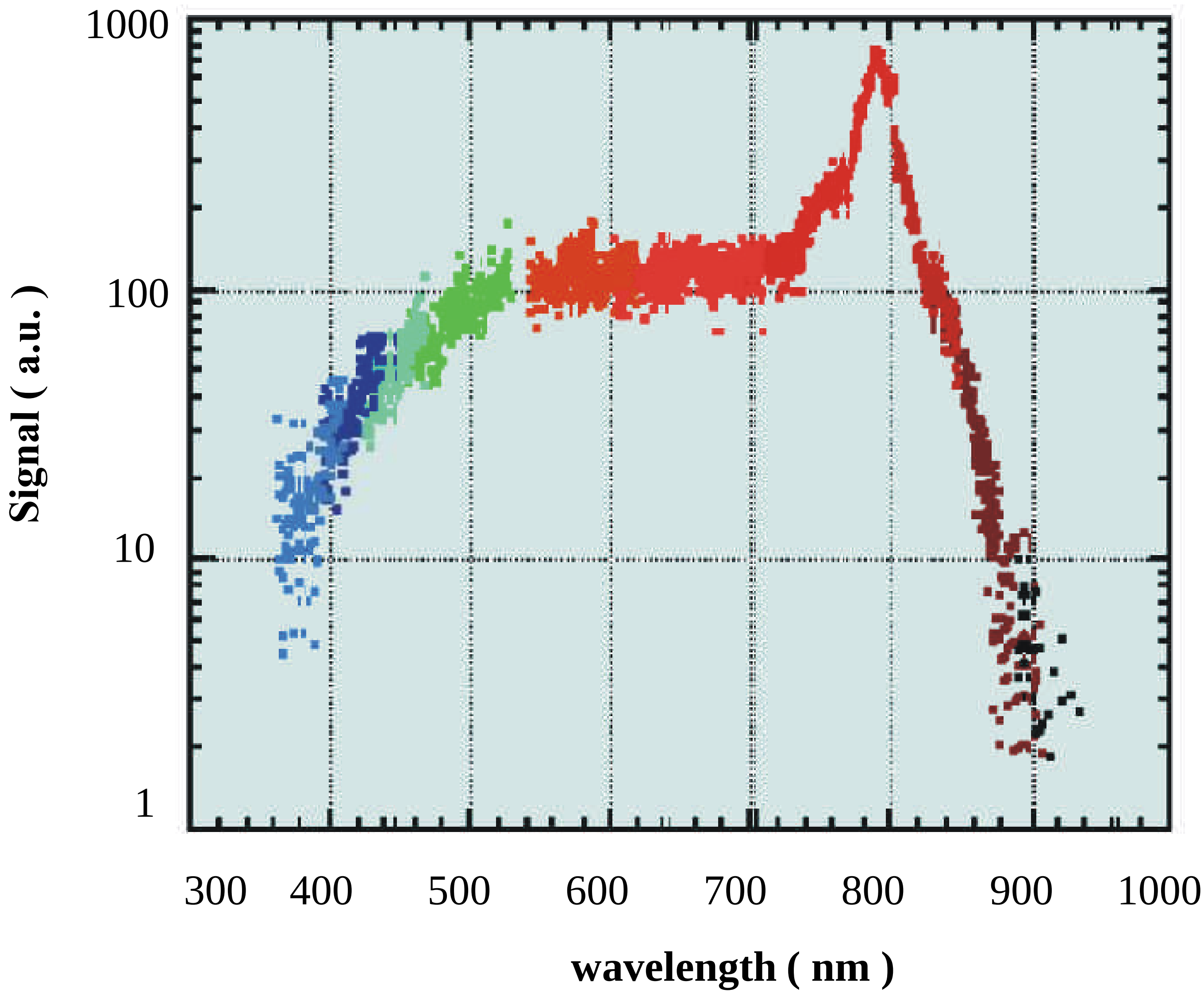
Up to 50% of filament energy can be exchanged !



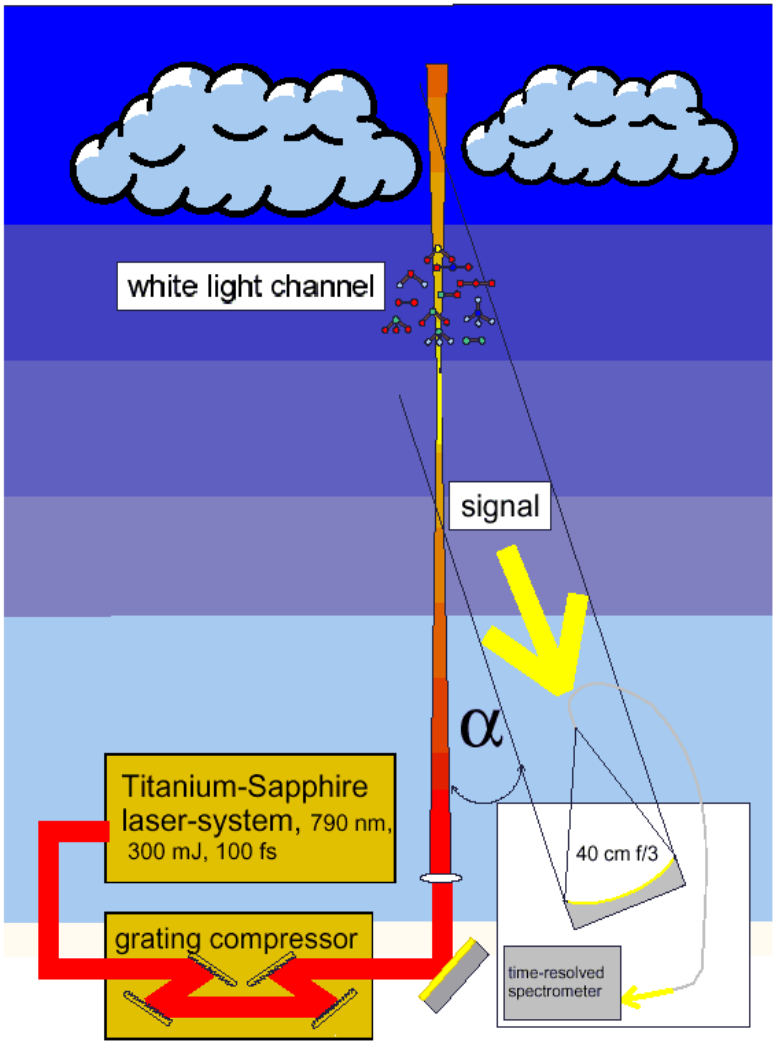
Applications

- Broadband Lidar
- LIBS (light-induced breakdown spectroscopy)
- Triggering of electric discharges
- Secondary source (3d Harmonic in air, High Harmonics, TeraHertz radiation, etc)
- Virtual antenna

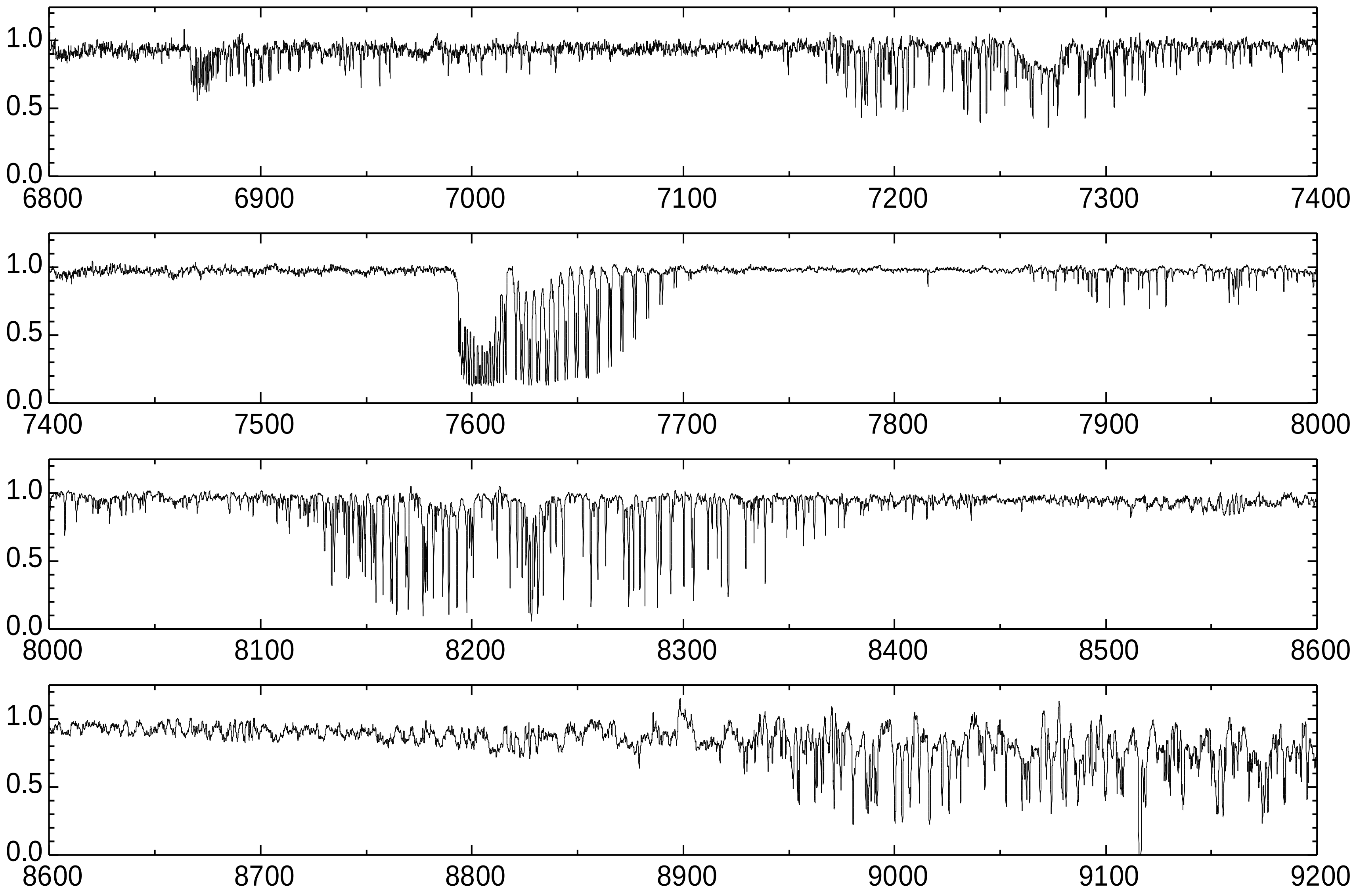
White Light Generation in air



Femtosecond lidar

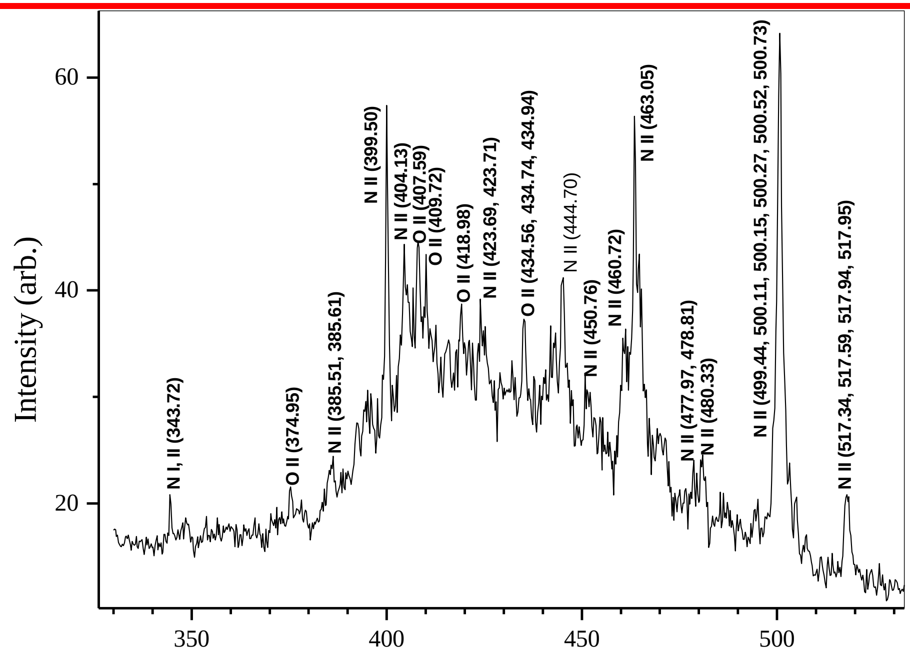


White-light Lidar: atmospheric absorption spectrum

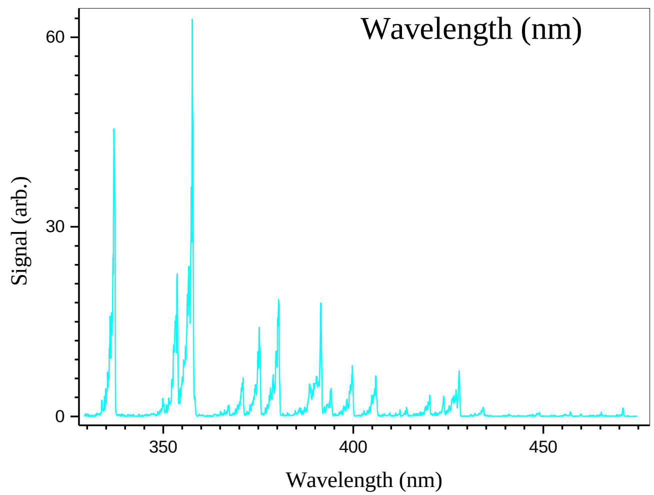


Clean fluorescence

UNIVERSITÉ LAVAL



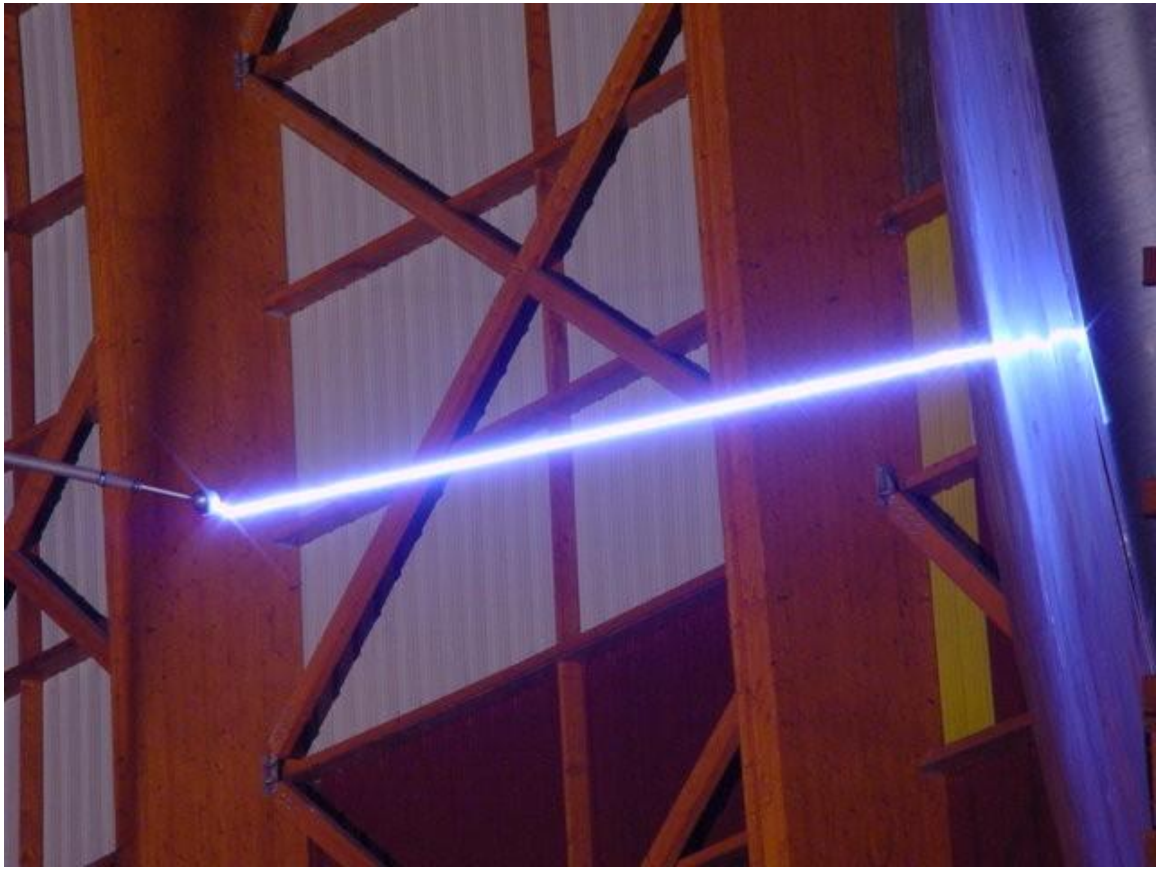
Fluorescence spectrum of air at one atmospheric pressure inside thew breakdown zone induced by a 0.2 ns Ti:Sapphire laser pulse centered at 800nm. It shows the plasma continuum superimposed by spectral lines from excited atoms and atomic ions. This type of fuorescence is typical of all laser induced air breakdown.



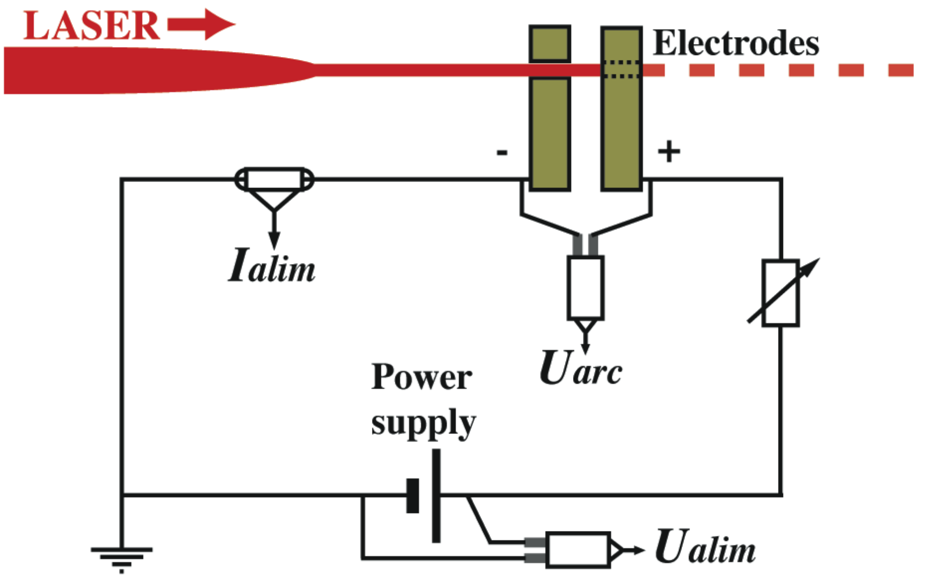
Fluorescence spectrum of air at one atmospheric pressure inside a filament of a 200 fs Ti:Sapphire laser pulse centered at 800nm. It shows the molecular spectrum originated from excited nitrogen molecules and nitrogen molecular ions. No plasma continuum is evident here because the plasma density in the filament is four orders of magnitude lower than that of atmospheric air. We call this clean fluorescence which can be applied to detecting pollutant molecules in the atmosphere.

Triggering, guiding of discharges
and
Capture of currents by filaments

4 m long Guided discharge



Electric Circuit



CW

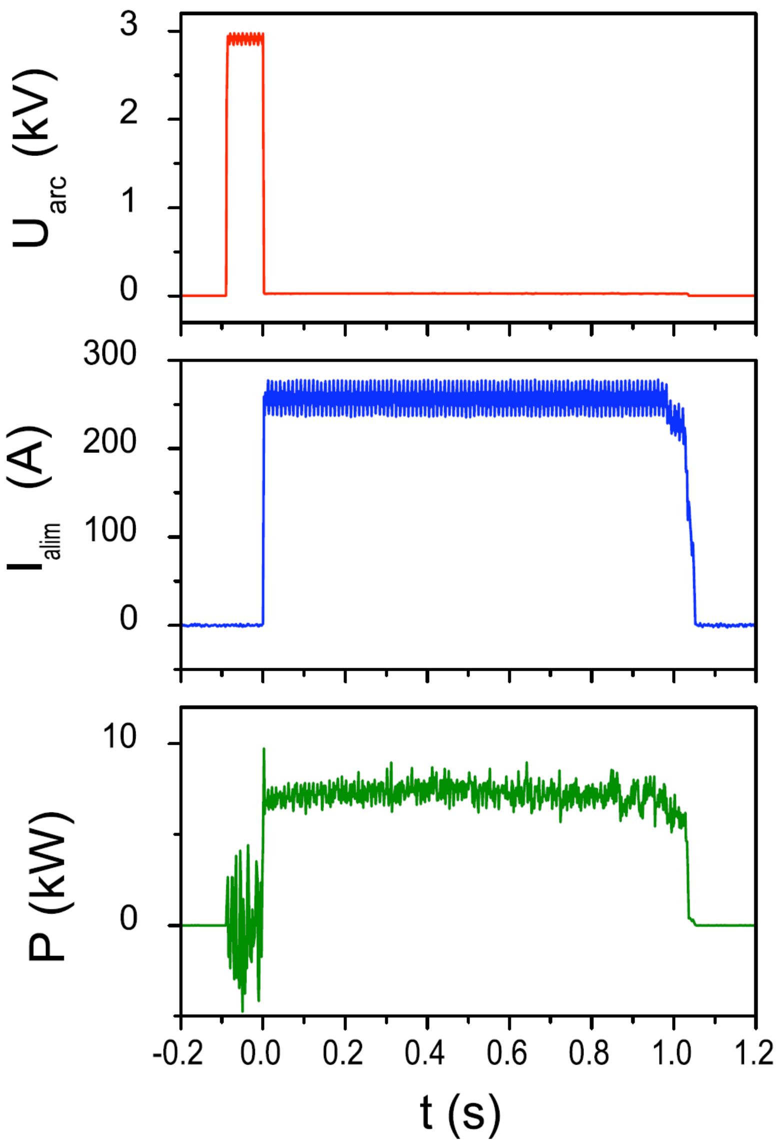
- U_{max} = 4kV
- I_{max} = 400 A

AC (50 Hz)

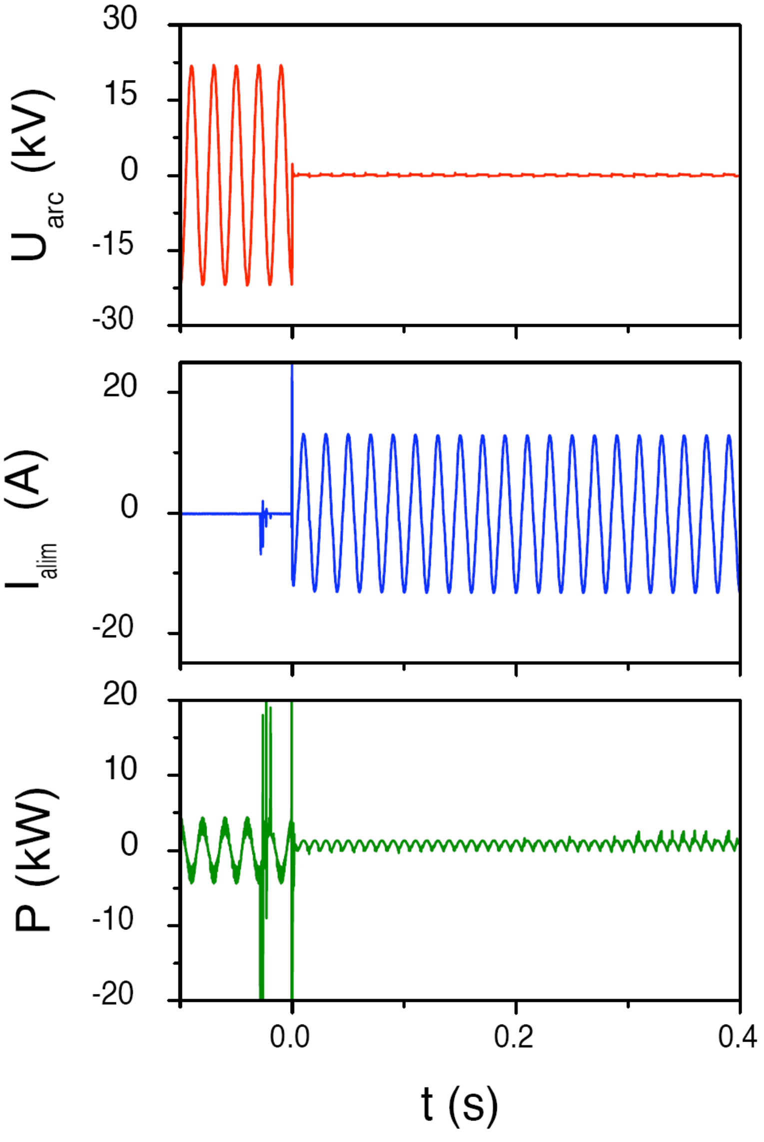
- U_c = 20 kV
- I_c = 10 A

Distance between electrodes :
3 mm < d < 60 mm

DC power supply (3 kV)

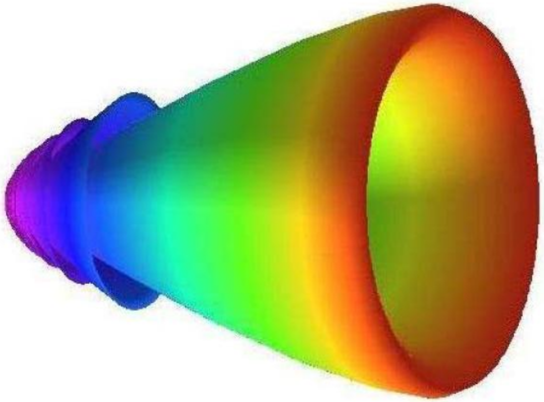


AC power supply (25 kV, 50 Hz)



- Discharge current is limited by the power supply (1 MW)
- Resistance of the plasma is low < 0.1 Ω/cm

THz generation by filamentation in air

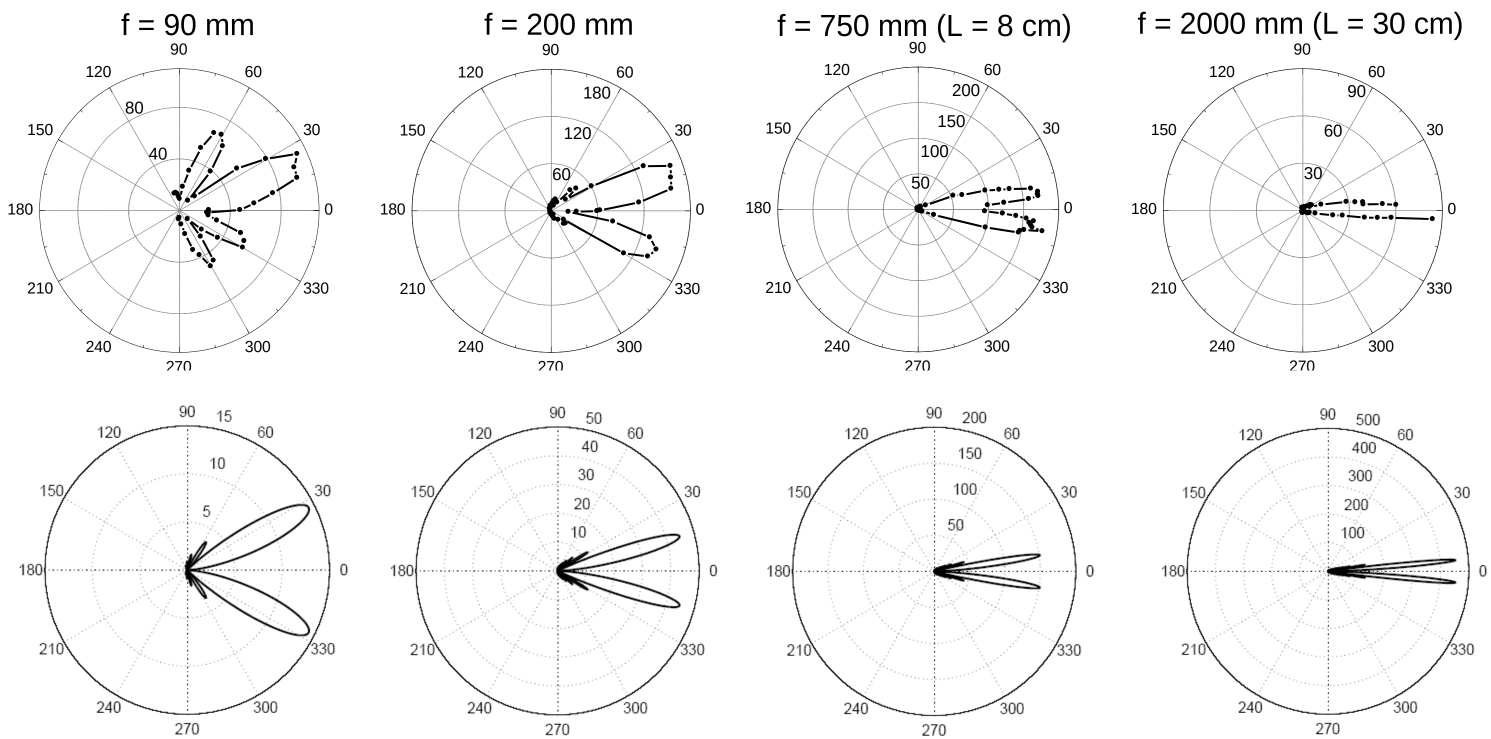


Physical Review Letters **98**, 235002 (2007)

Theory vs experiment

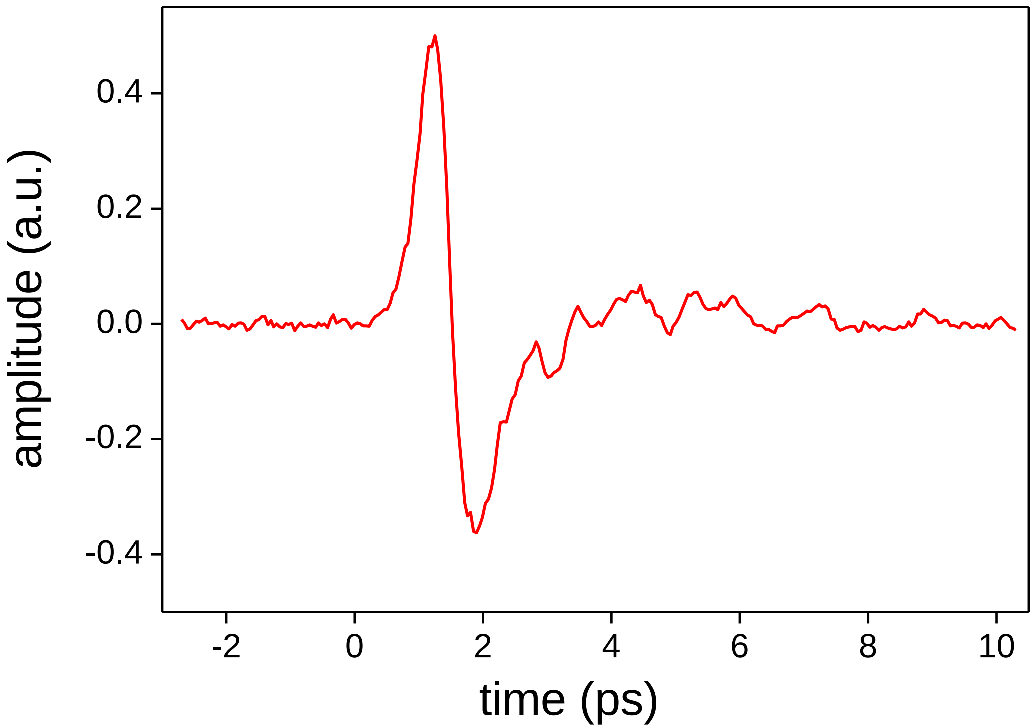
Experiments

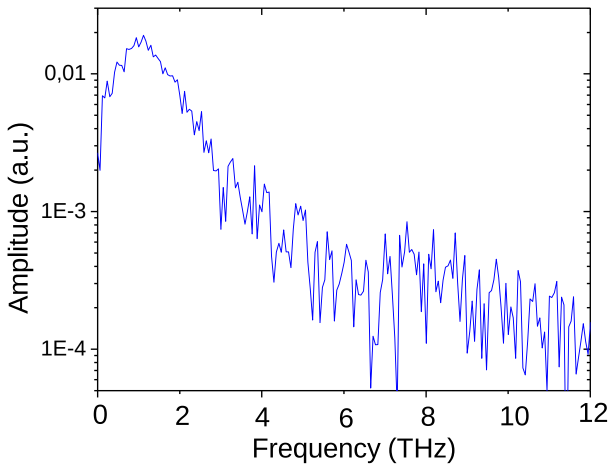
Calculations



L = 1 cm **L = 3 cm** **L = 8 cm** **L = 30 cm**

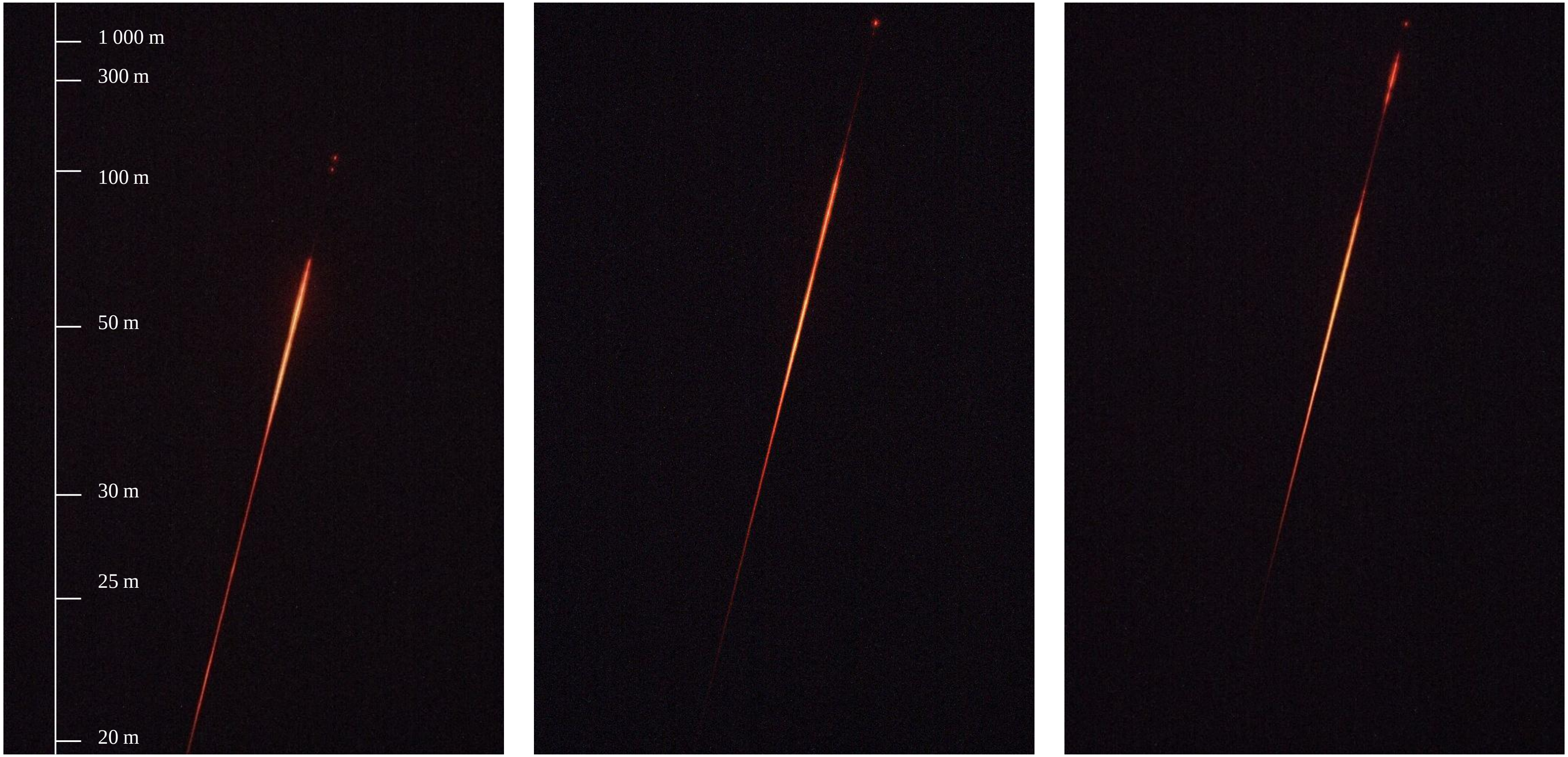
Duration of THz pulse





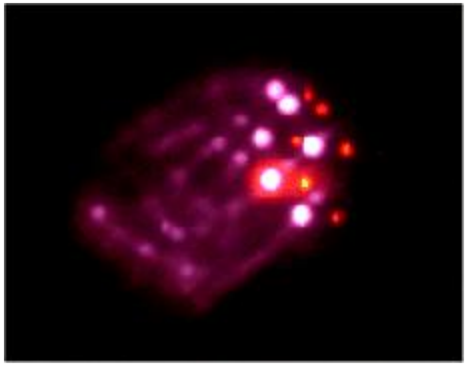
Vertical Propagation in the sky

Mechain et al. Teramobile Laser (5 TW) Tautenburg 2005



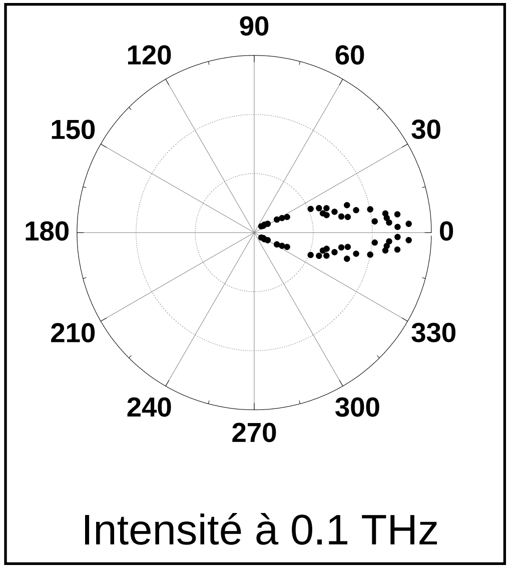
τ = 100 fs τ = 1 ps τ = 2 ps

Filamentation with TW laser



Power >> Pcr
200 mJ instead of 5 mJ

Formation of many filaments (~40)



THz signal is 40 times more intense than with a single filament
THz is detected 20 m from the laser

=> The THz can easily irradiate remote targets

The future

- Relativistic filamentation
- Triggering of lightning
- Standoff spectroscopy via backward-propagating laser beam
- Intense directional Coherent THz source