Long distance propagation of intense fs laser pulses in air

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Outline

1. Formation of plasma channels
2. Rich physics in plasma channels
3. Temporal and spatial control

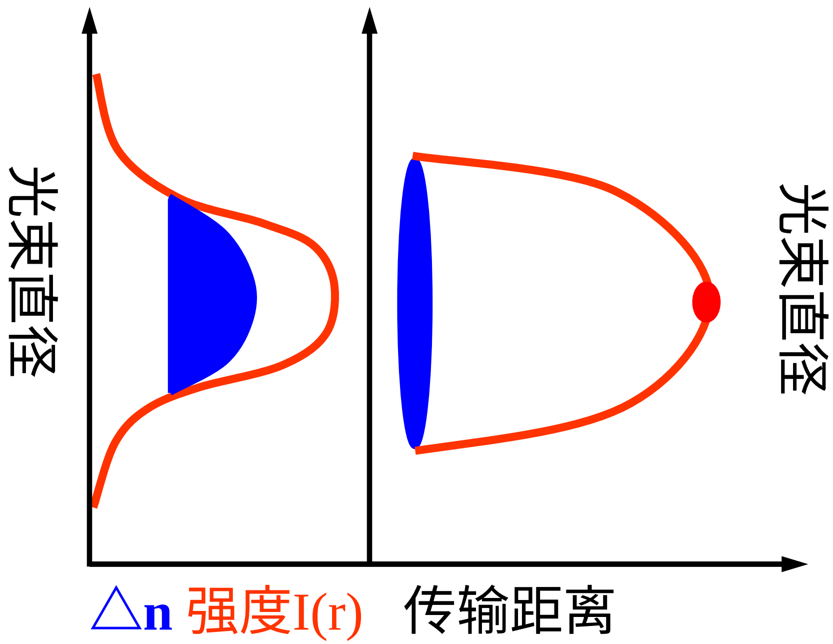
Formation of plasma channels

Mechanism for channel formation

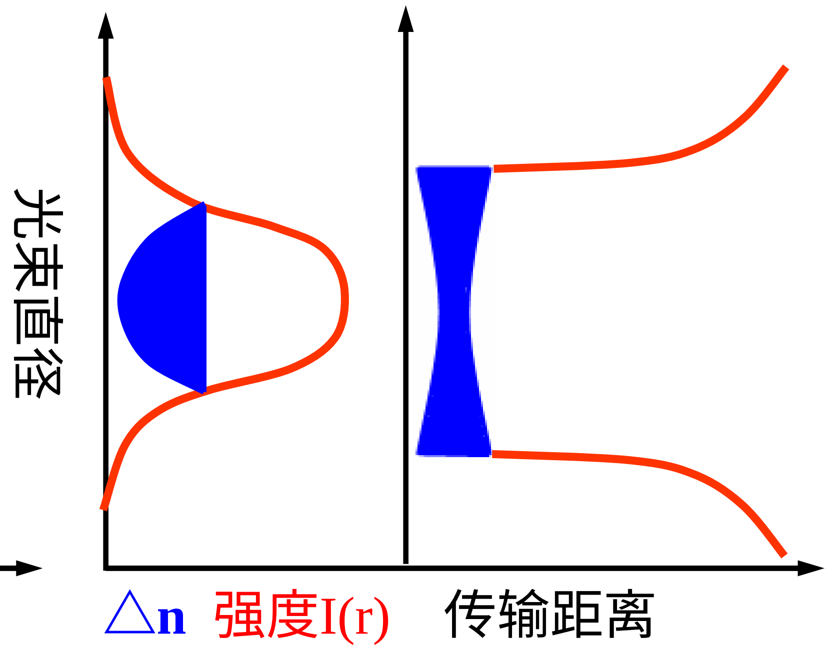
Propagation: $$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2}{\partial^2 t}E = k^2(1-\Delta n^2)E$$

$$\Delta n = 1 \quad + n_2 I \quad - N_e / 2n_c$$

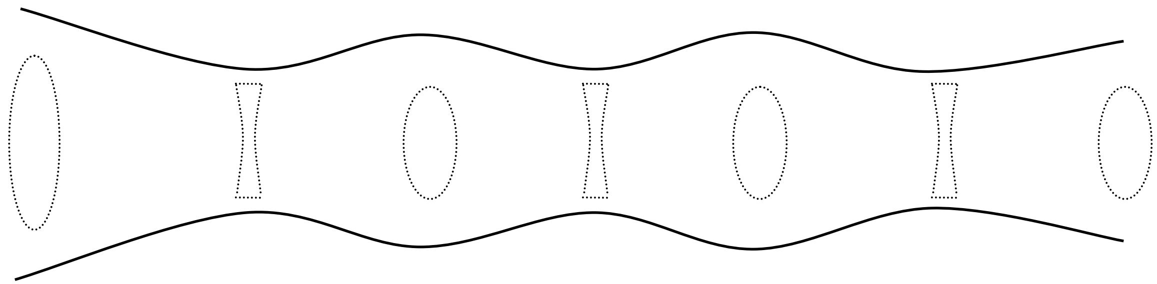
Kerr effect focuses



Ionization defocuses



Mechanism for channel formation

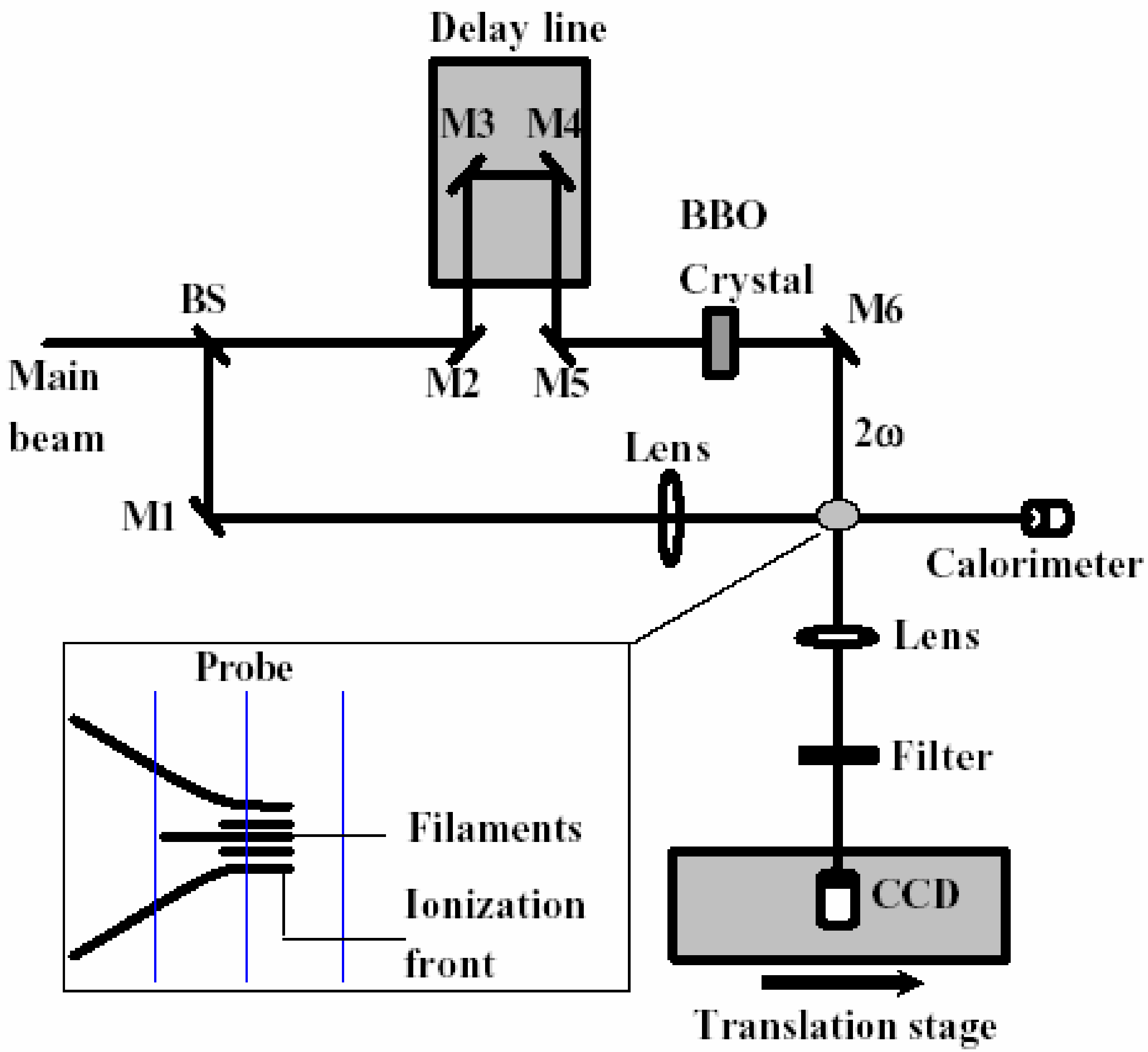


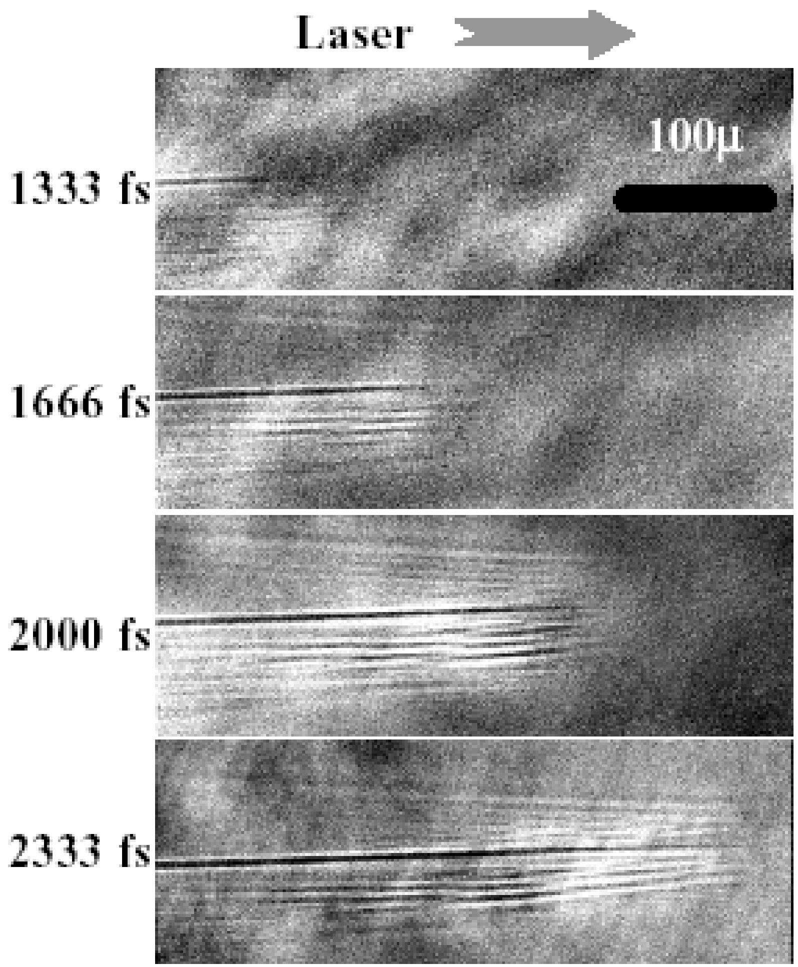
Balance between kerr focusing and plasma defocusing

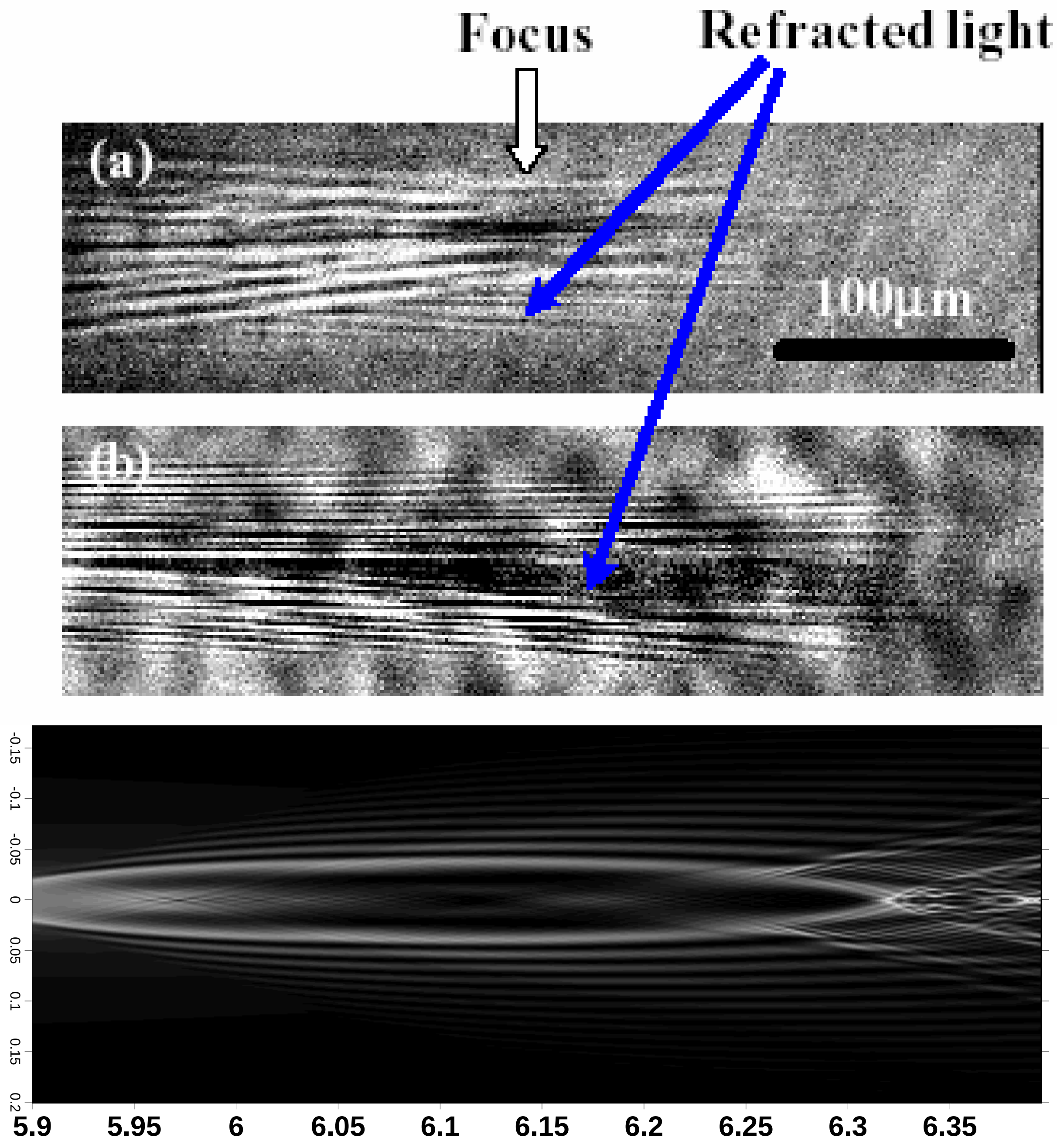
A plasma channel over km

Filaments in plasma channels

Setup for imaging the filaments

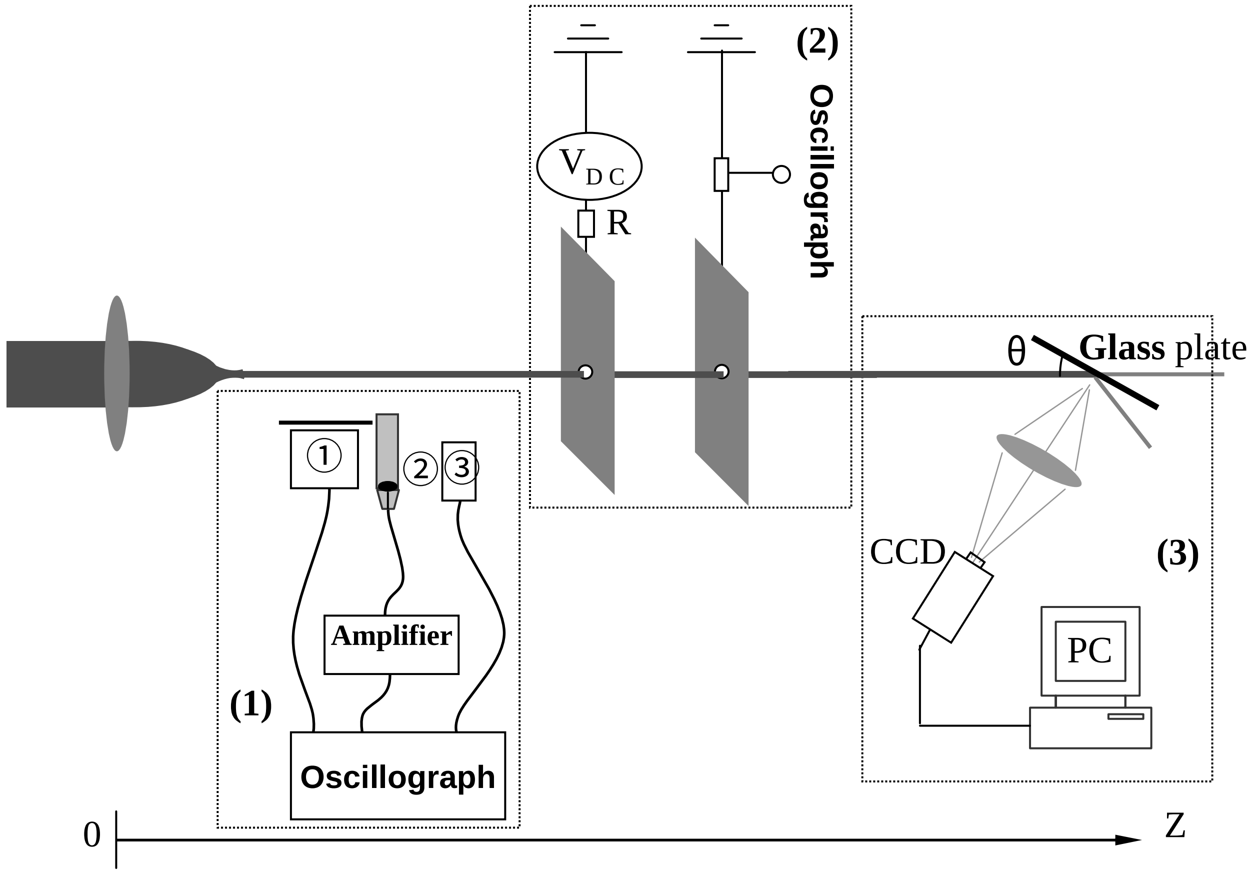



Laser
100µ
1333 fs
1666 fs
2000 fs
2333 fs



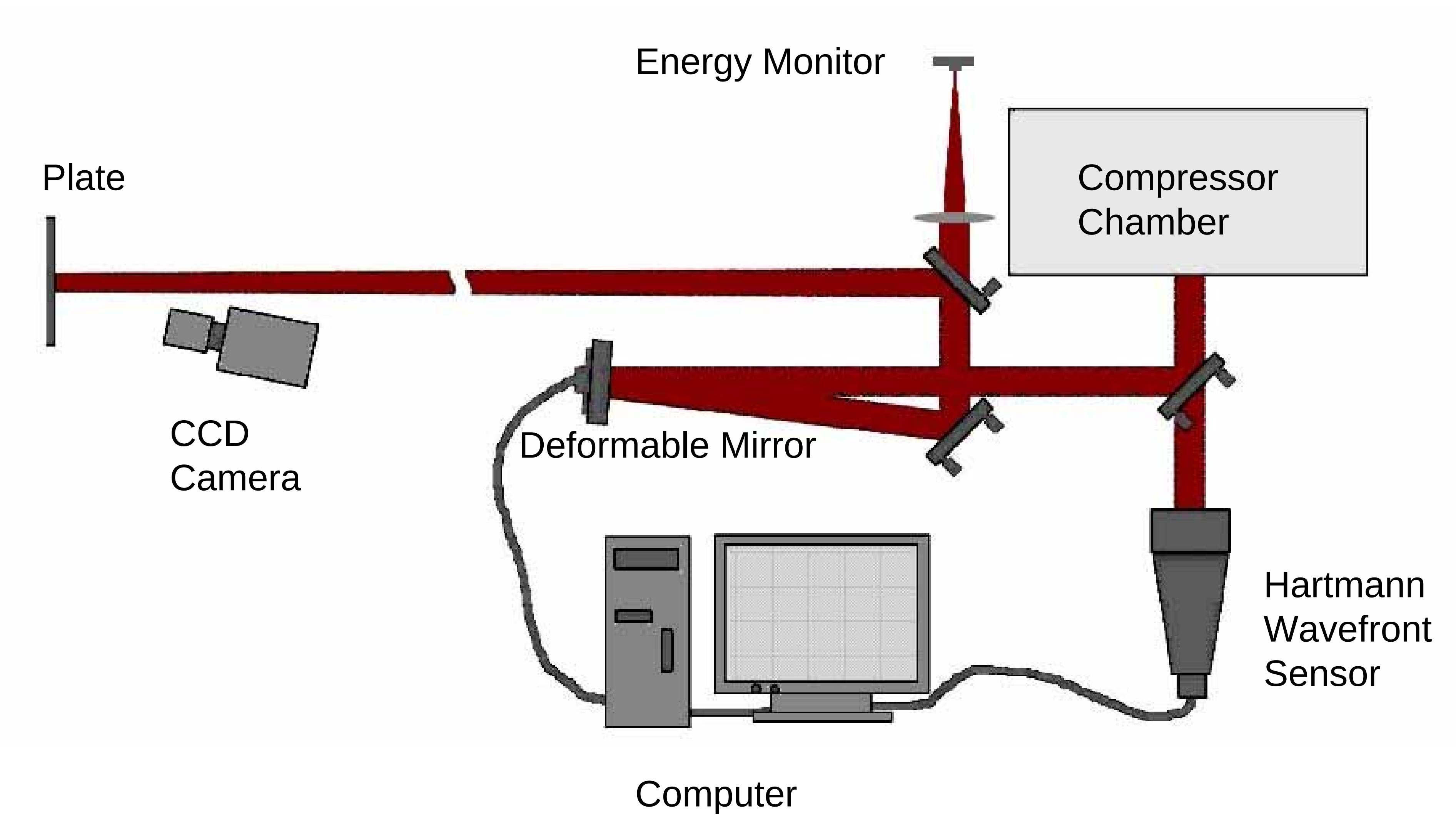
Focus
Refracted light
(a)
100µm
(b)
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
5.9
5.95
6
6.05
6.1
6.15
6.2
6.25
6.3
6.35

Diagnostics of plasma channels

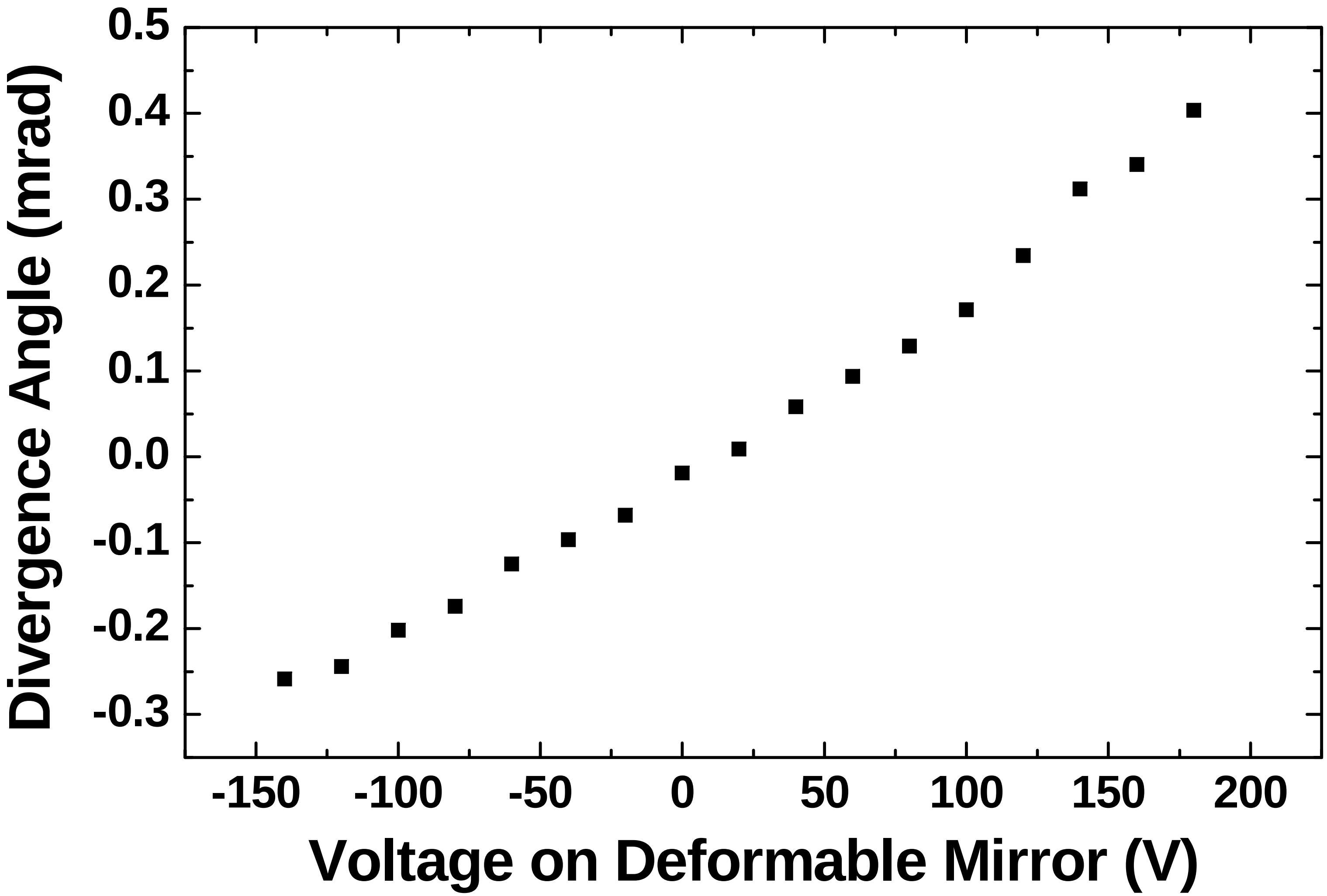


Spatial-temporal control of plasma channels

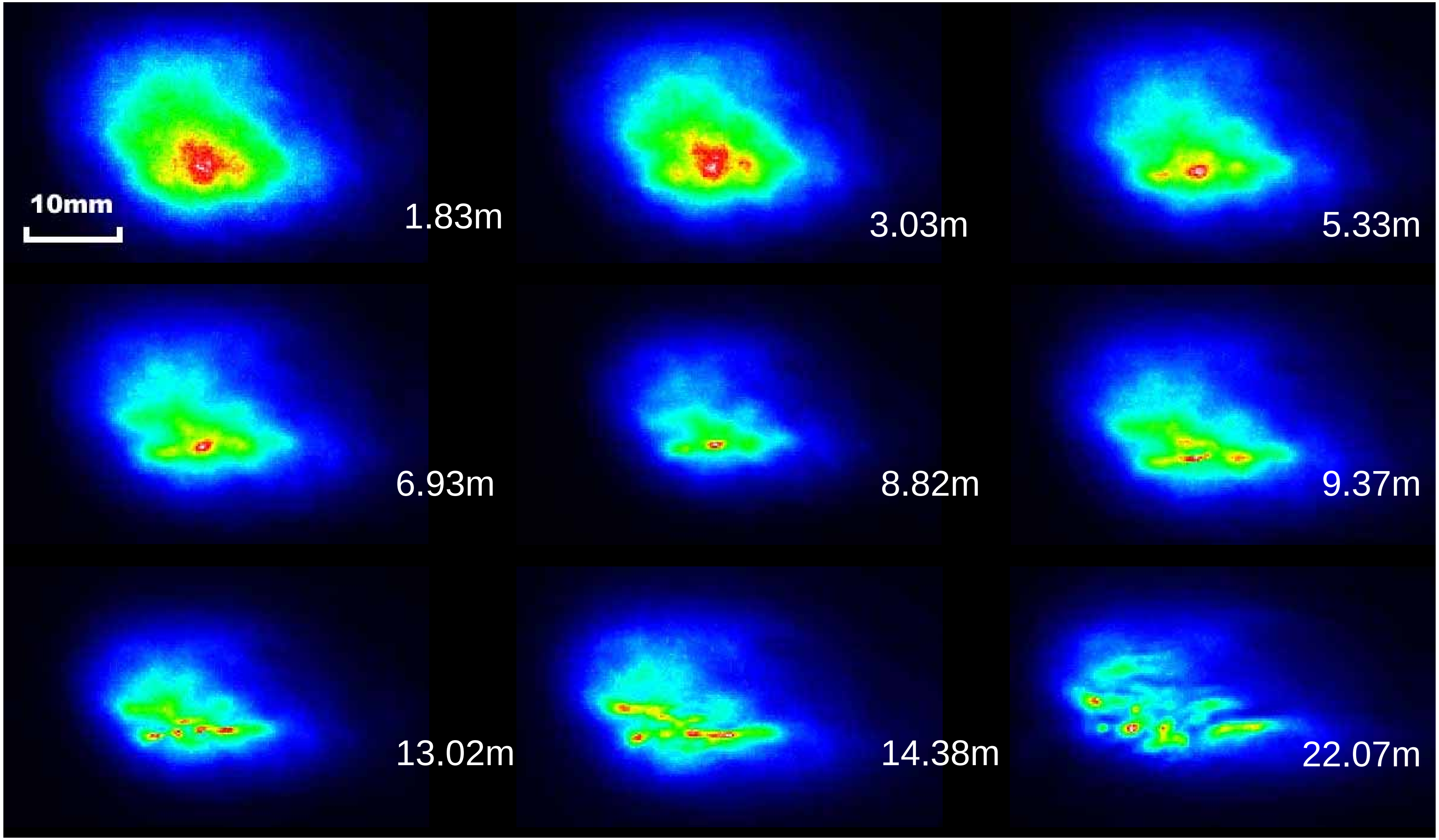
Control of self focusing



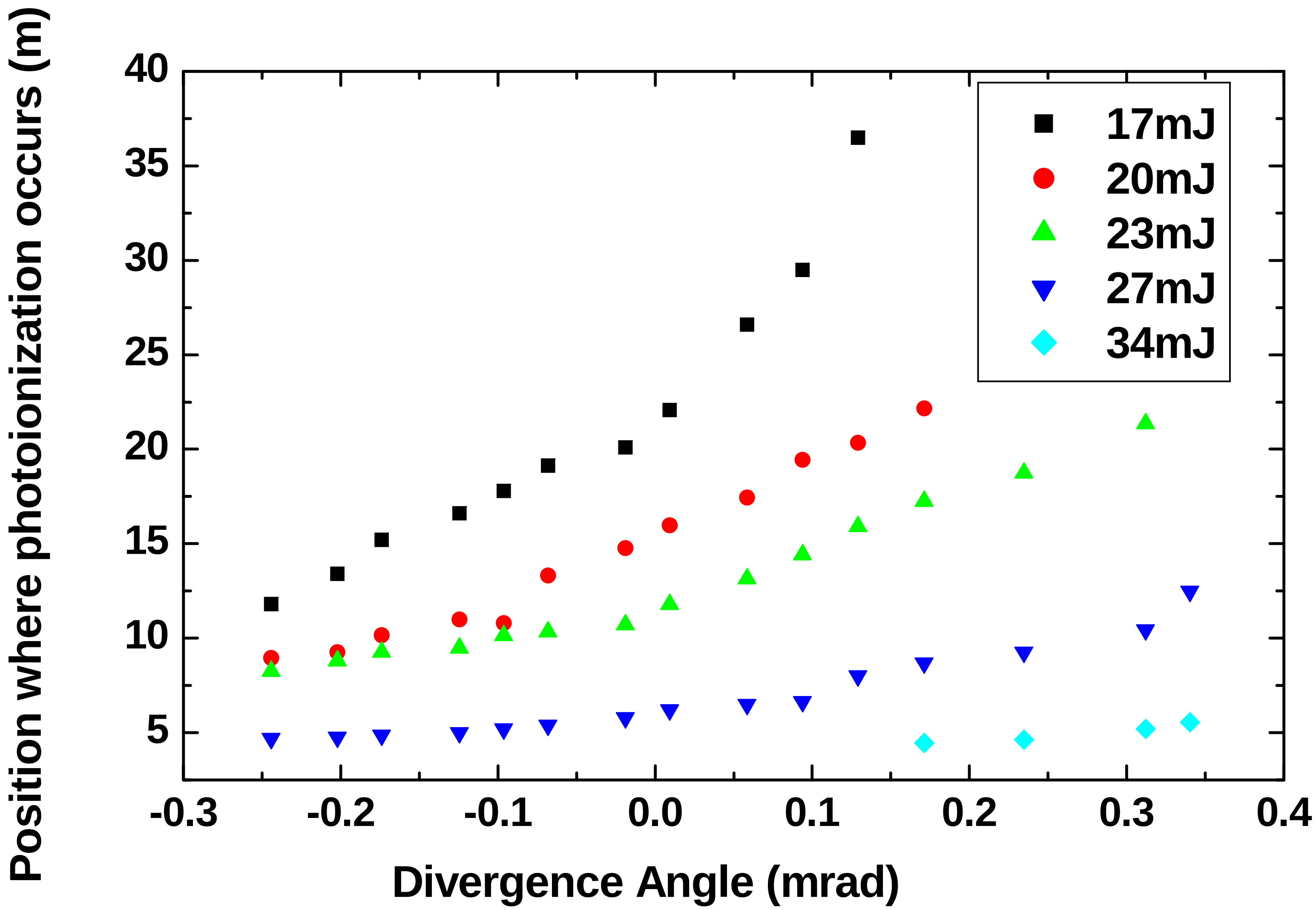
Divergence controlled by deformable mirror



Observation of self focusing

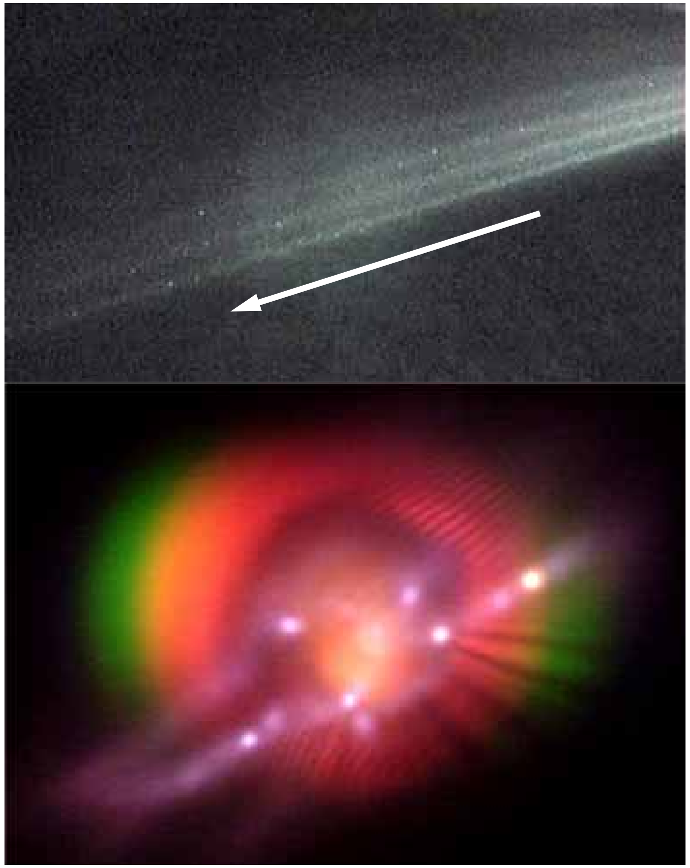


Self focusing vs divergence angle

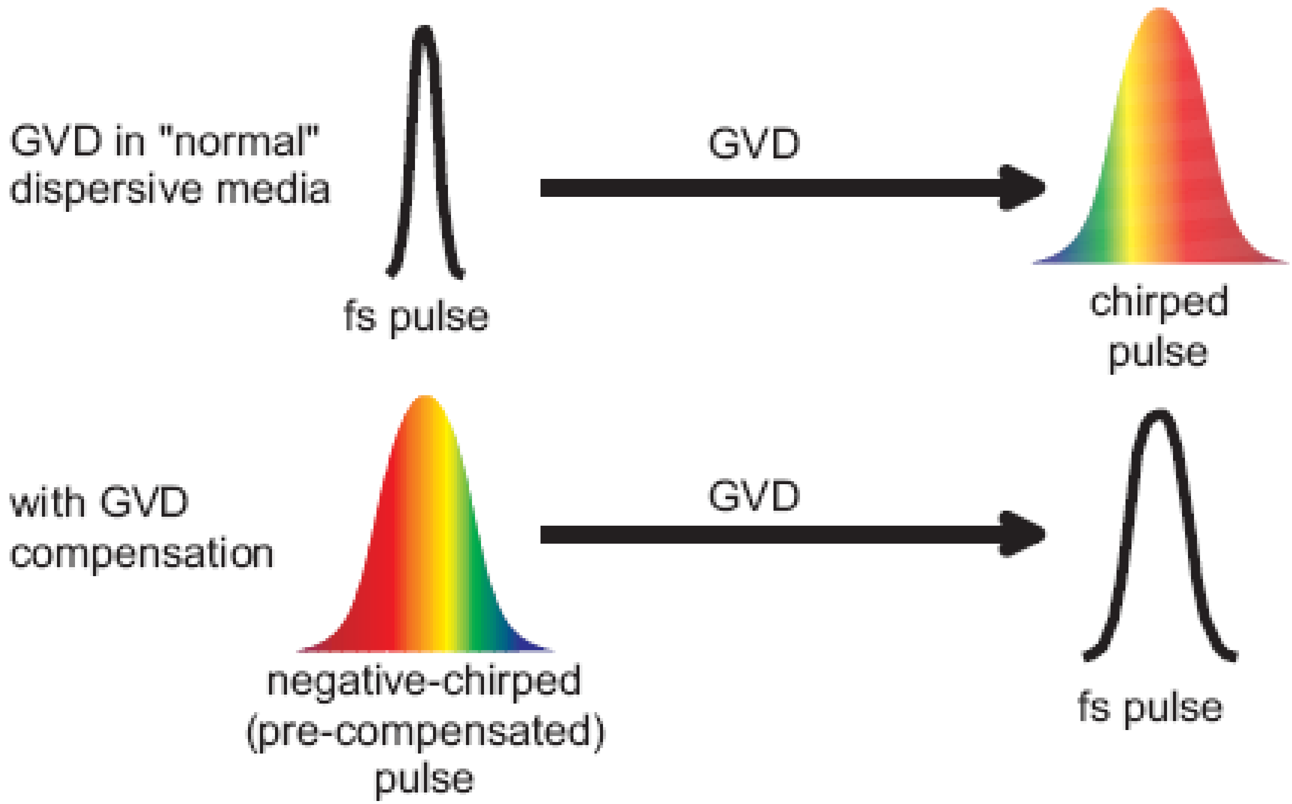


Control of temporal behaviour

- 1. 成丝起点
- 2. 成丝长度
- 3. 超连续光谱

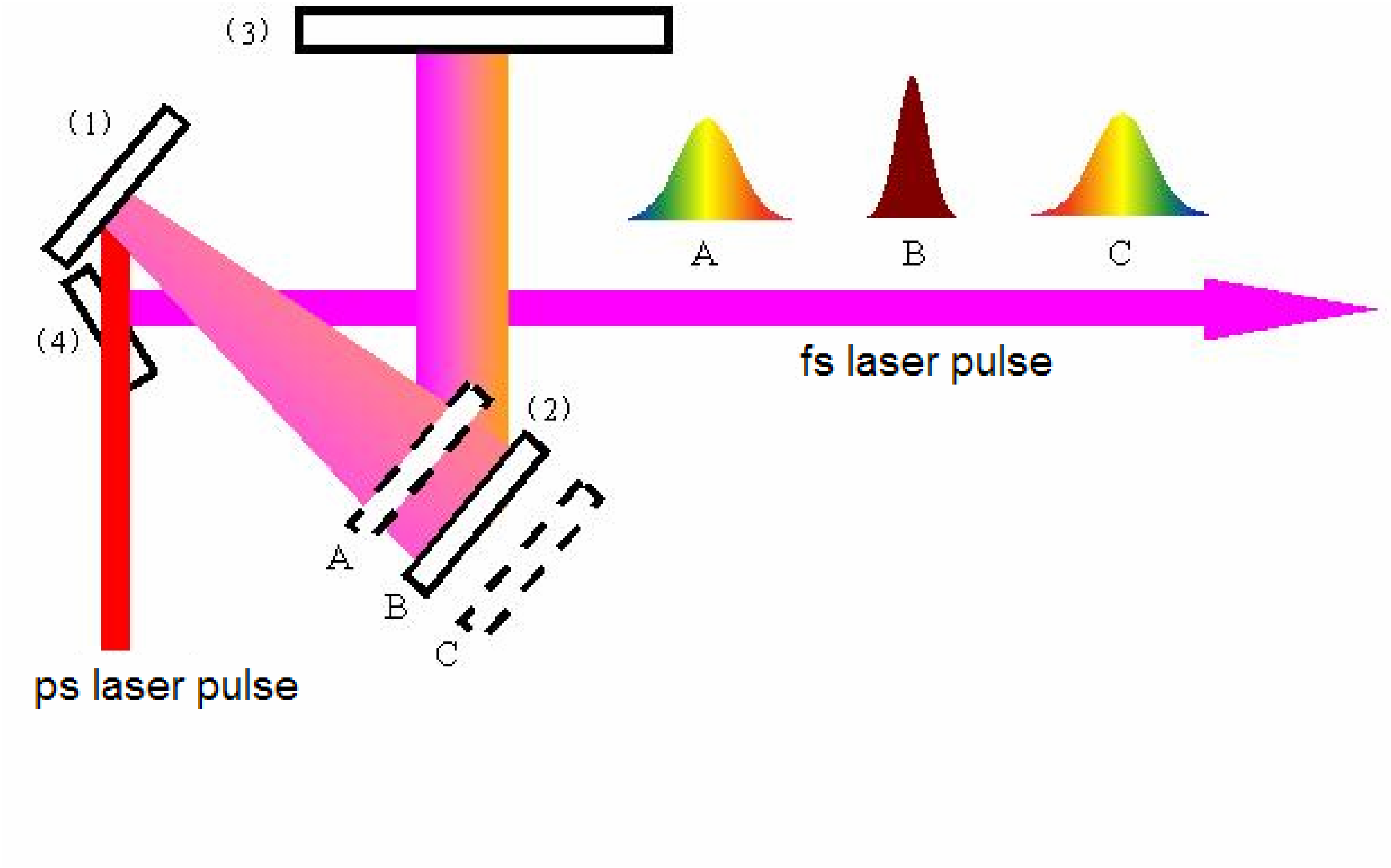


Effects of the initial chirp on the propagation



H. Wille, M. Rodriguez, J. Kasparian,*et al.* Eur. Phys. J. AP **20**, 183–190 (2002)

Control of initial chirp



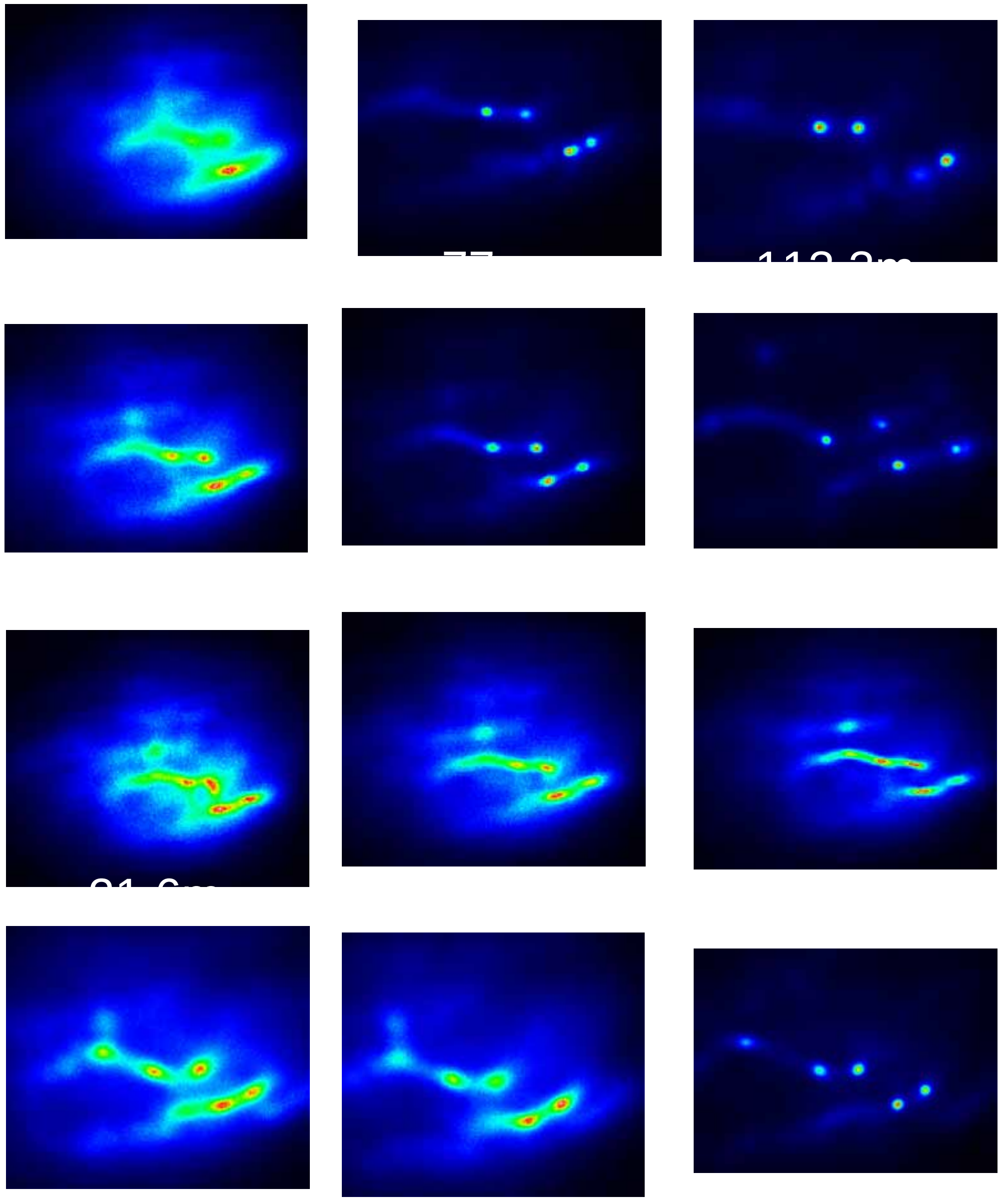
Effects of temporal charactertics

277.2 fs

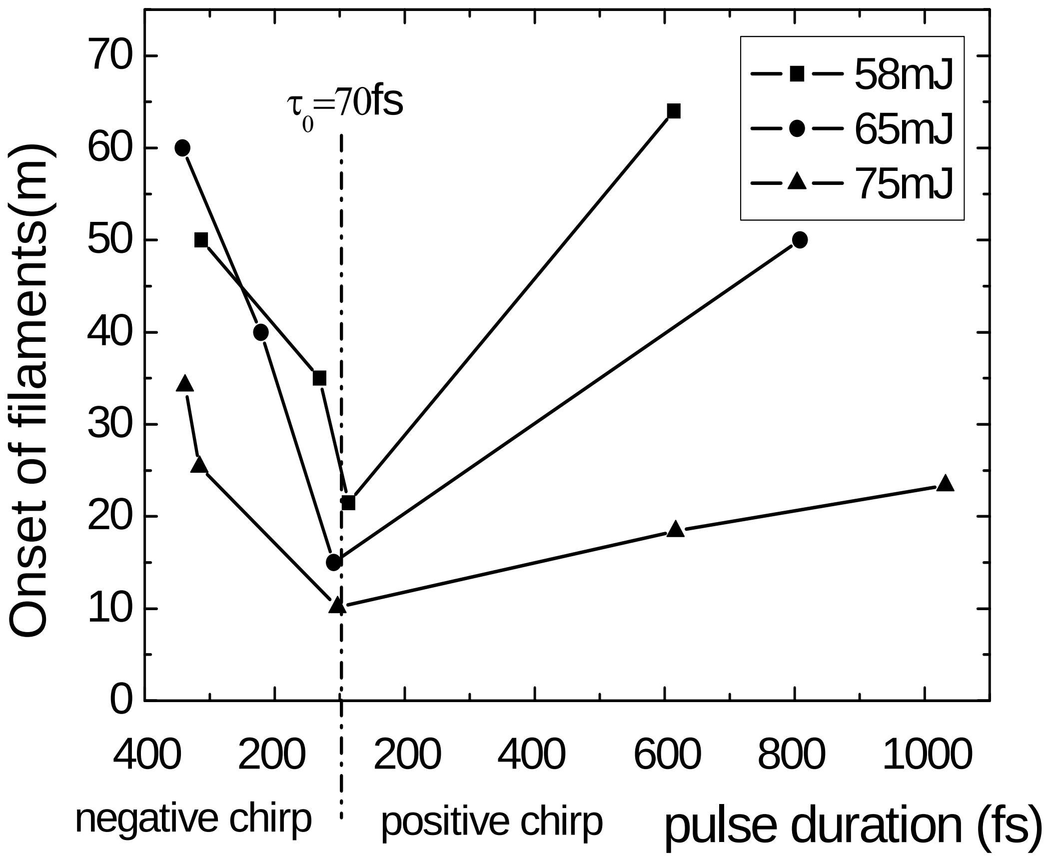
123.6 fs

79 fs

580 fs



Starting of the filaments

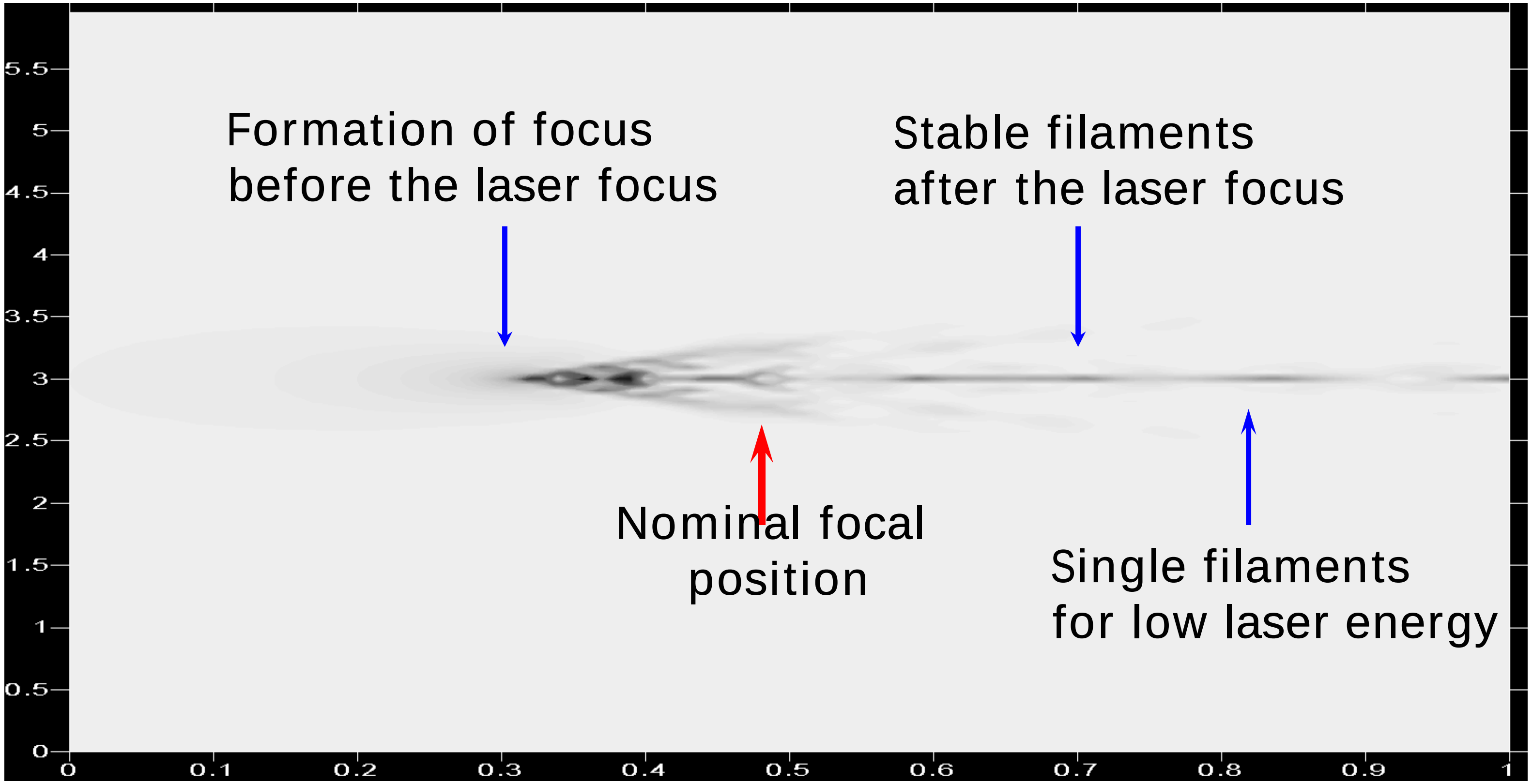


1. 随正/负啁啾增大成丝起点位置变远

2. 同样脉宽下，能量越大成丝越靠前

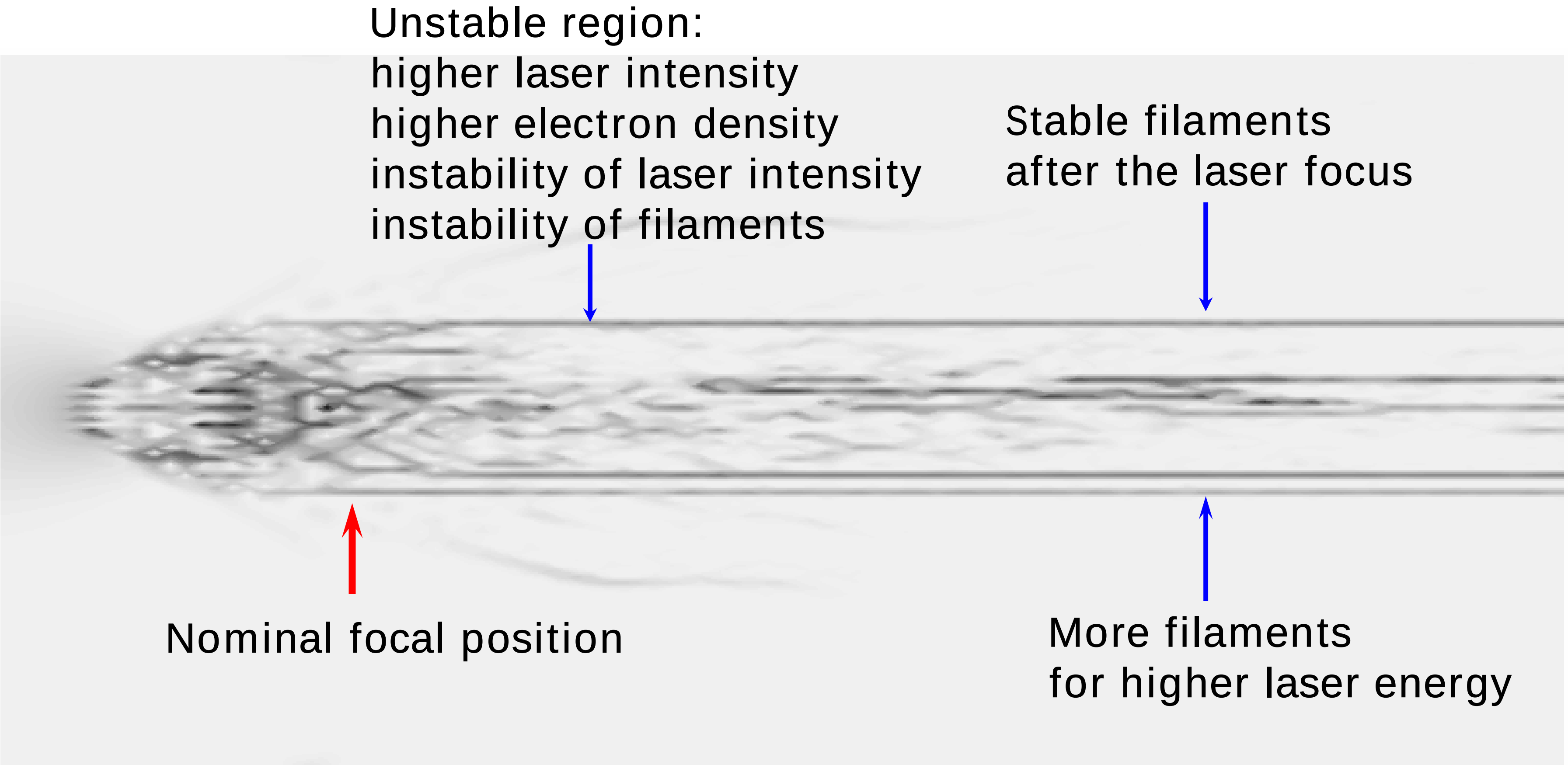
Development of filaments

Simulated filaments for small laser energy



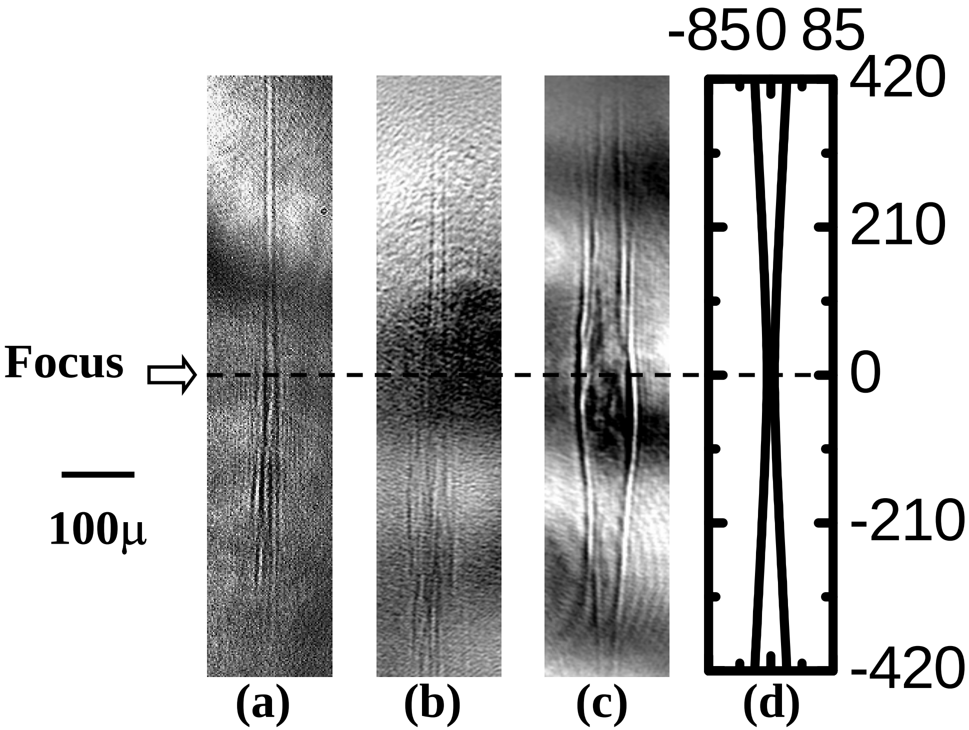
E=5mJ；τ=50fs； f=2m

Simulated filaments for increased laser energy



E=50mJ；τ=50fs； f=15m

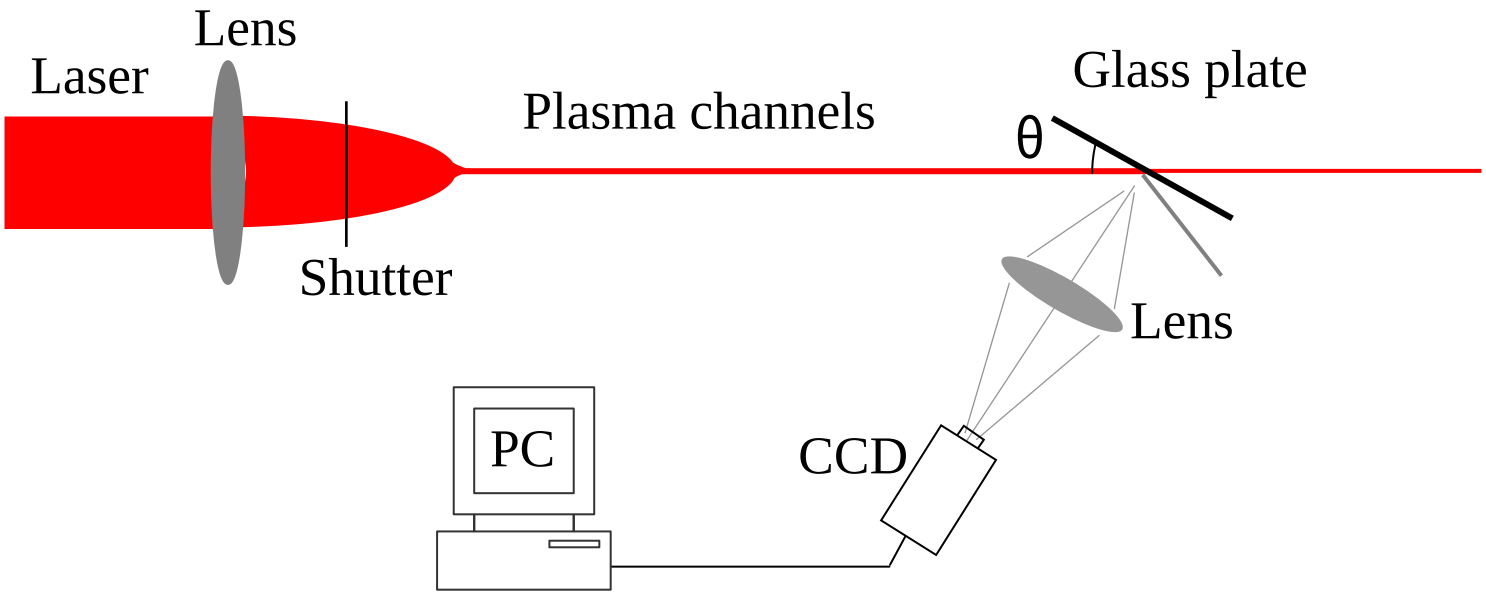
Temporal development of filaments



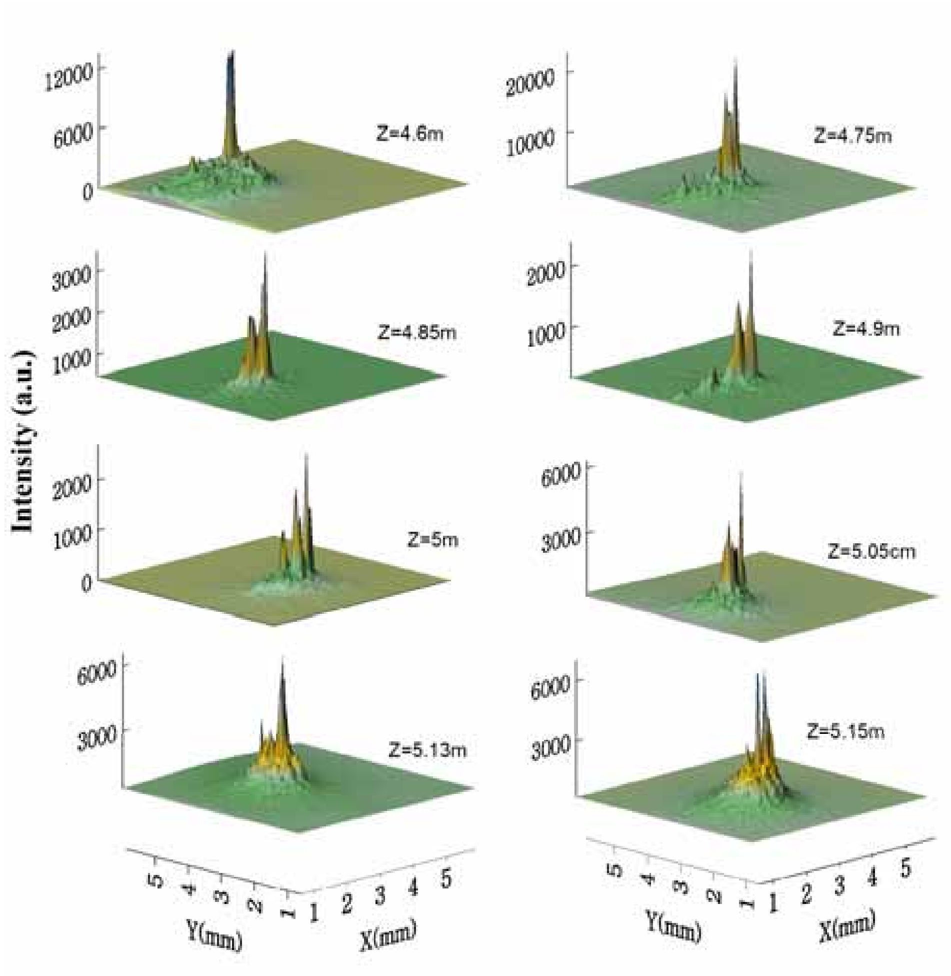
Splitting and fusing

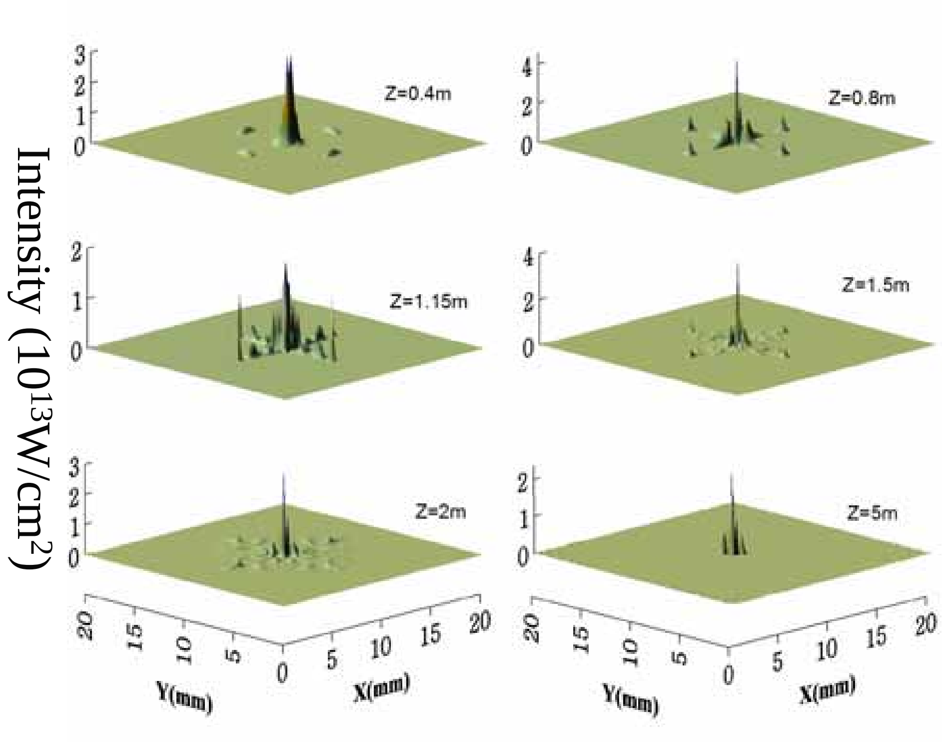
1 ns (a), 5 ns (b), and 10 ns (c)
1/e² **contours (d)**

Spatial development of filaments



Single and multi filaments

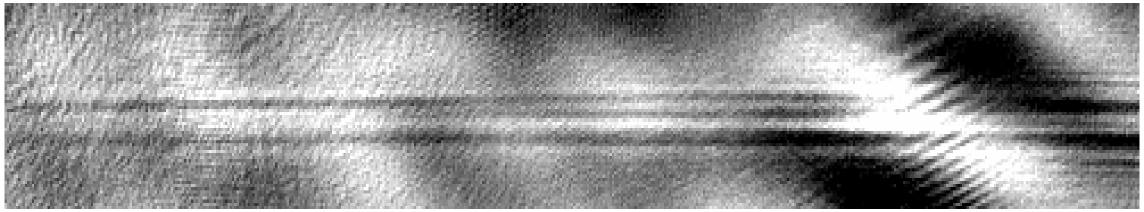




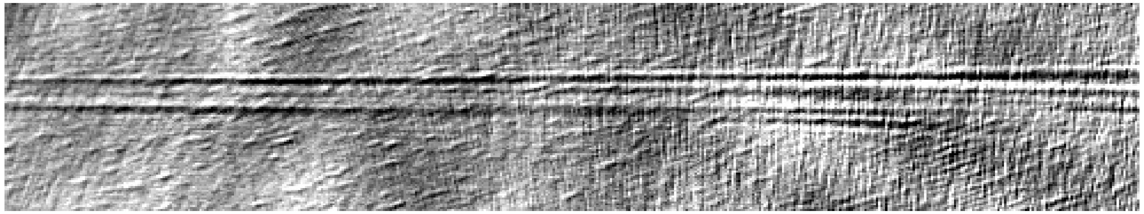
30fs, 22mJ, f=4m

30fs, 20mJ, f=1m

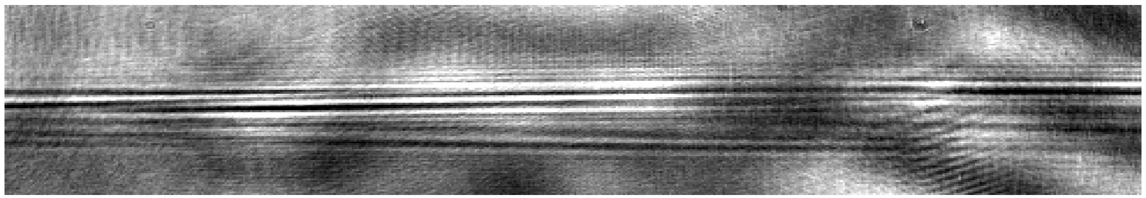
Filaments vs laser energy



10 mJ



15 mJ

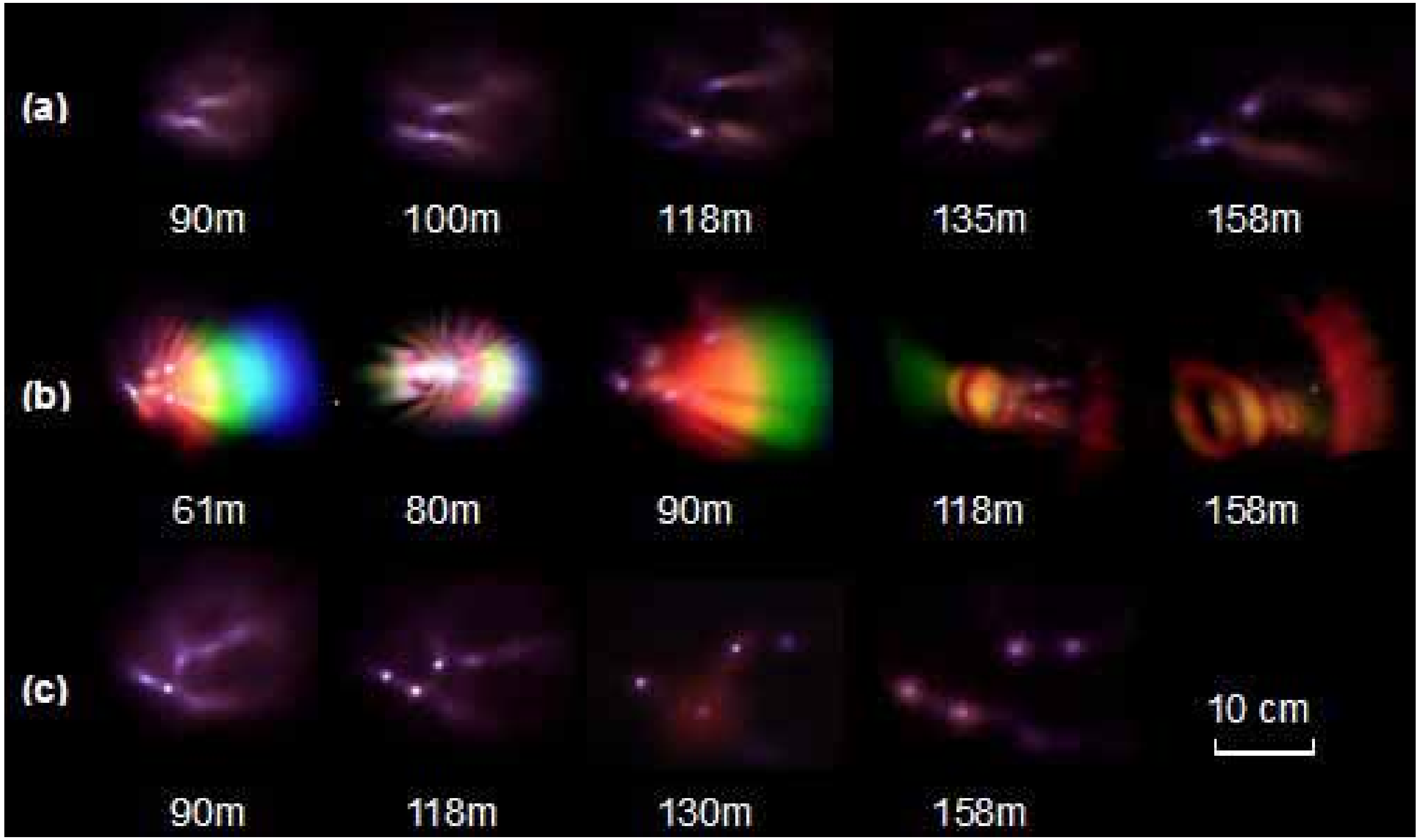


25 mJ

White light emission

Supercontinuum emission

Supercontinuum emission



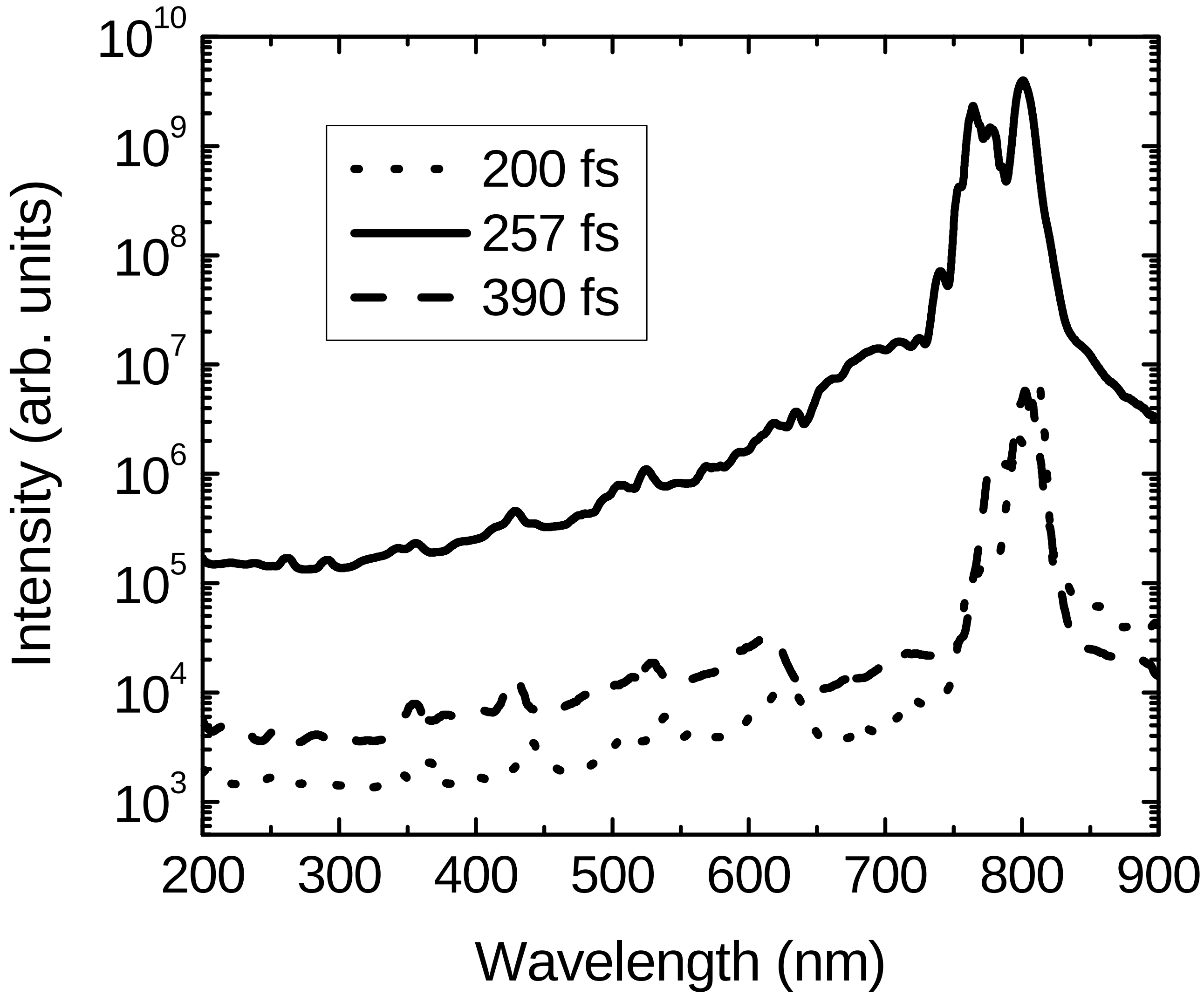
1. 超连续光谱辐射随脉宽增加先变强后变弱

2. 存在一个脉宽，超连续光谱的转换效率最高

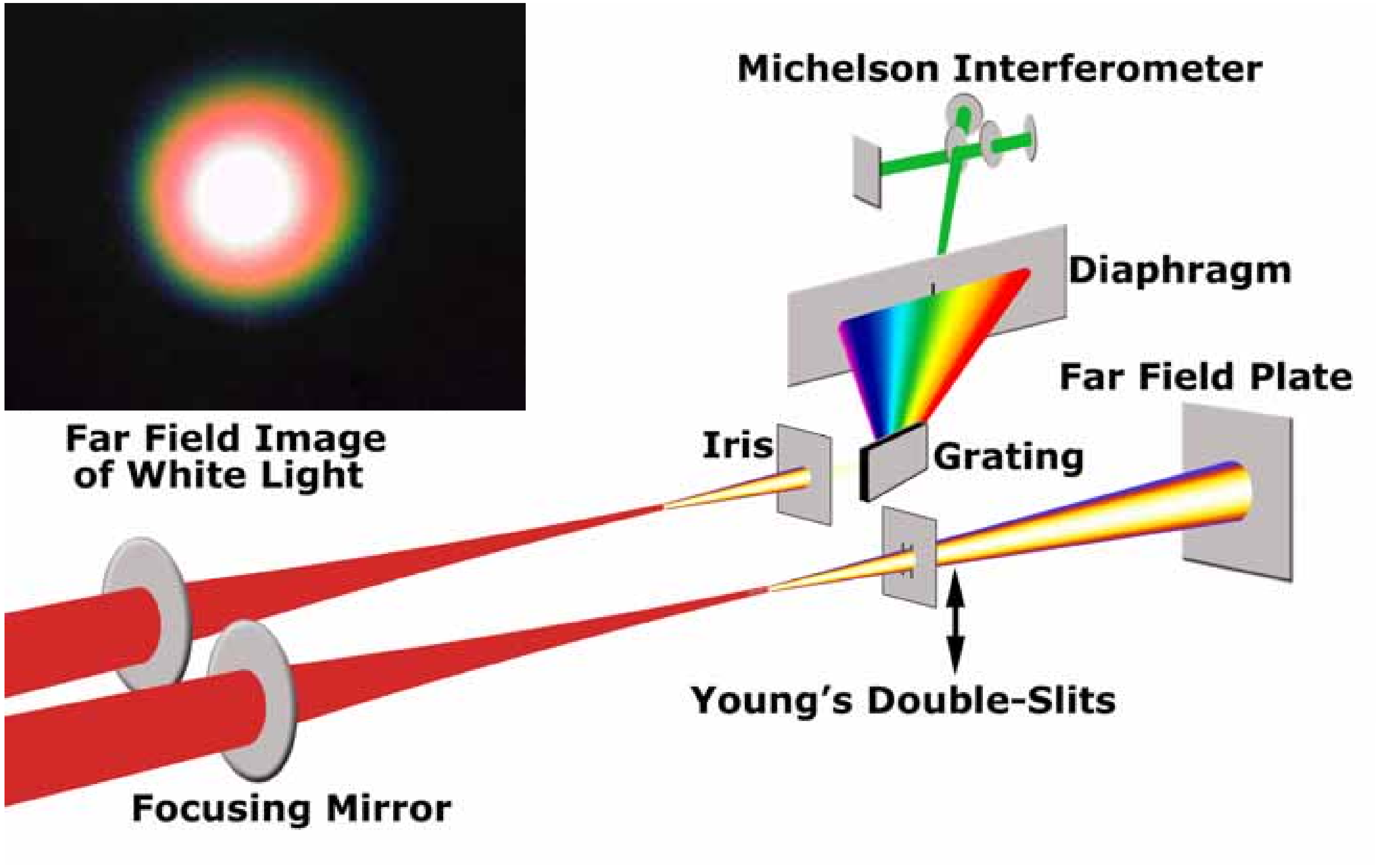
(a) 200 fs(正)
(b) 257 fs
(c) 390 fs

E = 50mJ

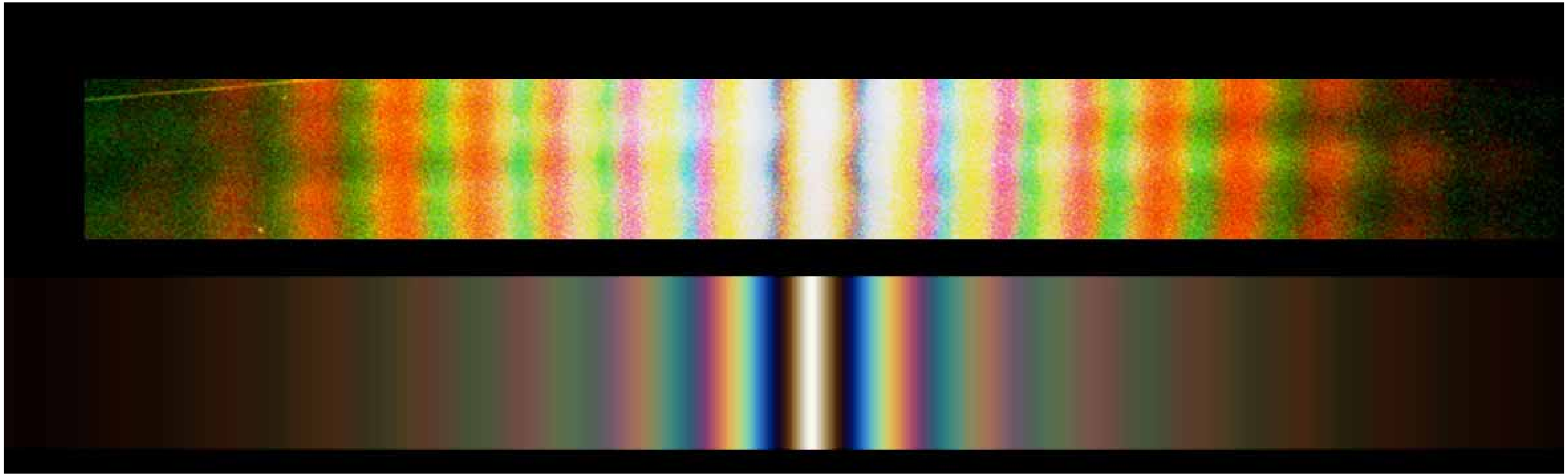
Supercontinuum spectrum



Spatial conherence - Young’s double-slit experiments

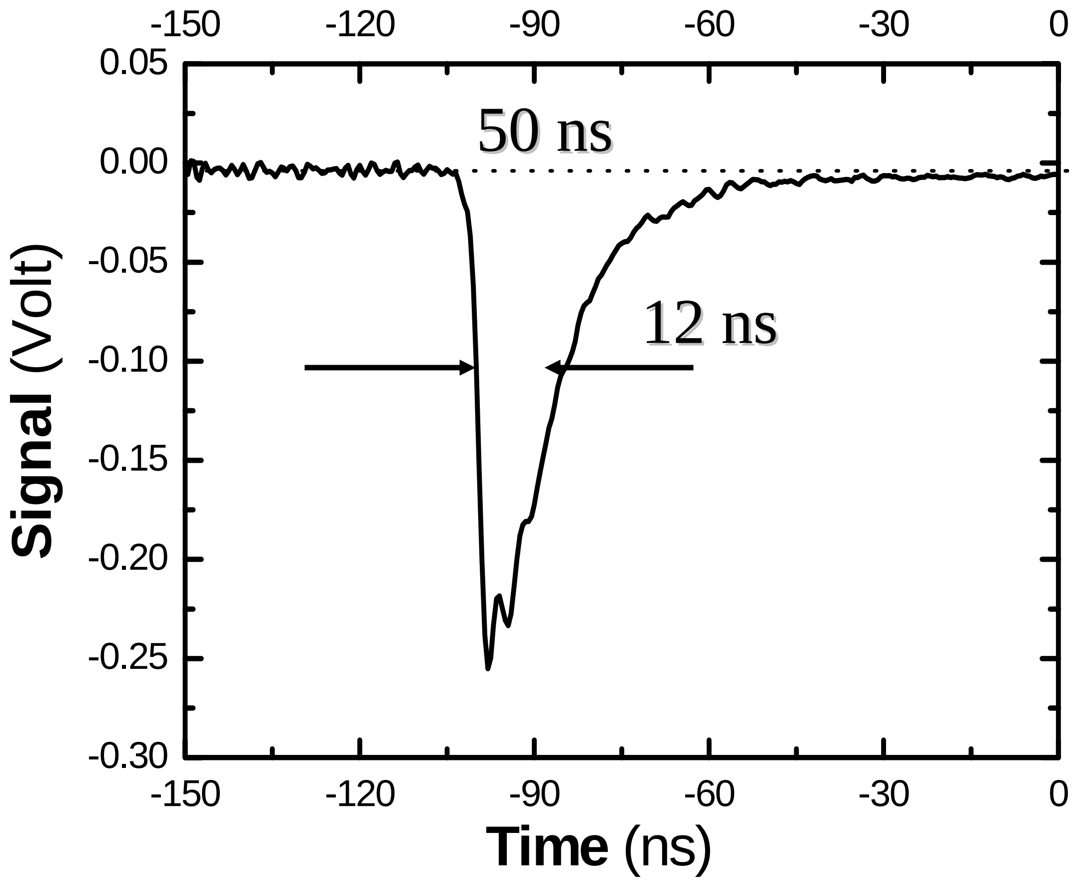


Coherence measurements at 400-900 nm



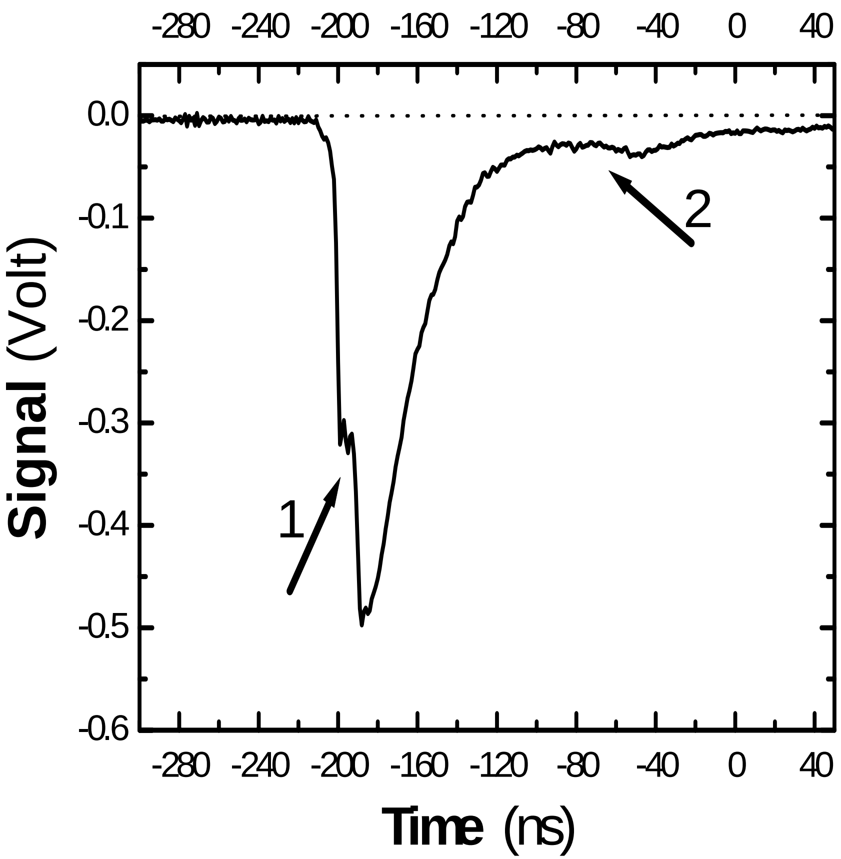
Prolonging the lifetime of plasma channels

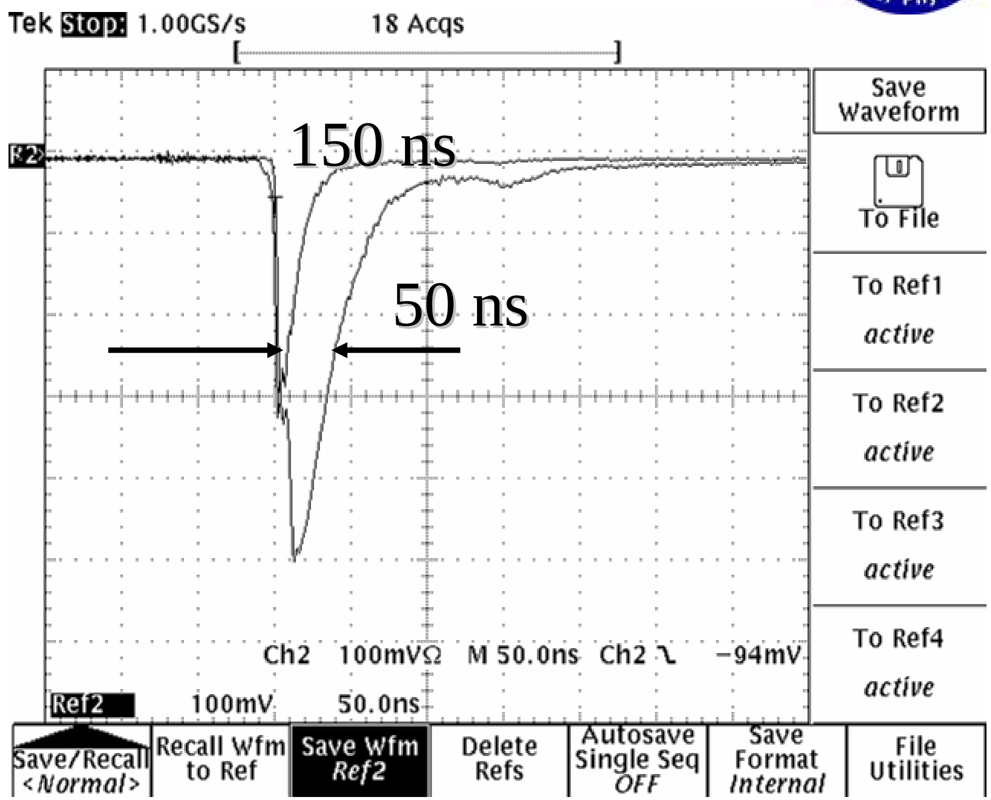
Results with a single pulse



单脉冲情况下的信号，半高宽大约12纳秒，底部宽度为50-60纳秒

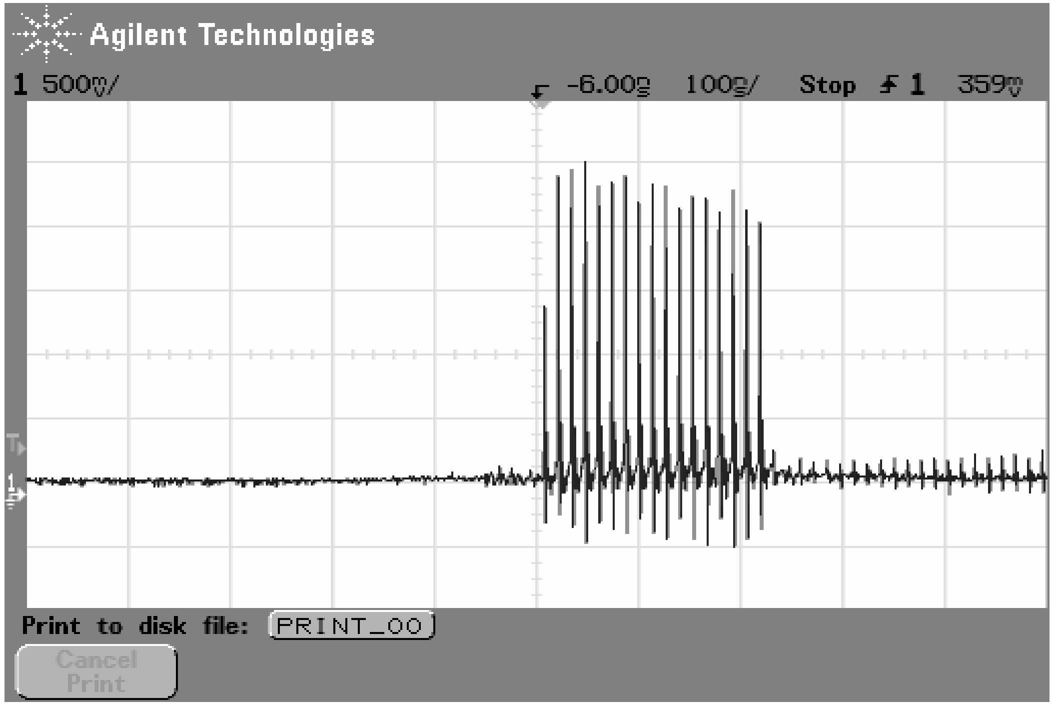
Results after adding the second pulse



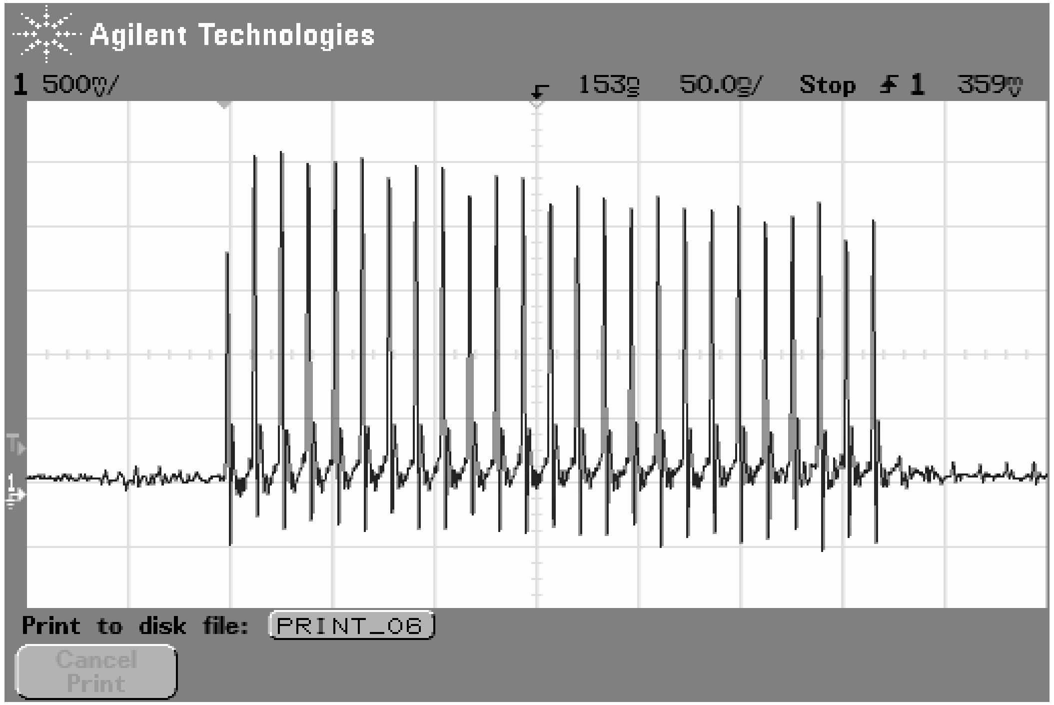


1箭头所指的是两个脉冲延时的位置。从图中可以看出信号的宽度的半高宽可以达到50ns，而且在信号的尾部存在一个长达150ns的平台，如箭头2所示

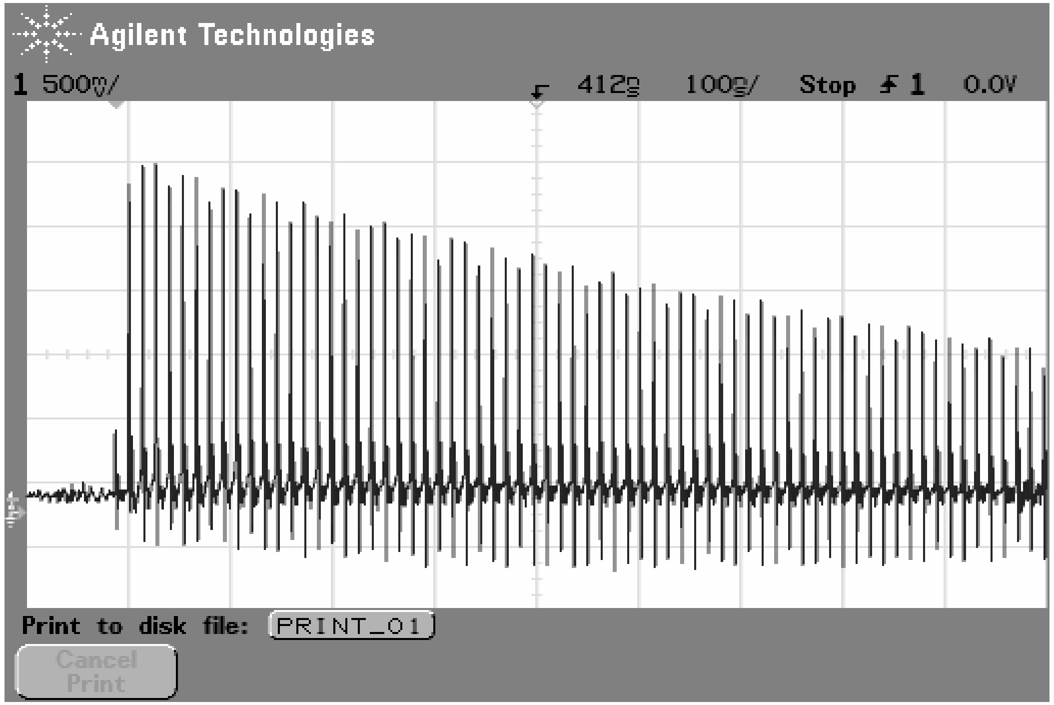
A pulse train with 16 pulses



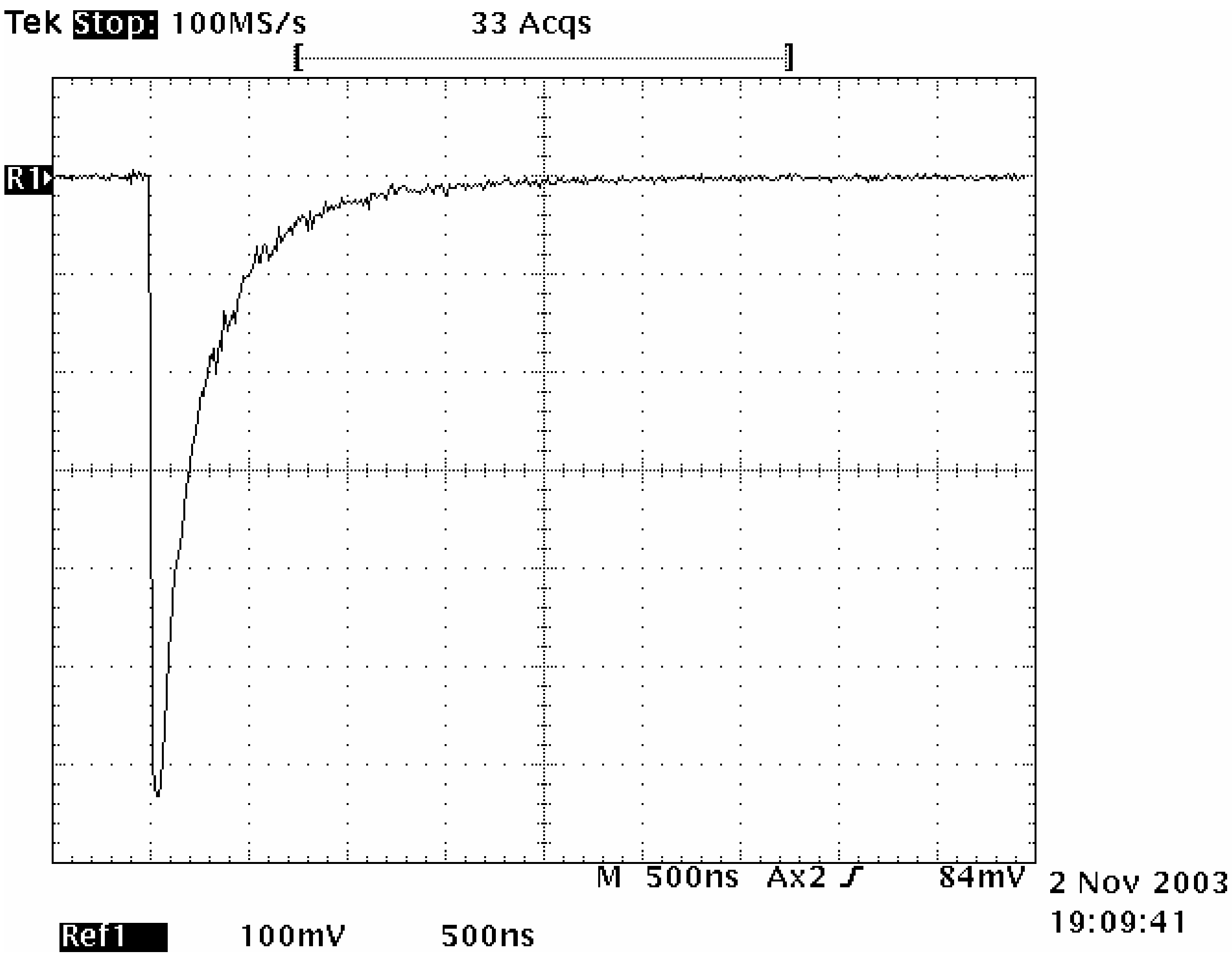
A pulse train with 25 pulses



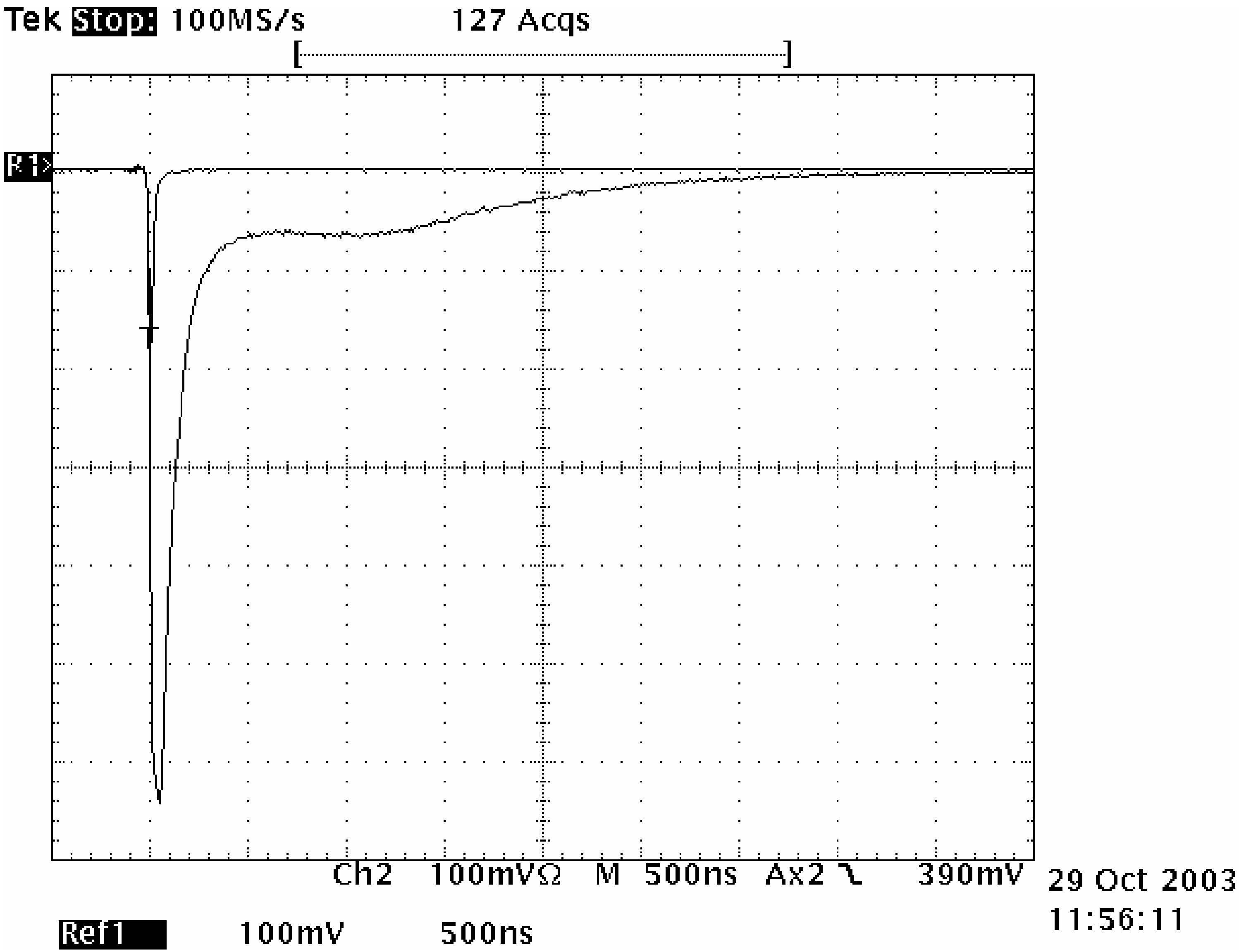
A pulse train with 70 pulses



A life time as long as 1.2 μs

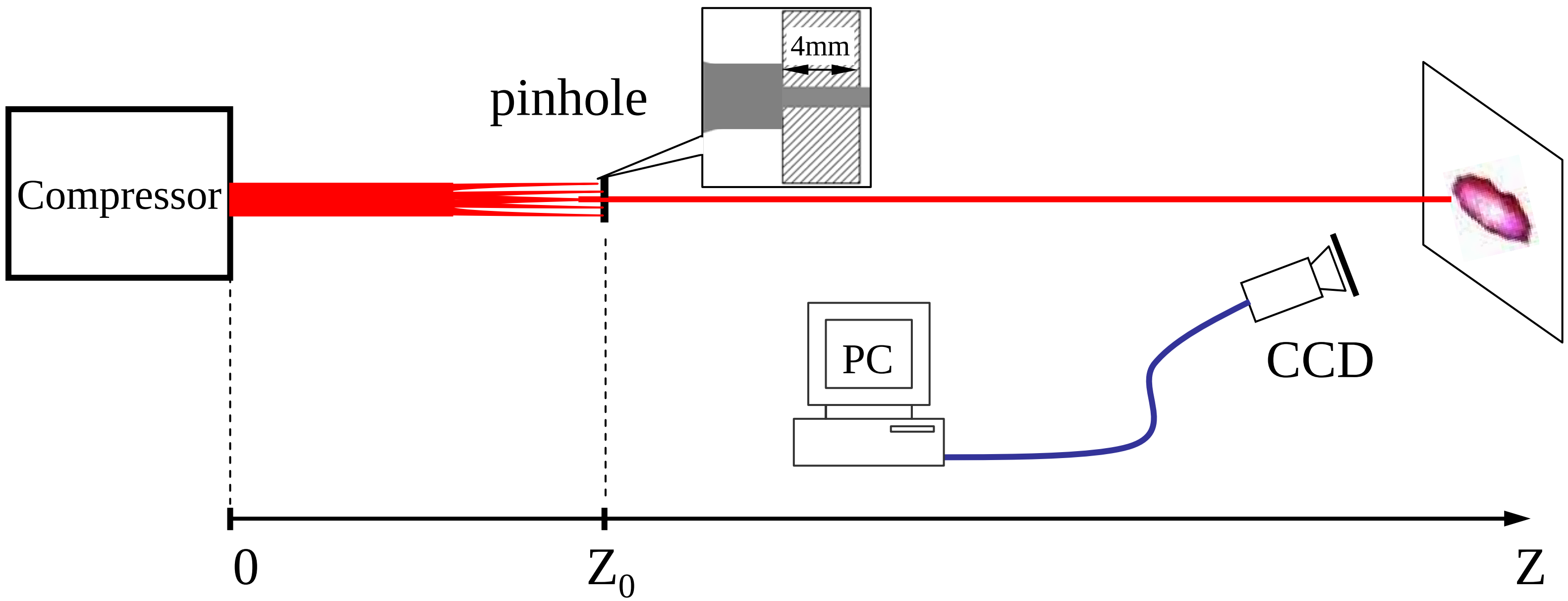


Best result of 2.2 μs



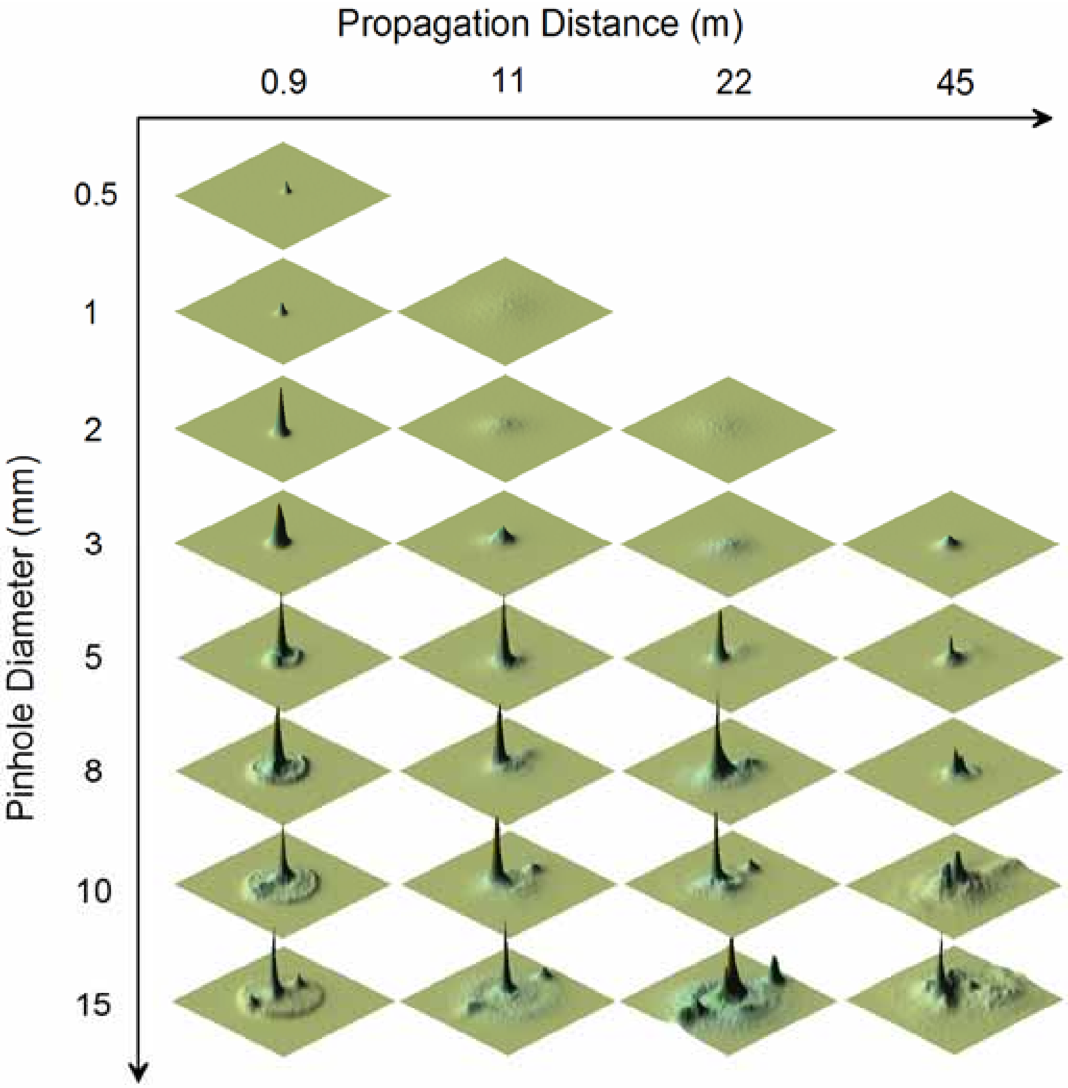
Energy interchange between the filaments and its background

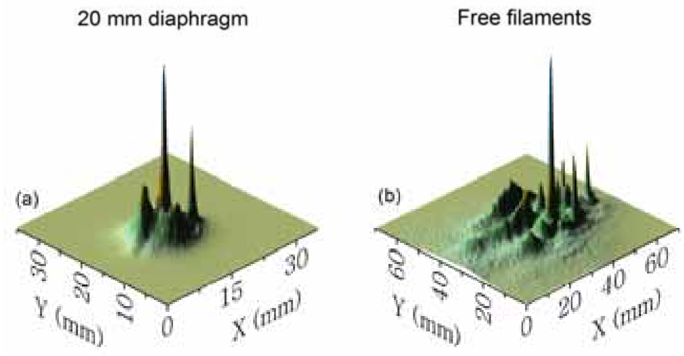
Isolating the filament from the background



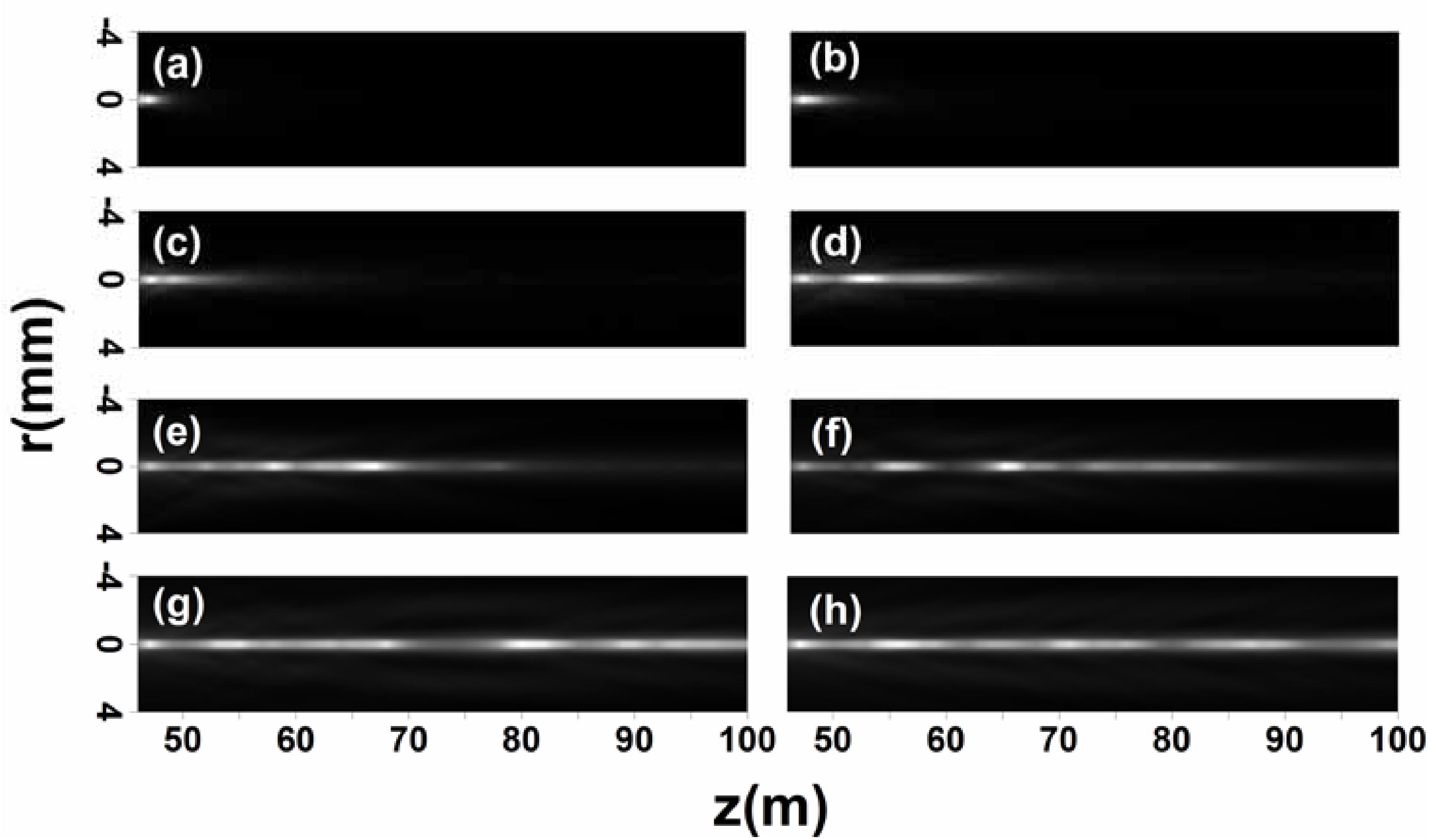
Z0 = 46m   E = 60mJ

Development of the filament after the pinhole

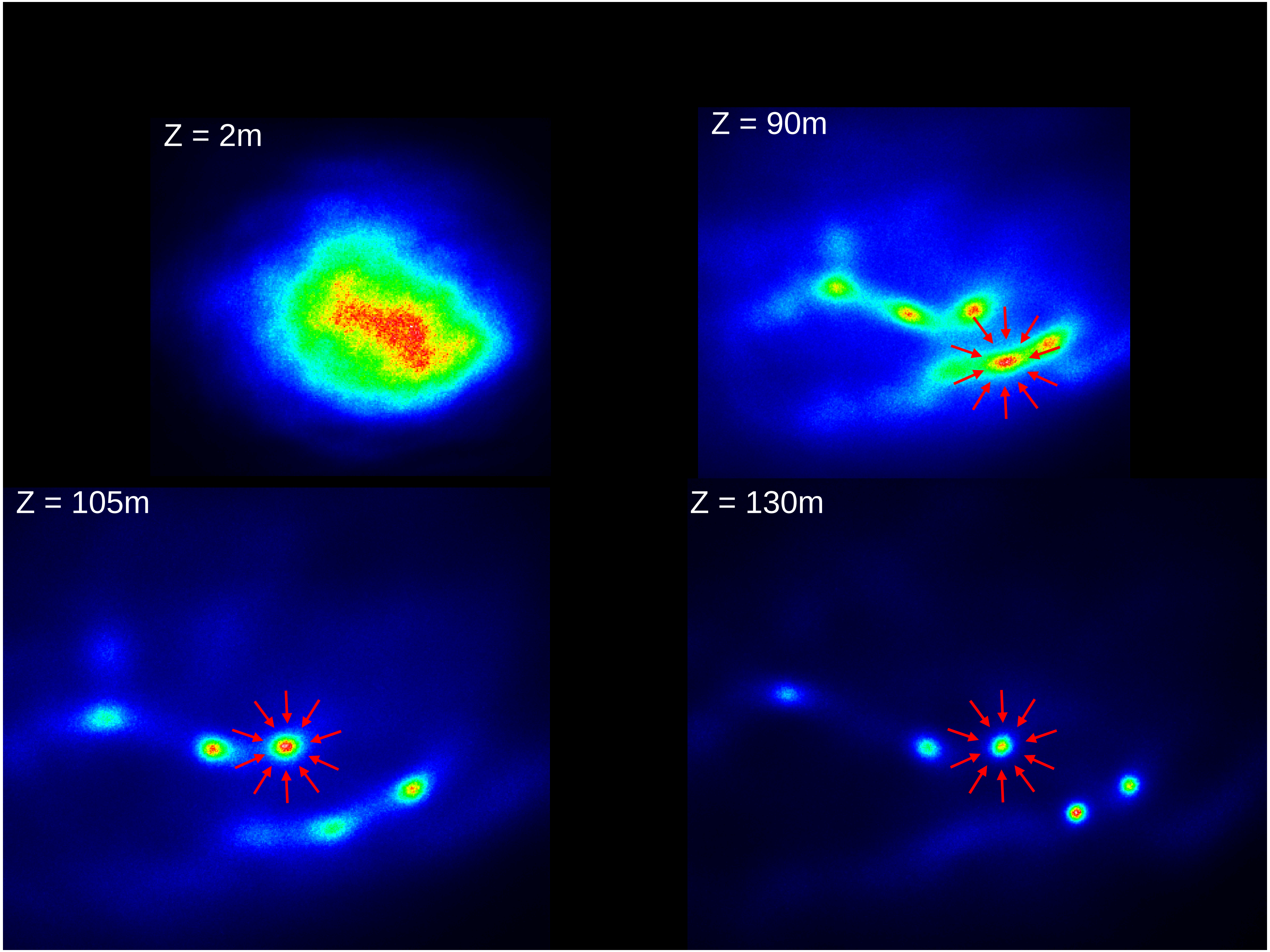




Simulation



1mm (a), 2 mm (b), 3 mm (c), 5 mm (d), 8 mm (e), 10 mm (f), 15 mm (g), +∞ (without pinhole) (h)


Z = 2m
Z = 90m
Z = 105m
Z = 130m

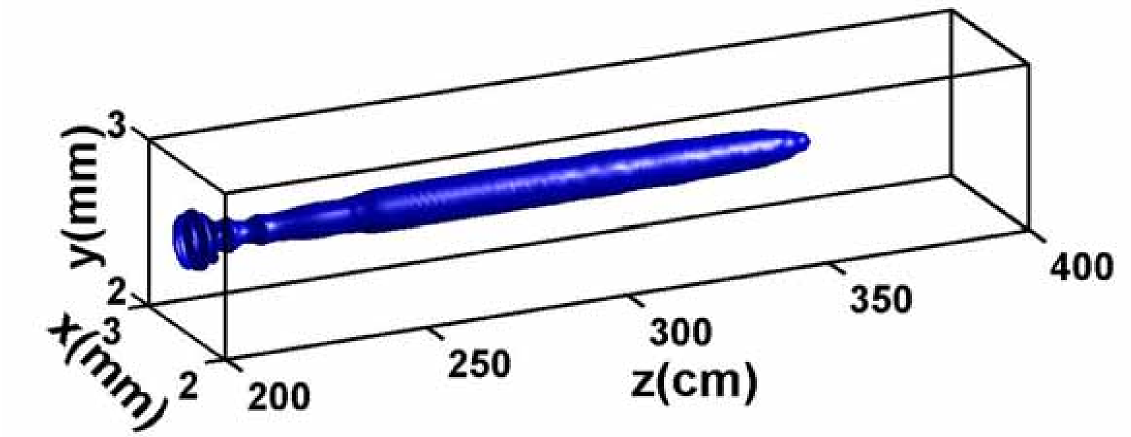


Fig 1 The energy fluence distribution of a single light bullet with doubled energy

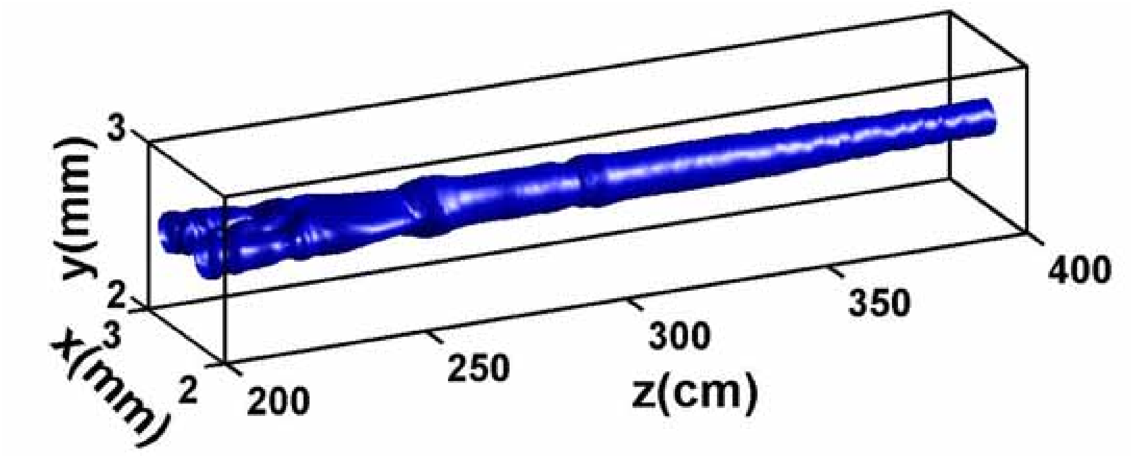
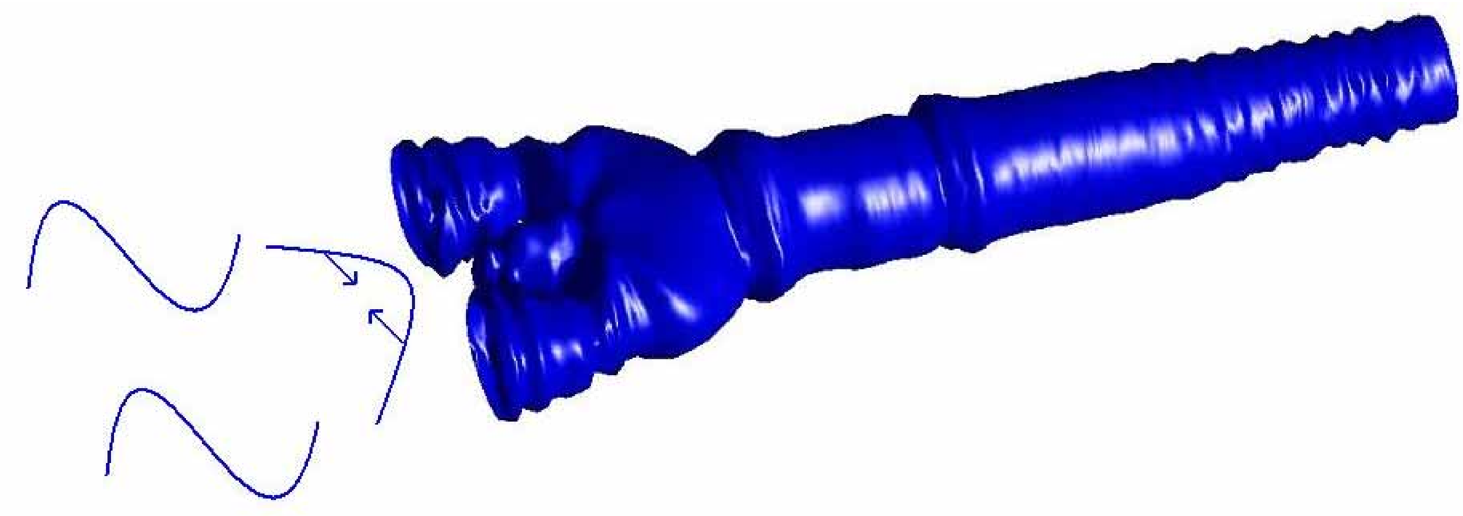
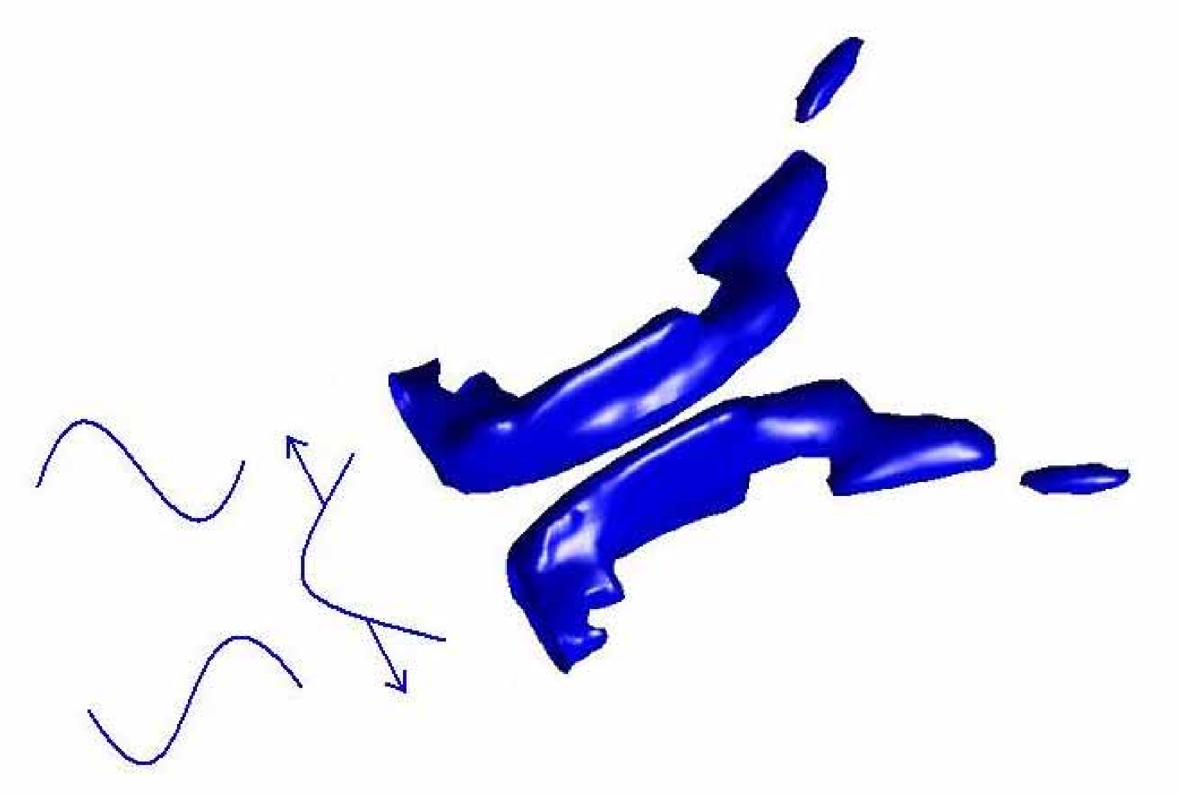


Fig 2 The energy fluence distribution of two interacting bullets which are in-phase

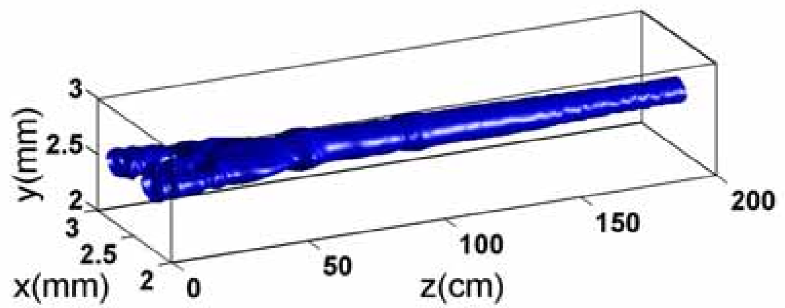


The fusion of two in-phase bullets

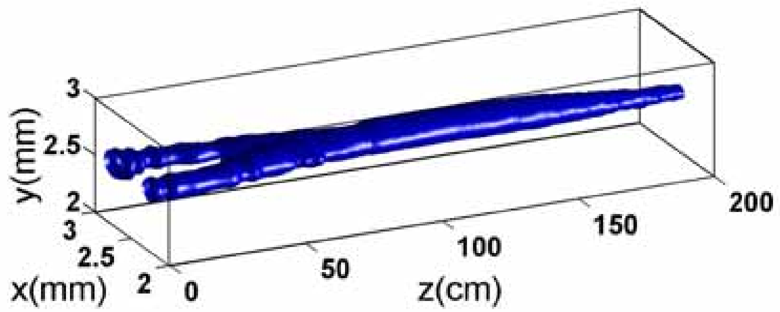


入射角为0.1^0,反相位的两根光丝的相互作用

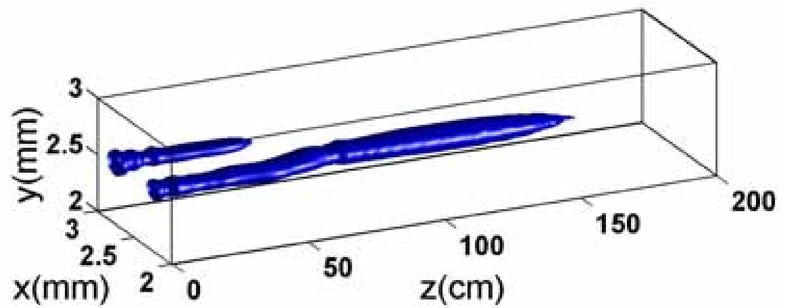
不同相位的双丝相互作用



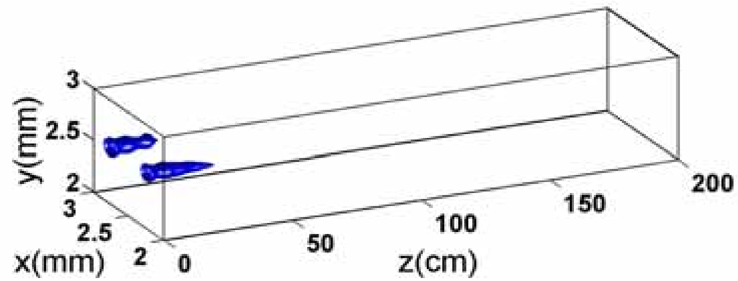
相位差为0



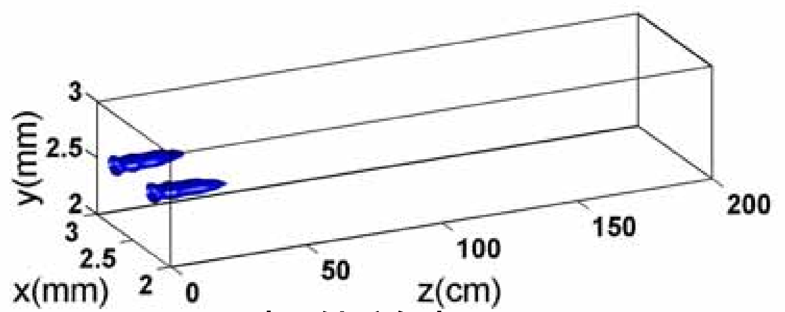
相位差为0.25π



相位差为0.5π

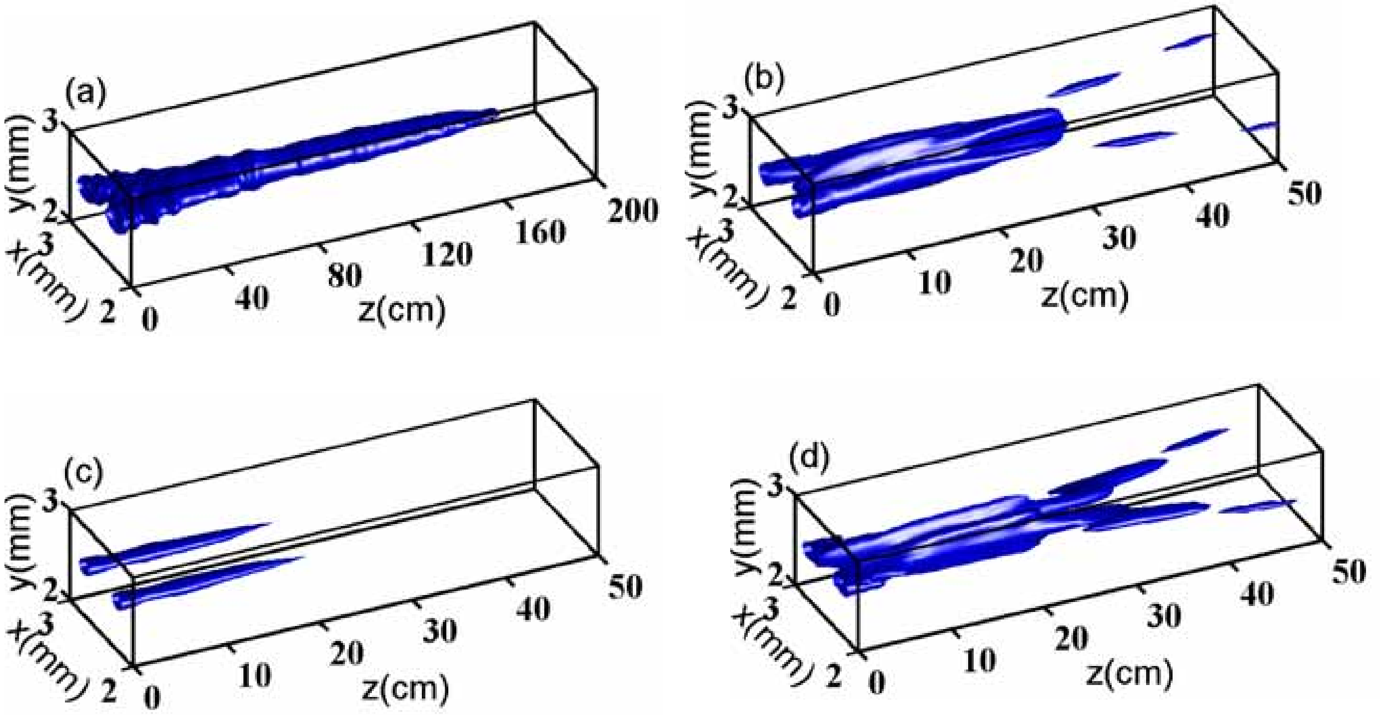


相位差为0.75π



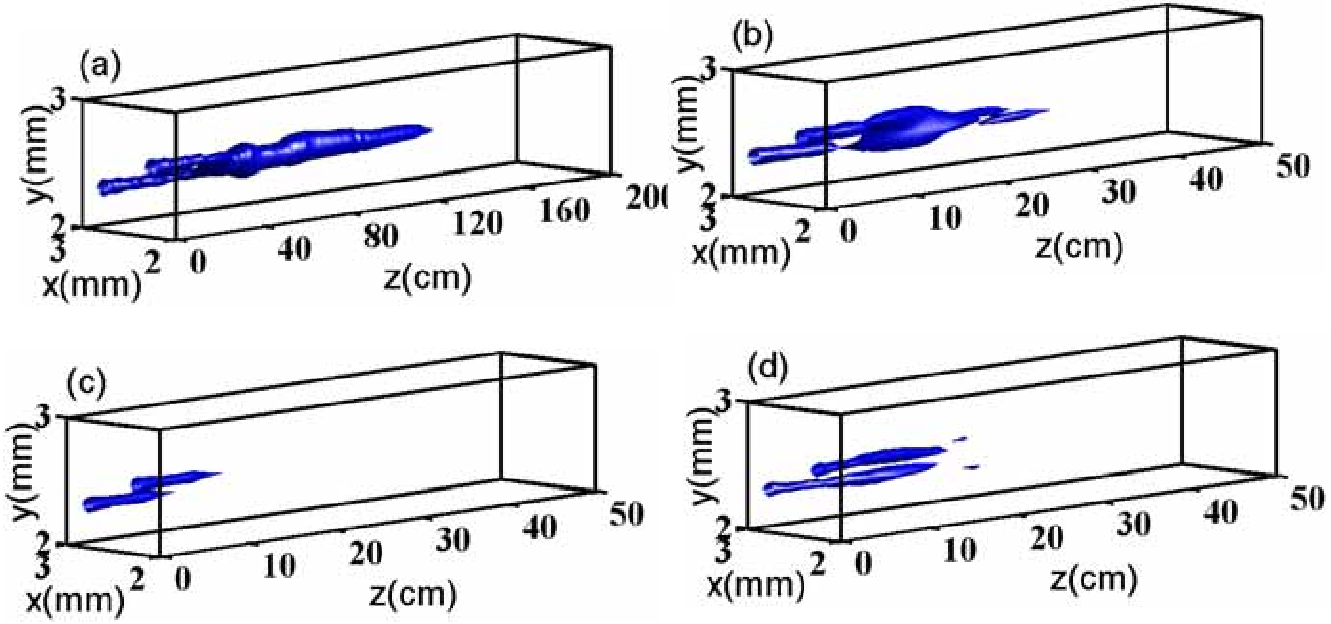
相位差为π

同平面，有入射角的情况



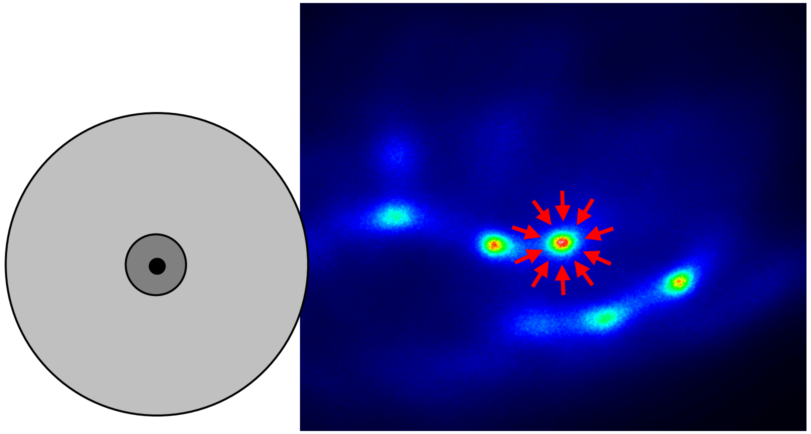
(a)入射角为0.01^0,同相位(b)入射角为0.1^0,同相位
(c)入射角为0.01^0,反相位(d)入射角为0.1^0,反相位

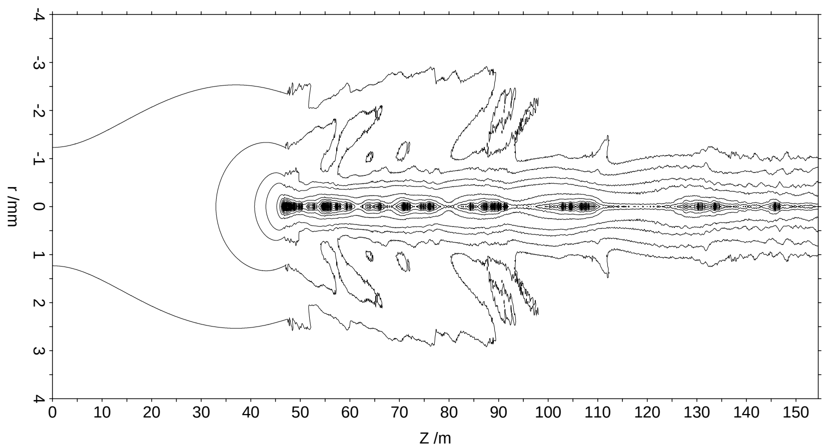
不同平面的双丝相互作用

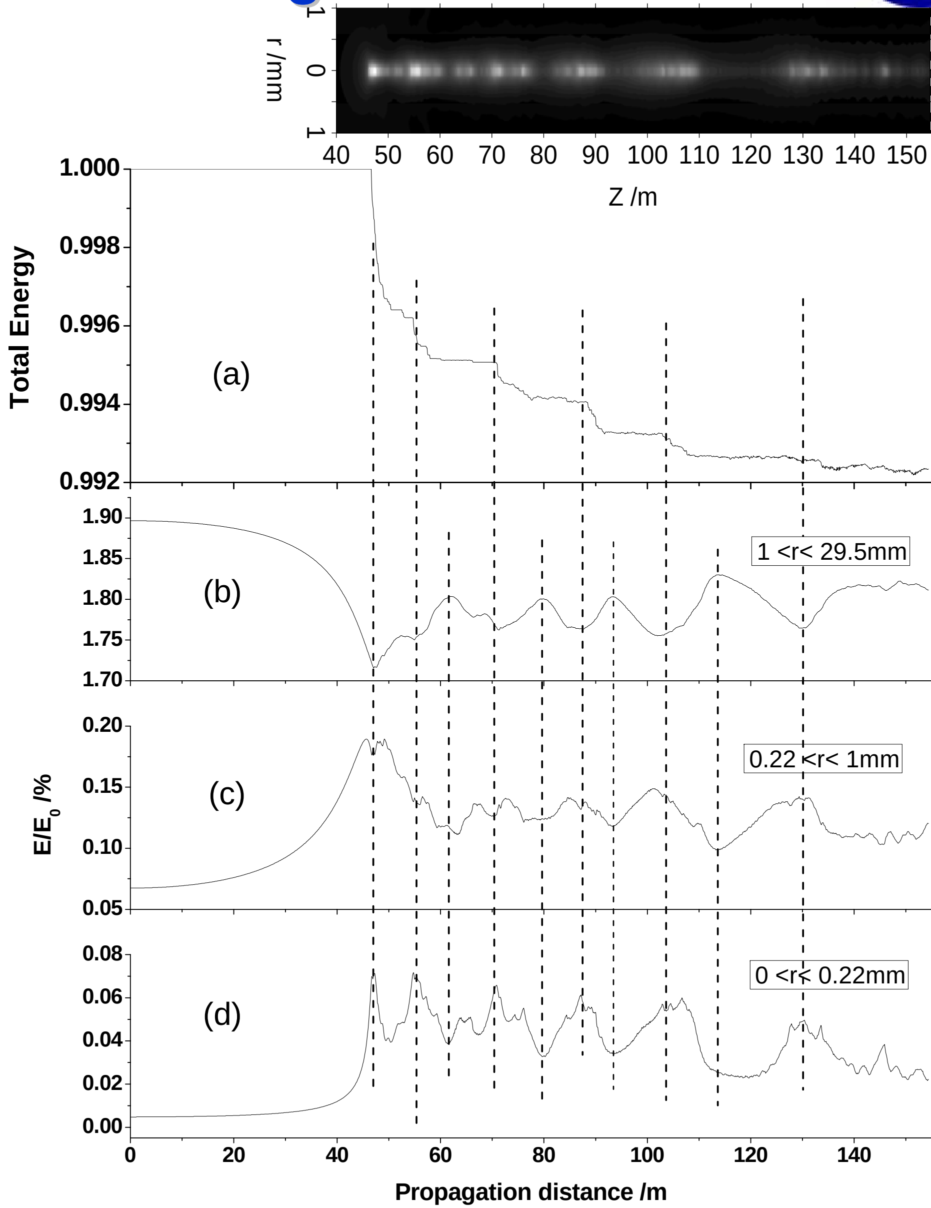


(a)入射角为0.01^0,同相位(b)入射角为0.1^0,同相位
(c)入射角为0.01^0,反相位(d)入射角为0.1^0,反相位

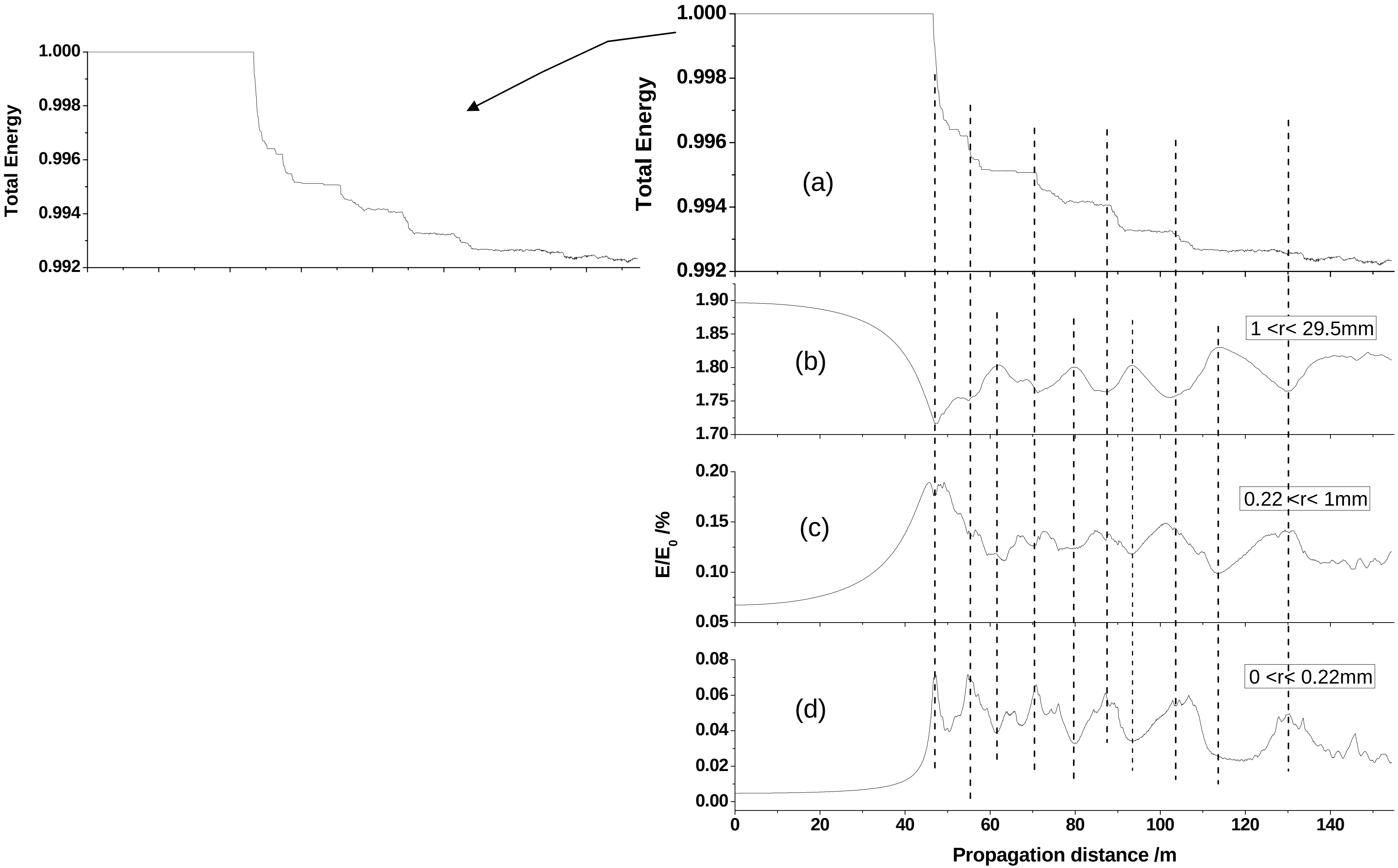
Energy interchange

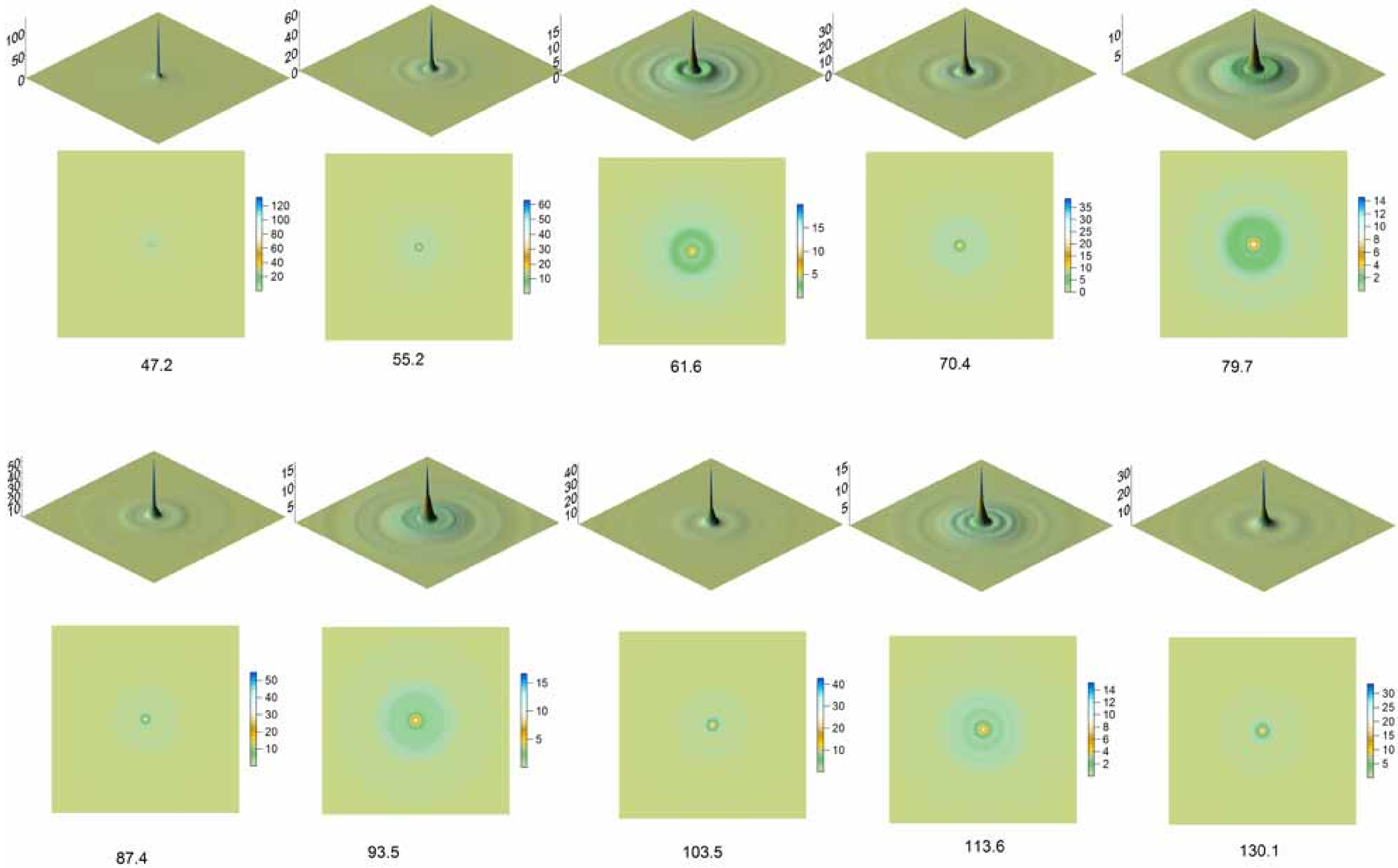






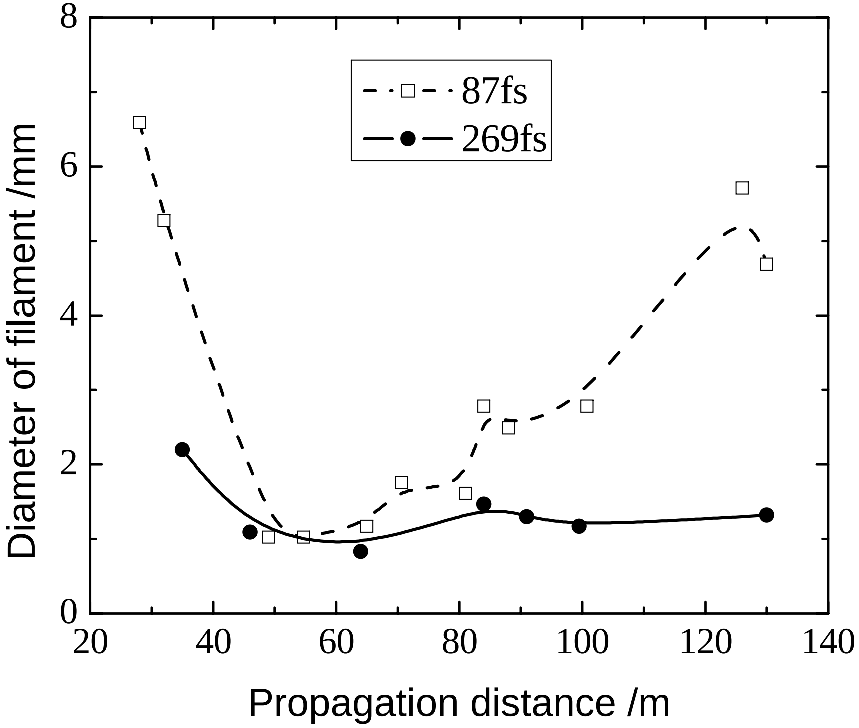
Long distance propagation - theory

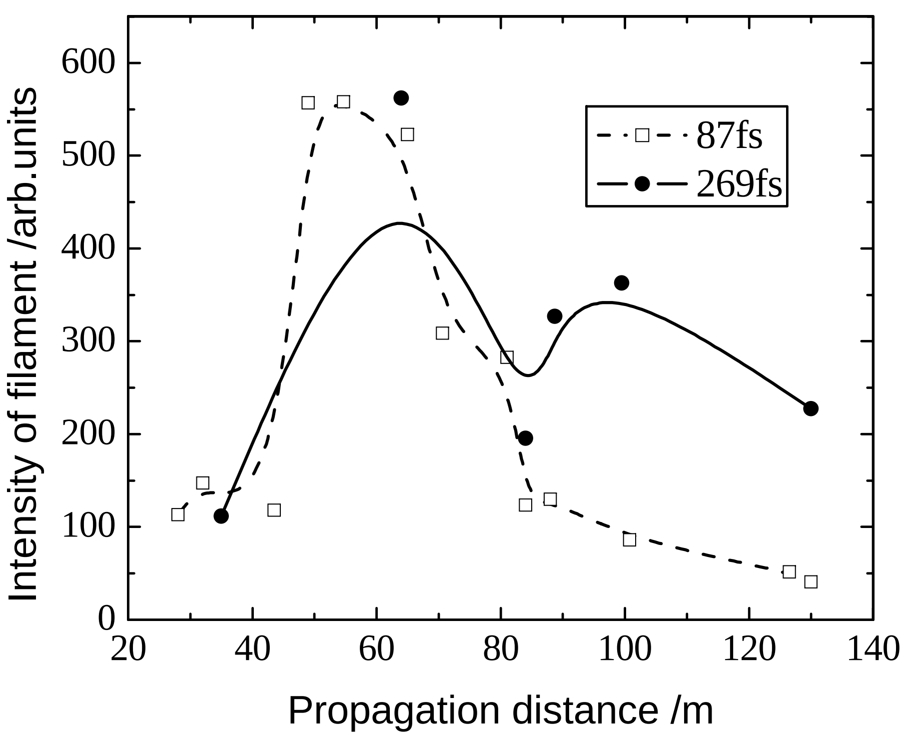




Frame size: 9mm X 9mm

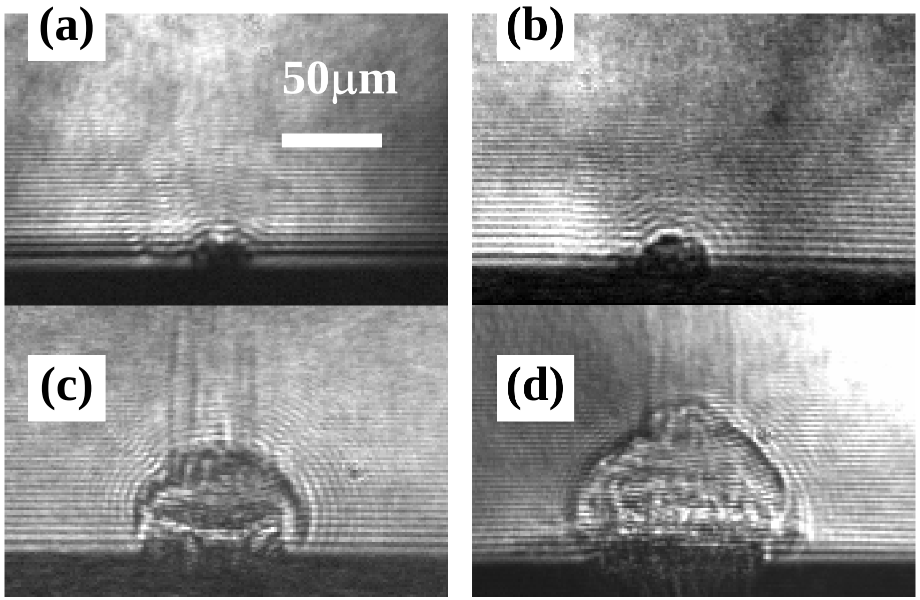
Long distance propagation - experiment





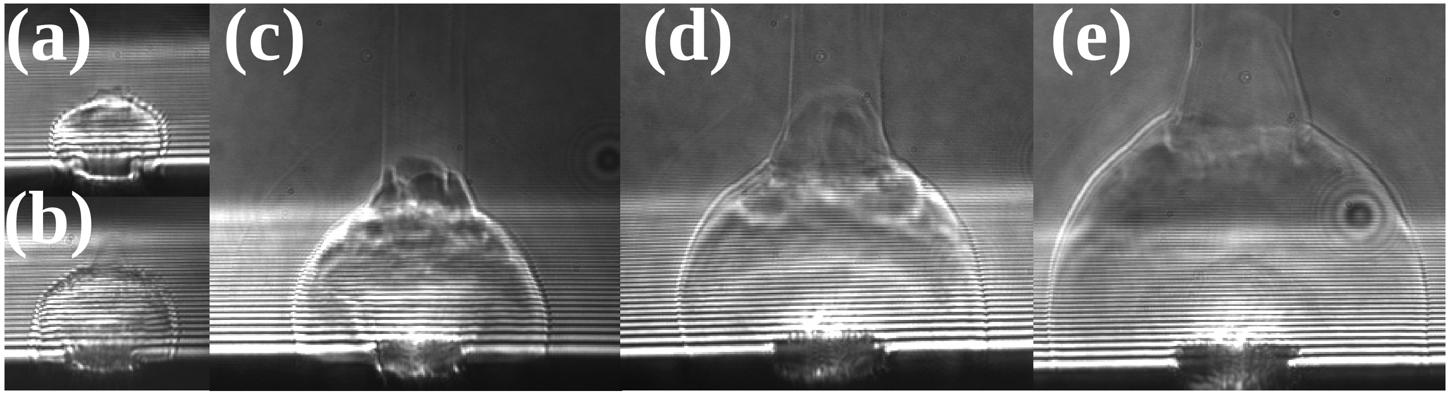
Investigation of inside of plasma channels

Launching another shock wave inside the channel



Evolution of the backward plasma expansion above water surface at (a) 1ns, (b) 2.5 ns, (c) 5ns and (d) 10ns, respectively, for a 5mJ of laser energy.

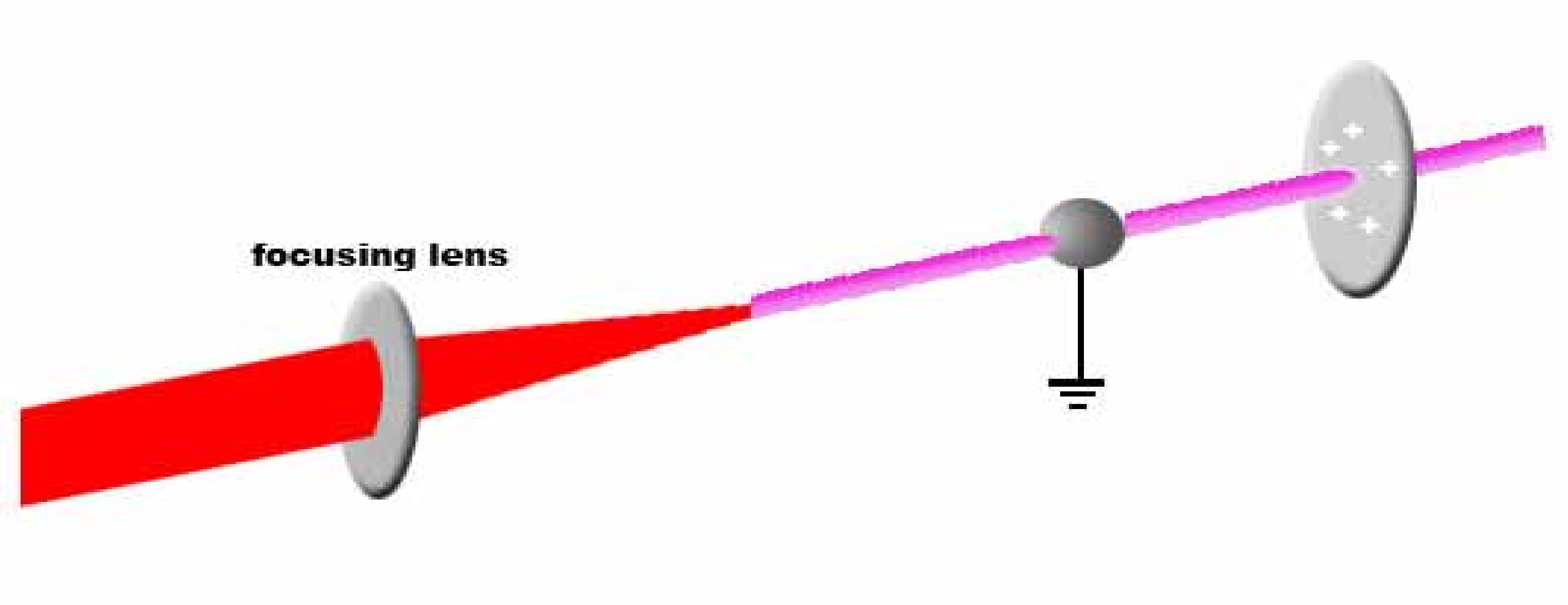
Temporal development of the shock wave



Laser Induced discharge

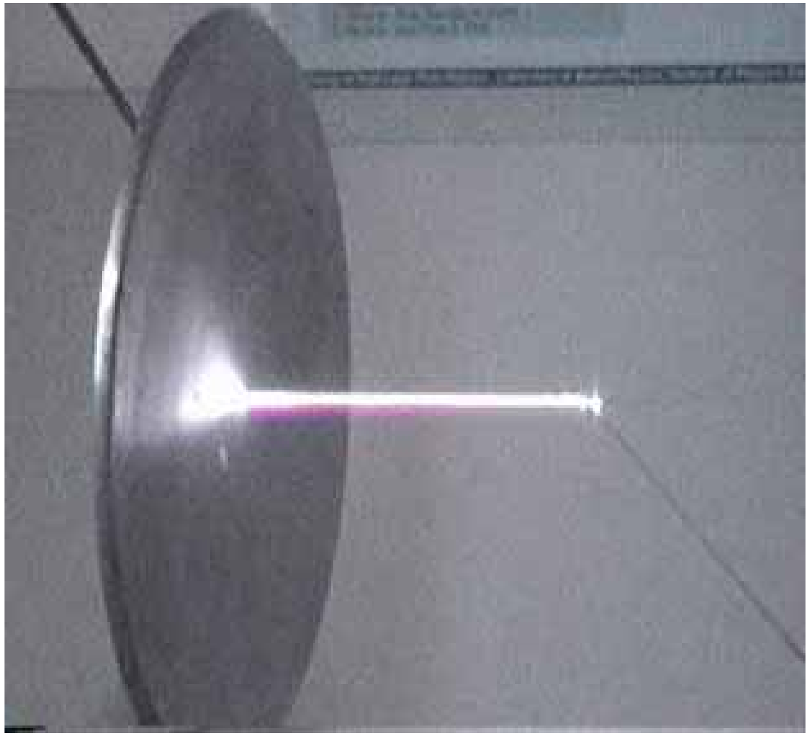
Setup for laser induced discharge experiment

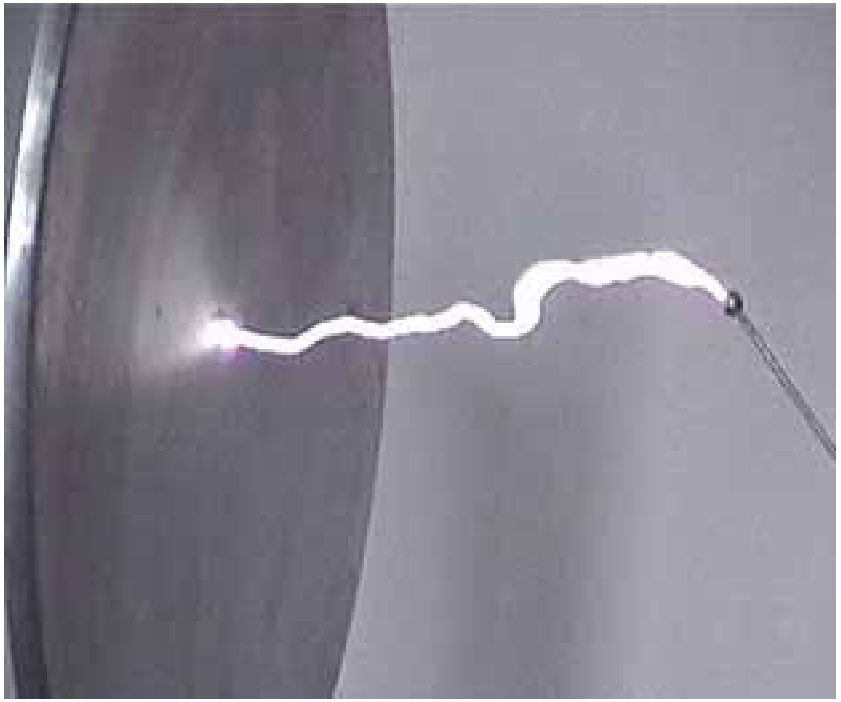
- 极板加上正高压，小球接地
- 超短脉冲激光在大气中聚焦形成等离子体通道
- 由形成的通道引导小球和极板间放电



Natural discharge and laser induced discharge

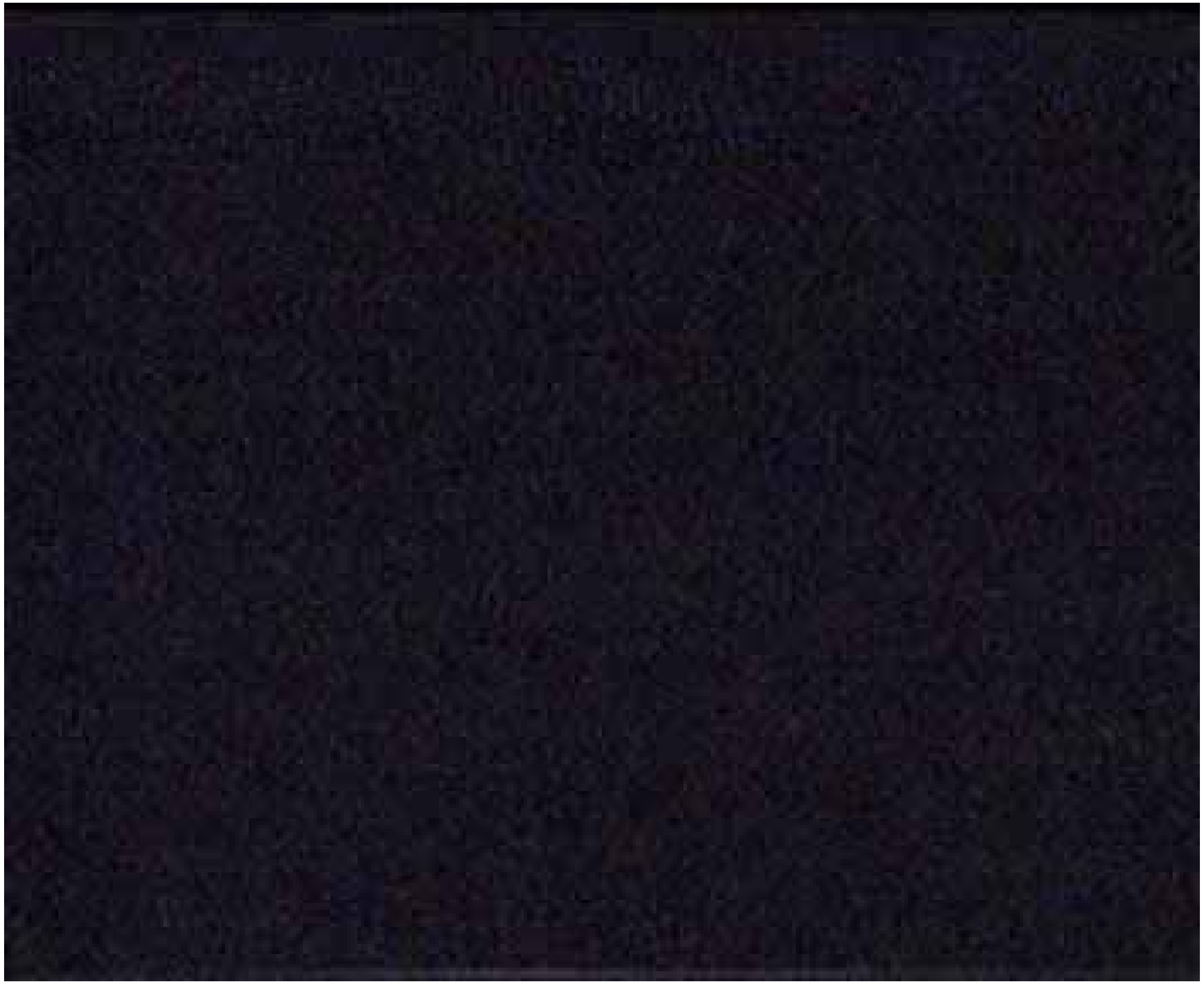
- 自然放电





- 激光诱导放电

Experiment for discharge



Summary

- km long plasma channels with rich physics
  - Energy Interchange
  - White light emission
  - Cone emission
  - Third harmonic generation
  - Splitting and fusing of the filaments
  - Vacuum channel
  - • • •
- Possible applications in laser lightening, fs lidar etc.


衷心感谢我的同事、合作者和我的学生们