Control of High Intensity Laser Propagation in the Atmosphere

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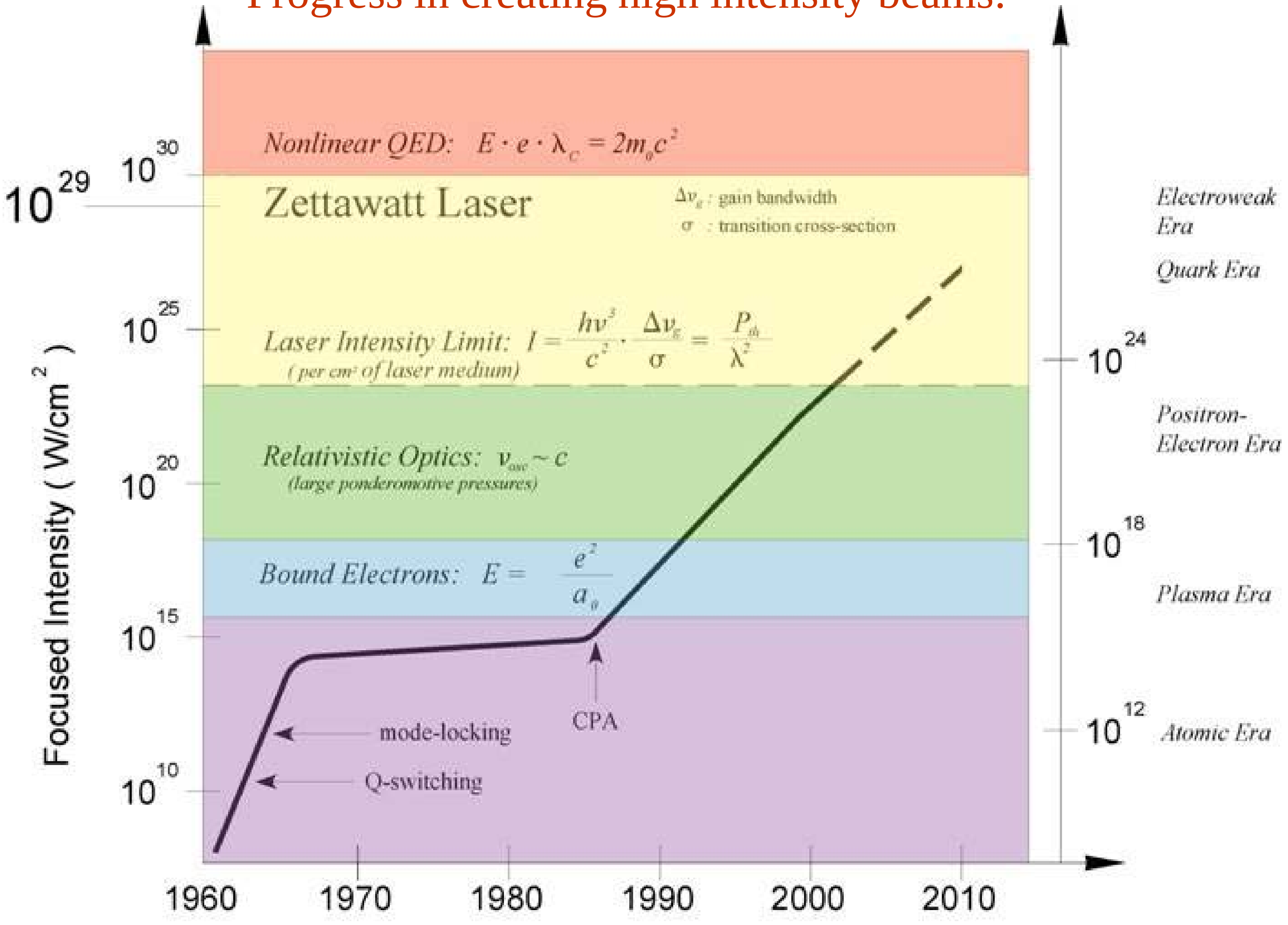
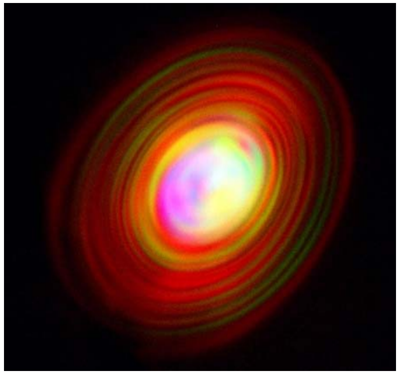
Chirped Pulse Amplification – Reaching Ultra High Intensities

Progress in creating high intensity beams:



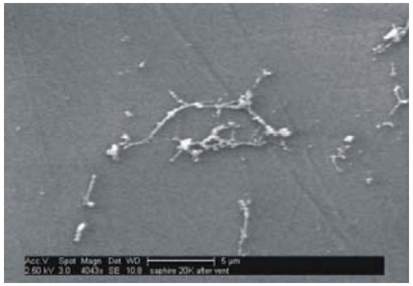
High Intensity Laser

Research Directions:



- Laser Propagation in the Atmosphere.

- Laser Wakefield Electron acceleration.
  (Guiding of 10^{18} W/cm^2 – in plasma channels up to 20cm, Electron Injection, etc…)



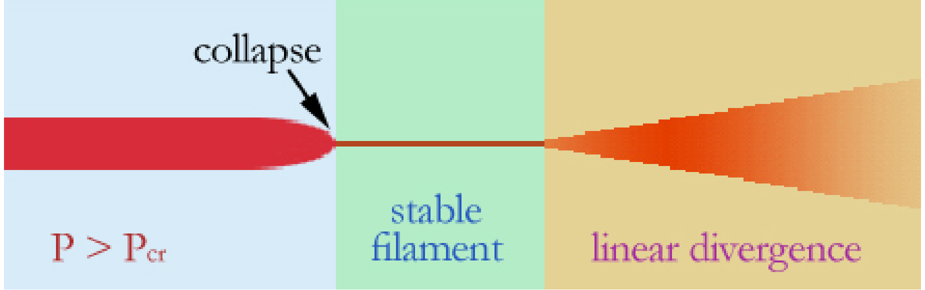
- Laser interaction with Solid and Cluster Targets – ion acelleration.

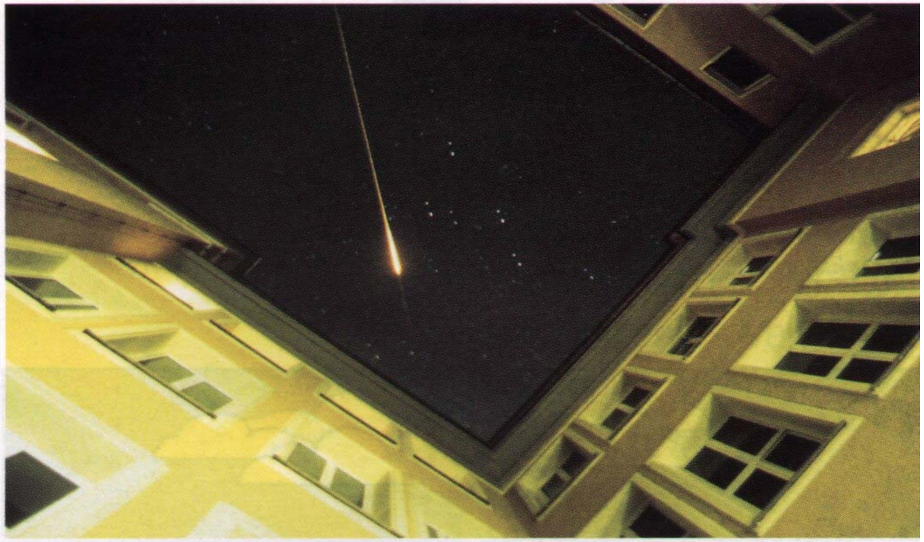
- Fast Ignition

Propagation in the Atmosphere

- The light creates a waveguide in the atmosphere through nonlinear interactions.
- This enables propagation of high intensities to long distances (km’s).
- Light filament leave in their wake a thin ionized channel.

Stages in propagation of a high intensity beam





$$\lambda = 0.8\,\mu m,\ P = 2.2\,TW,\ \mathrm{E} = 240\,mJ,\ \tau = 110\ f\sec$$

$$10\,Hz\ \ rep - rate,\ L_{peak} = 2\,km,\ L_{\max} = 12\,km,\ \eta = 40\%$$

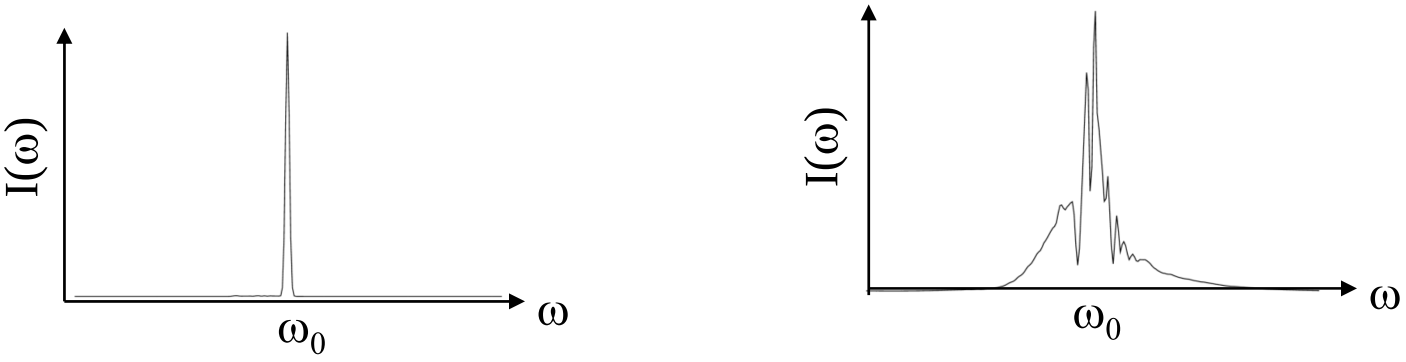
Laser Pulse Filamentation

- Laser pulse undergoes white light generation and forms plasma and optical filaments

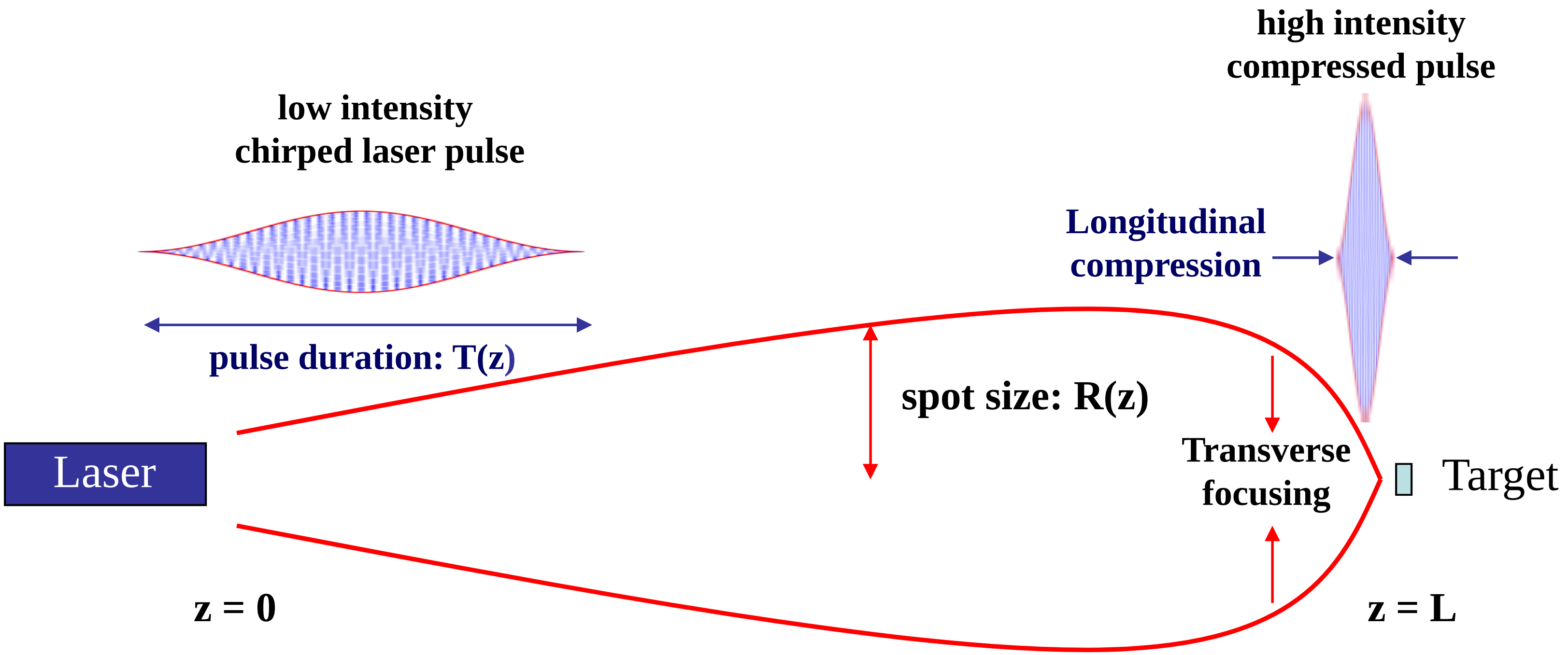
refractive index:

$$n = 1 - \underset{\substack{\uparrow \\ \text{concave lens}}}{\omega_p^2 / 2\omega^2} + \underset{\substack{\uparrow \\ \text{convex lens}}}{n_2 I}$$

Spectral Broadening



Laser Pulse Compression and Breakdown in the Atmosphere



- The compressed pulse induces localized atmospheric breakdown and generates directed white light

Potential Applications

•Remote Sensing

-White light source for spectroscopy,

-Air breakdown produces UV for fluorescence

-Generation of III harmonics (268nm) – excitation of organic molecules

- Powerful radiation point sources

• Countermeasures

- Direct broadband blinding of optical sensors

-Material (Sensor) Damage

- Compressed laser pulse can damage coatings, CCDs, Windows, etc.

•Induced plasma channels

-high conductivity plasma channel can initiate breakdown- Lightning control ?

- Plasma channels can be used as reflectors.

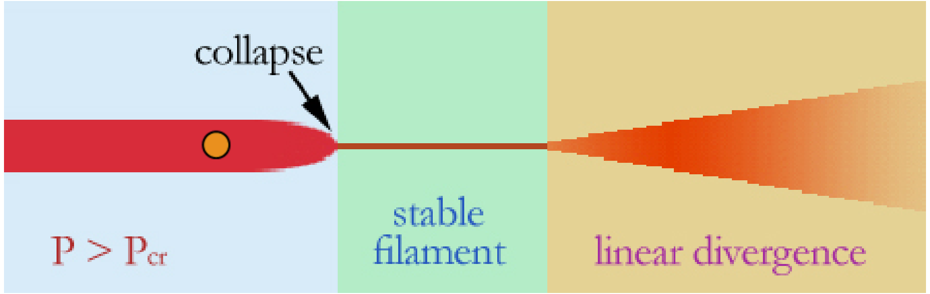
Long Distance Filamentation

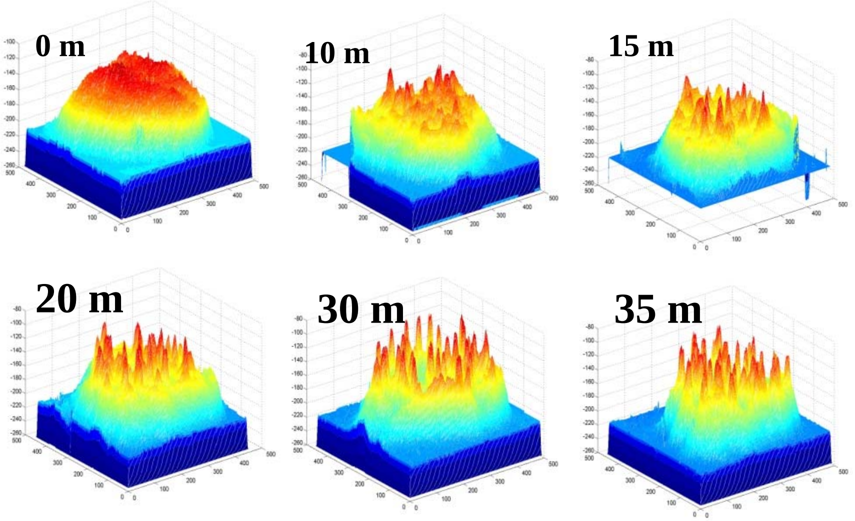
- The collapse distance is not easily controlled.

- The spatial pattern is random and cannot be reproduced or predetermined.

→ Theses issues are crucial for applications – control?

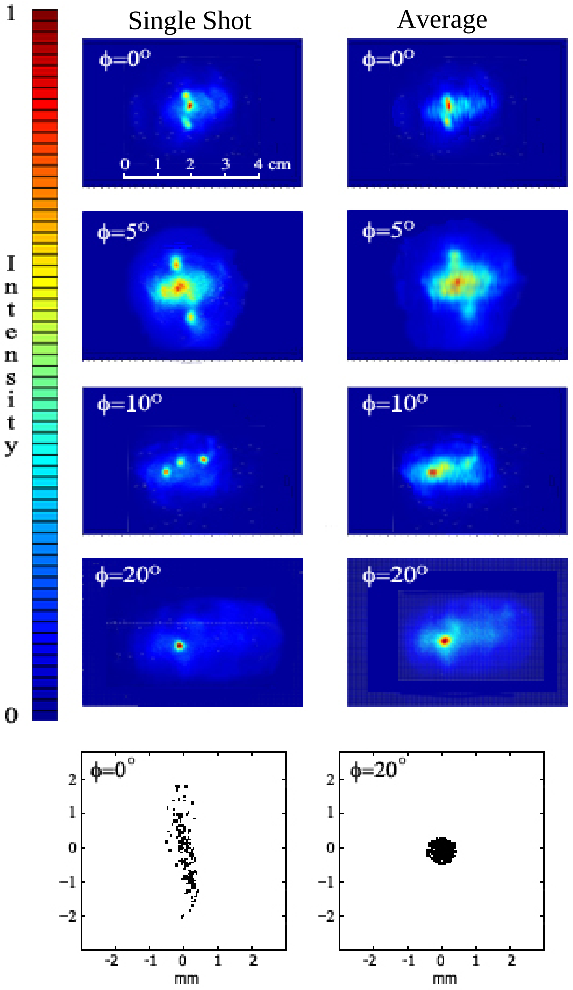
Stages in propagation of a high intensity beam





Control of Filamentation

- Development of simple methods for:
    - Control of filamentation pattern.
    - Control over number of filaments
    - Shot to shot stability



OPTICS LETTERS ***29,*** *p.1772 (2004)*

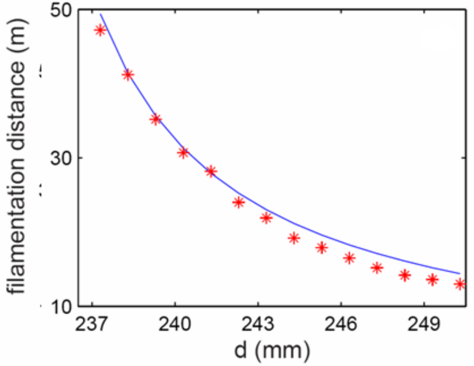
Control of Filamentation

Main Challenge – delay the collapse to km's

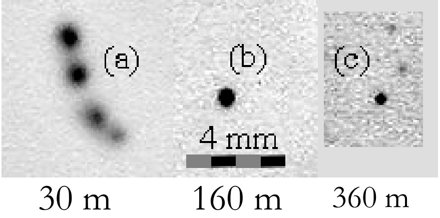
II.Control of collapse distance:

- New method for the delay of collapse (linear defocusing + nonlinear self focusing)
- Demonstrated experimentally up to 400 meters.
- Longitudinal control combined with transverse control.

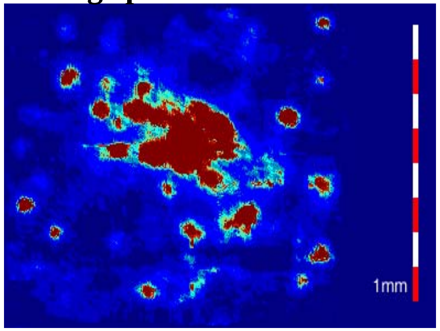
Control of collapse distance



PVC Damage

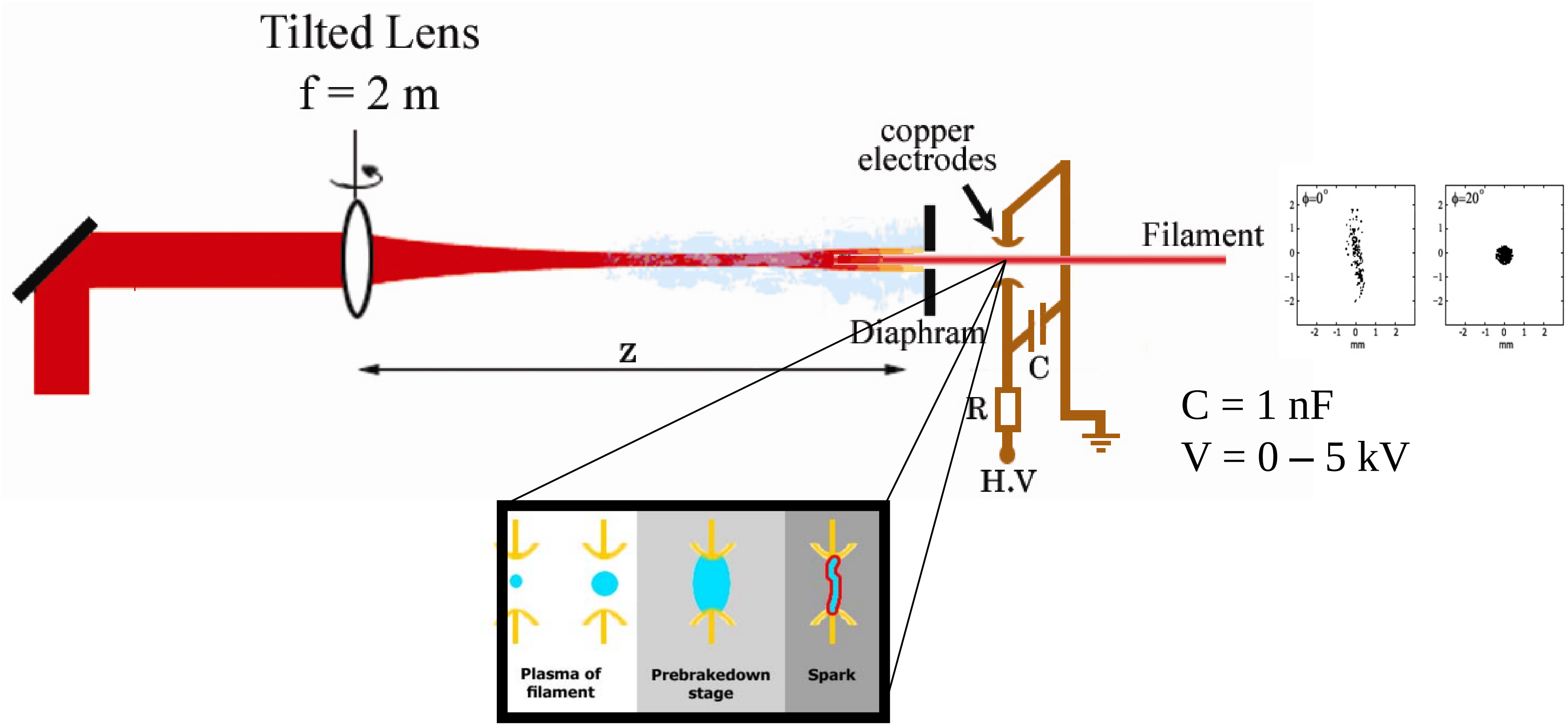


Damage pattern at 360 meters



OPTICS EXPRESS ***14,*** *p. 4946 (2006)*

Plasma filament - Experimental Setup



C = 1 nF
V = 0 – 5 kV

We recorded the value of the voltage breakdown with and without the presence of filament between the electrodes.

The ratio is $h = \frac{V_{fil}}{V_0}$ is our parameter for electron density.

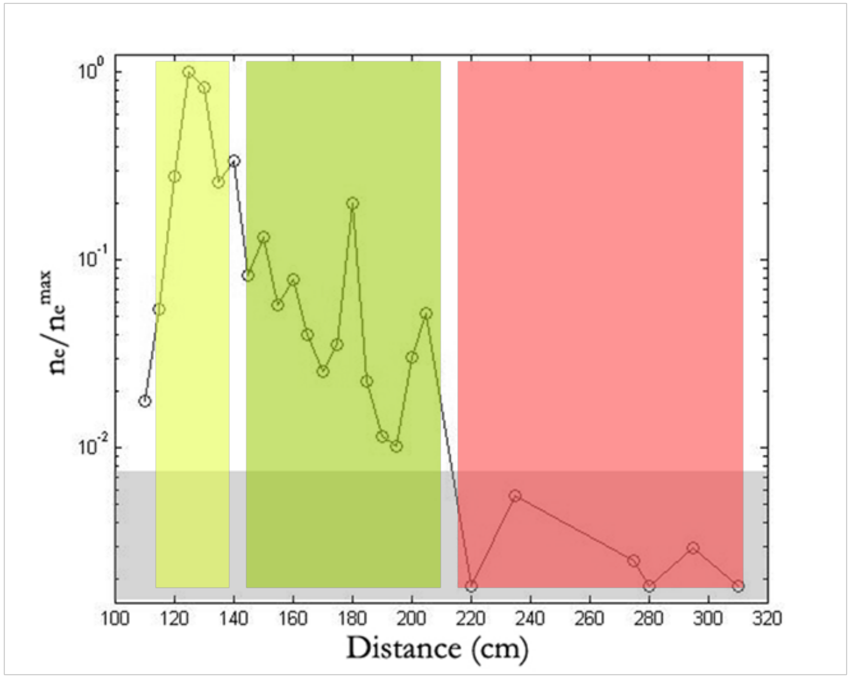
Results: Fine Structure of a Laser-Plasma Filament

A 266 GW, 100 fsec pulse was launched to the atmosphere.
It was focused & arranged using a *f* = *5m* lens, to our setup.

I. Peak electron density ~ 5x10^{16} cm^{-3}

II. Rapid electron density variation.
An order of magnitude change over a distance of 5 cm.

III. Postionization regime –
Guided light structure supported by a low electron density region ($n_e < 10^{14}$ cm^{-3})



PRL 2007

Filaments generated by single short pulse laser

- Random filament formation can be simply controlled by introducing pulse astigmatism

- Number of filaments can be reduced to one pulse.

- Filamentation distance can be continuously controlled with a double lens setup to at least length scales of hundreds of meters.

- Electron density in plasma channel is not constant – can vary over three orders of magnitude.

- Filament energy ~ 1 mJ/ filament

How to produce powerful radiation source at remote location?

Generation of remote radition source

LPL Absorption

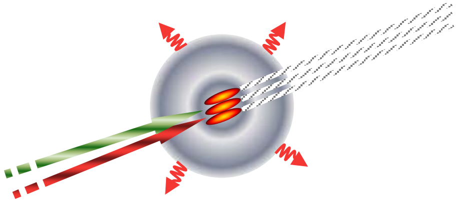
In Air L_{abs} = km's

In plasma $L_{abs} = \frac{c}{\nu_e}\left(\frac{\lambda_p}{\lambda}\right)^2$ ~ 6 cm

λ = 10.6 μm n_e= $5 \cdot 10^{16}$ cm^{-3}

Plasma Channels:
Formation
Stability

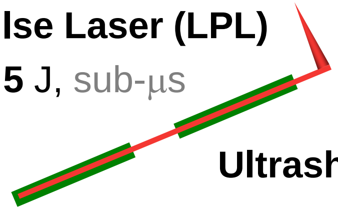
Plasma Flare:
Radiation Spectrum



Interaction with plasma:
Absorption
n(r,t), T(r,t)

Propagation:
USPL
LPL

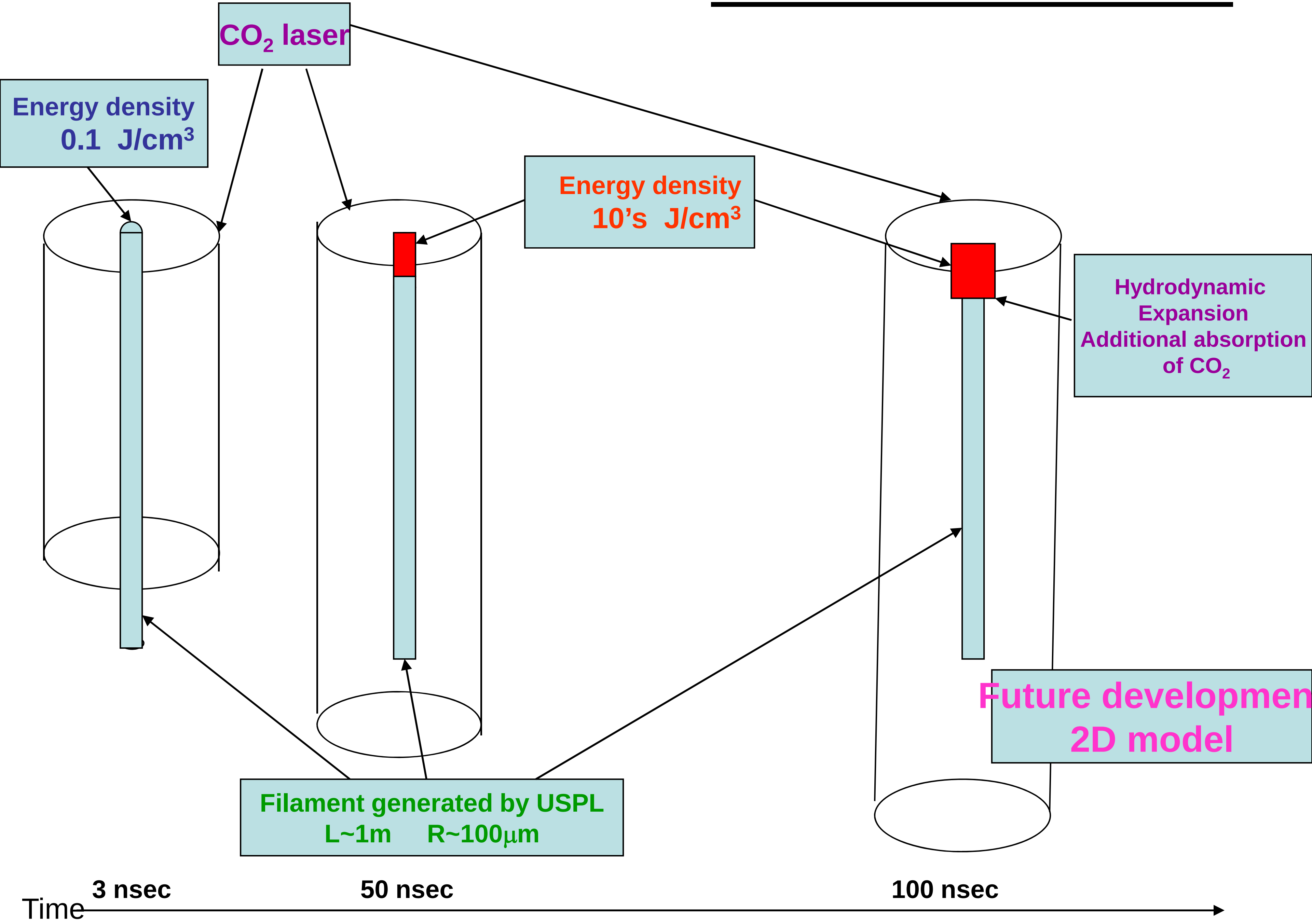
Long Pulse Laser (LPL)
E < 5 J, sub-µs



Ultrashort Pulse Laser (USPL)
10's mJ, sub-ps,

Our code are predicts that **hundreds** of microjoules will be emitted by plasma flare

Plasma evolution vs time



CO_2 laser

Energy density
0.1 J/cm^3

Energy density
10’s J/cm^3

Hydrodynamic
Expansion
Additional absorption
of CO_2

Future developmen
2D model

Filament generated by USPL
L~1m R~100μm

3 nsec

50 nsec

100 nsec

Time

Detailed model for plasma channel evolution generated by DLP

- Multiphoton and impact ionization.
- Electron Joule heating.
- Thermal conduction
- Cooling by expansion
- Radiation losses (LTE).
- 1D hydrodynamics – channel expansion.
- Electron-ion and ion-ion recombination.
- Attachment.
- Detachment.
- Dissociation.
- Excitations (molecules (vibrations), atoms, ions)
- Radiation (molecules, atoms, ions)

Plasma channel emission

Time dependent plasma chemistry model coupled to hydrodynamics

Time integrated net emission coefficient - LTE

Detailed emission of molecular bands, atomic and ion lines

Radiation output for energy balance

Flare Radiation

Electron and air temperatures

$$\frac{dT_e}{dt} = J_h - \frac{T_e - T_i}{\tau_{eqe}} - \frac{4}{3} T_e \frac{\dot{r}}{r} - \frac{r}{l_{opacity}} \sigma T^4$$

Radiation losses

Electron heating by absorption of laser energy

Energy transfer from electrons to air

Cooling by expansion

$$\frac{dT_i}{dt} = \frac{T_e - T_i}{\tau_{eqi}} - \frac{4}{7} T_i \frac{\dot{r}}{r} - 4d\chi_h \frac{T_i - T_s}{r^2}$$

Cooling by heat conduction at plasma boundary

Radial expansion acceleration

Air pressure

$$\frac{dr^2}{dt^2} = 2\frac{(P_e + P_i - P_s)}{m_i n_{mol} r}$$

Shock pressure generated in ambient air

Electron pressure

Laser parameters for generating a light source in air

	Intensity (W/cm^2)	Pulse duration (s)	Wavelength (μm)
Short Pulse Laser	$8 \cdot 10^{13}$	10^{-13}	0.8
Long Pulse Laser	$x \cdot 10^{7}$	$1 \cdot 10^{-7}$	10.6

Channel initial radius 100 μm

Emission from DLP laser generated plasma

(per single filament)

CO_2 laser intensity on the plasma	**W/cm^2**	**$5*10^7$**	**$3*10^7$**	**$1*10^7$**
Emission by molecules				
• Total Emission in 2^+ band	J	$2.5\ 10^{-6}$	$4.4\ 10^{-6}$	$0.1\ 10^{-6}$
Emission by atoms				
• Total O emission	J	$2.5*10^{-4}$	$5.3*10^{-4}$	$1\ *10^{-4}$
• Total N emission	J	$2.6*10^{-4}$	$6.5*10^{-5}$	$2.1*10^{-5}$
Emission by ions				
• Total O+ emission	J	$3*10^{-4}$	$1.2*10^{-6}$	$6.1*10^{-11}$
• Total N+ emission	J	$1*10^{-4}$	$1.8*10^{-6}$	$4.3*10^{-11}$

Emission from DLP laser generated plasma

(per single filament)

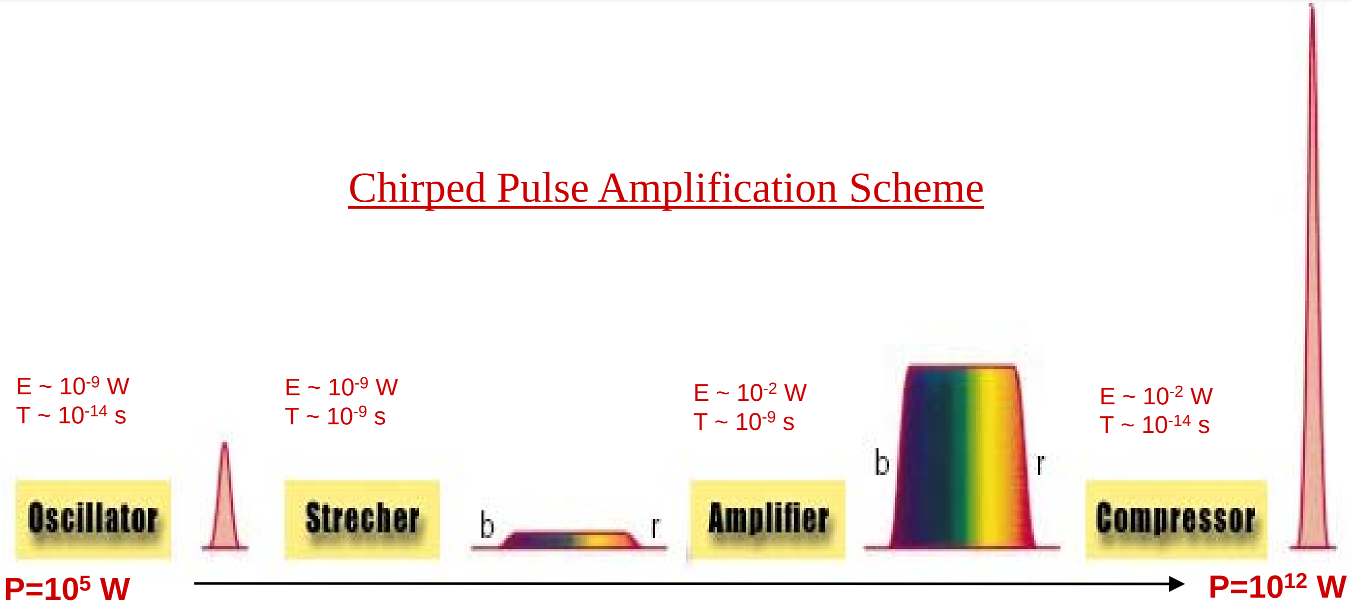
Total Emission in bands:

CO_2 laser intensity on the plasma	W/cm^2	$5*10^7$	$3*10^7$	$1*10^7$
Range: 0.3-0.7 microns	J	$5*10^{-4}$	$6*10^{-5}$	$2.5*10^{-5}$
Range: 0.7-1.2 microns	J	$4*10^{-4}$	$5*10^{-4}$	$1.2*10^{-4}$

- **CONCLUSION** : more than **100 MICROJOULES** can be emitted by the single filament using **DLP approach**

Chirped Pulse Amplification – Reaching Ultra High Intensities

Chirped Pulse Amplification Scheme



E ~ 10^{-9} W
T ~ 10^{-14} s

E ~ 10^{-9} W
T ~ 10^{-9} s

E ~ 10^{-2} W
T ~ 10^{-9} s

E ~ 10^{-2} W
T ~ 10^{-14} s

P=10^5 W

P=10^{12} W

Overcoming :

- The optical threshold damage.
- Nonlinear deformations of beam.

Creating :

- Ultrashort ($\tau \sim 10^{-15}$ sec)
- Energetic (E > 100 mJ)