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- Omics group has organised 500 conferences, workshops and national symposium across the major cities including SanFrancisco,Omaha,Orlado,Rayleigh,SantaClara,Chicago,Philadelphia,Unitedkingdom,Baltimore,SanAntanio,Dubai,Hyderabad,Bangaluru and Mumbai.

Polarization evolution; a method to measure nonlinear interaction in light filaments

Ladan Arissian

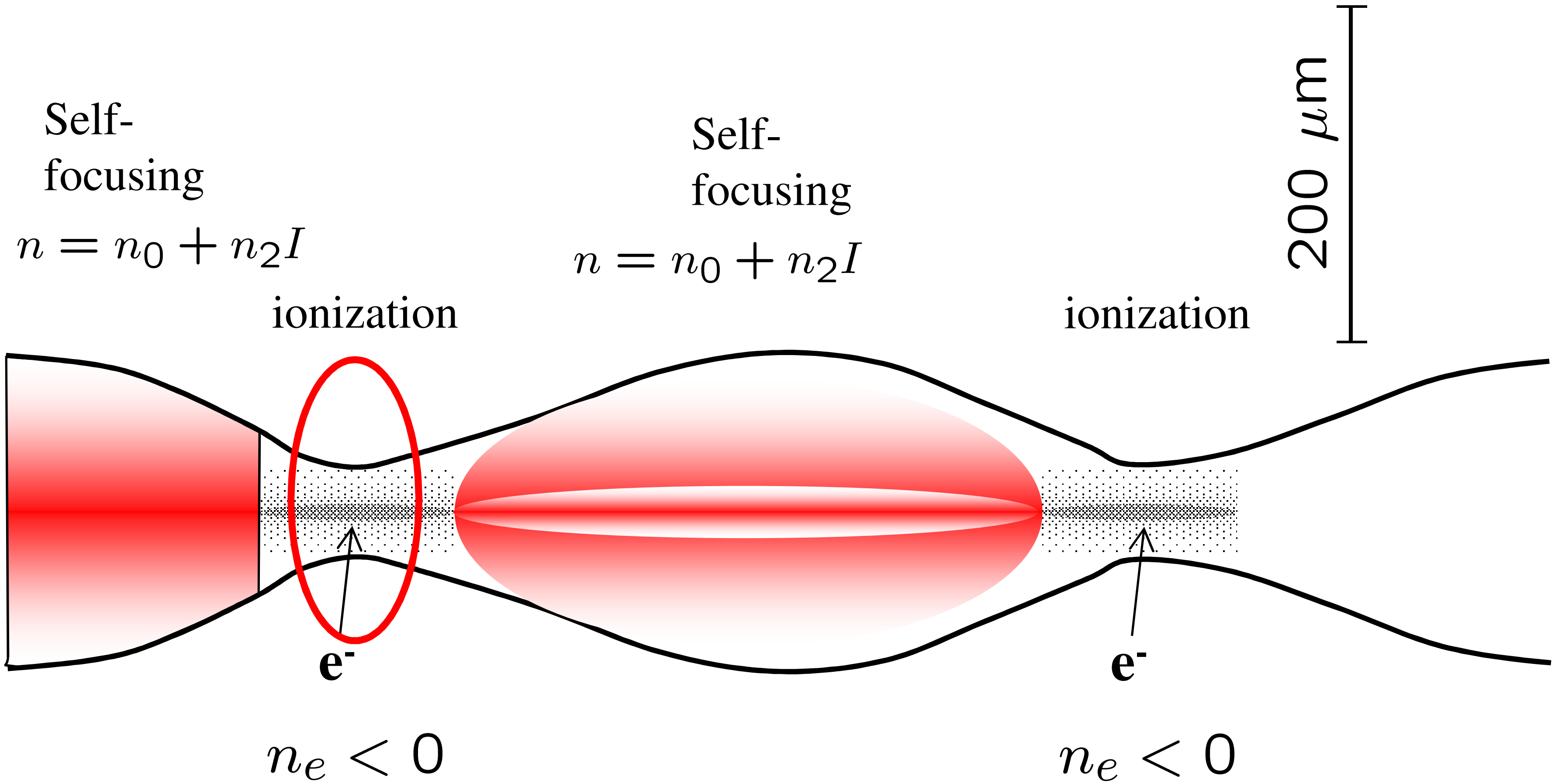
2nd International Conference and Exhibition on Lasers, Optics & Photonics

09/08 /2014

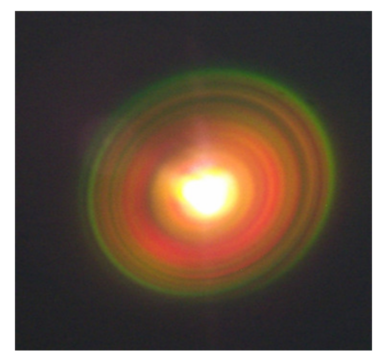
Outline

1) Laser filamentation in air ; a balance between electronic Kerr focusing and plasma defocusing
2) Nonlinaer polarization; a spatio-temporal effect
3) Tunnel ionization follows the light polarization (also the electron current)

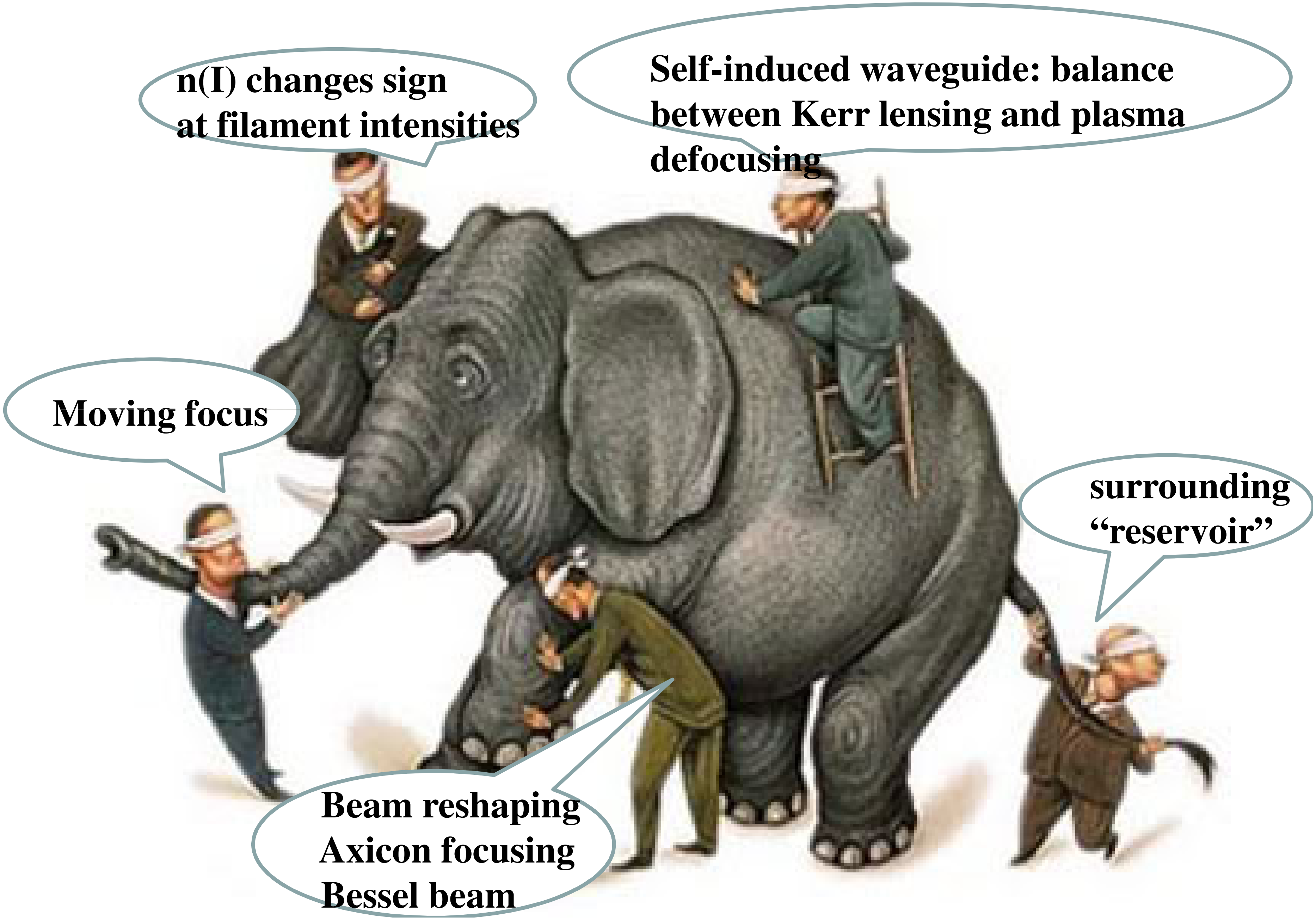
Laser filamentation in air

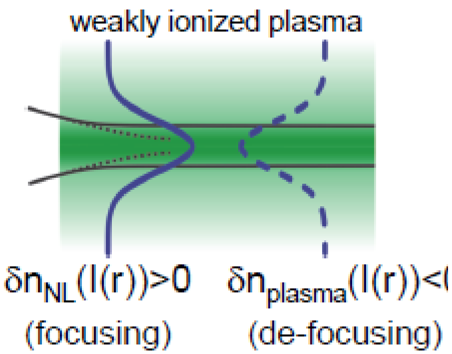


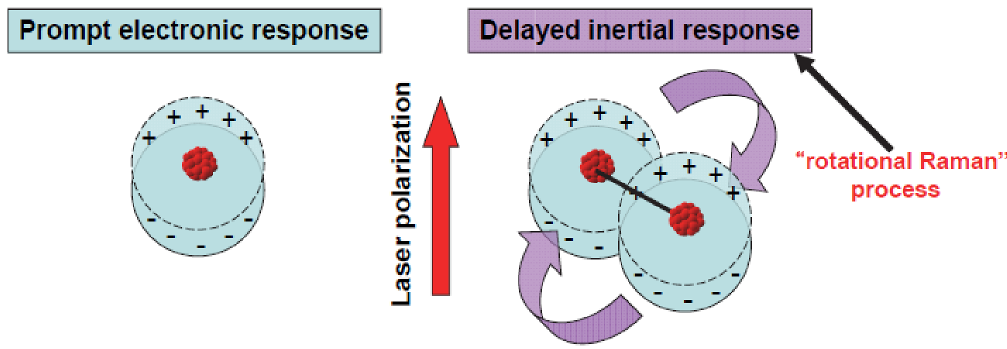
Filament is a unique light-matter interaction in which both light and matter have to be fully considered.



Filamentation theories



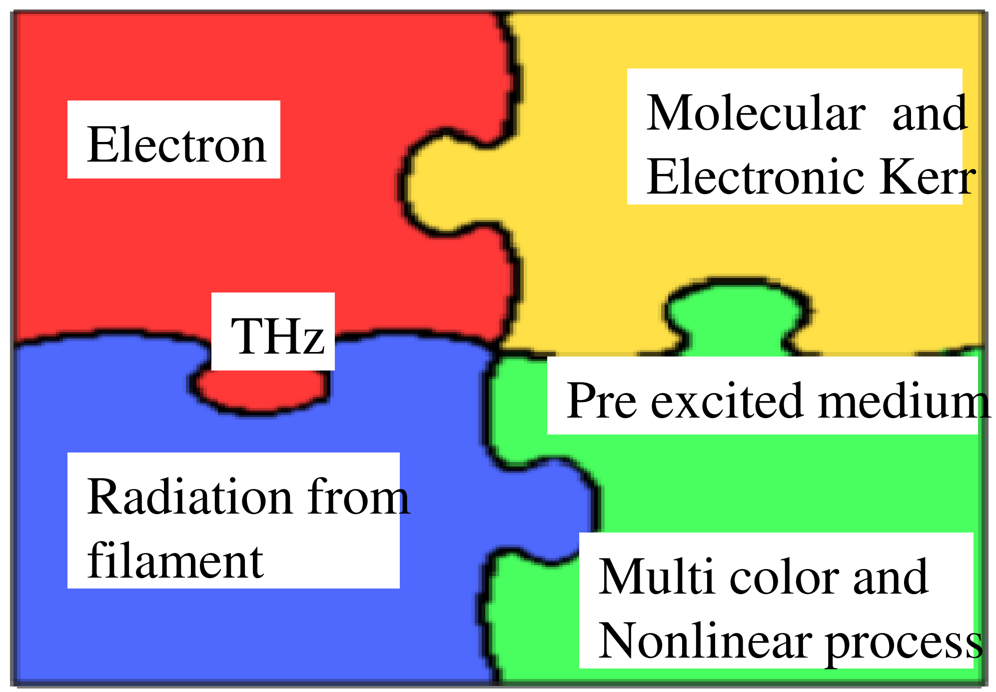




1. **Pre-filamentation propagation**
2. **Polarization evolution**
3. **Fluorescence**
4. **Nonlinear interaction**

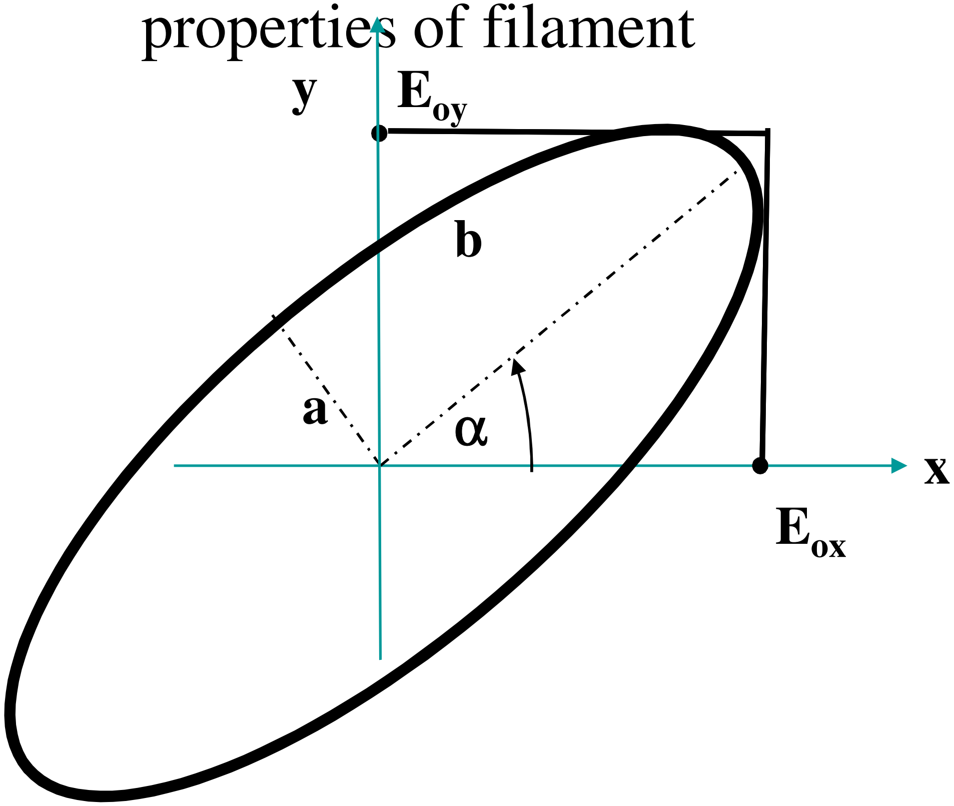
   Stimulated Backward Raman

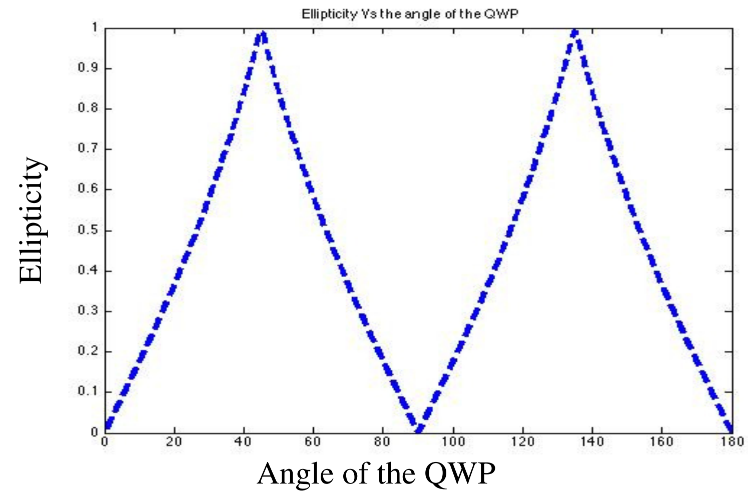
   Four wave mixing
5. **Electron current**
6. **THz detection**



Measuring polarization state

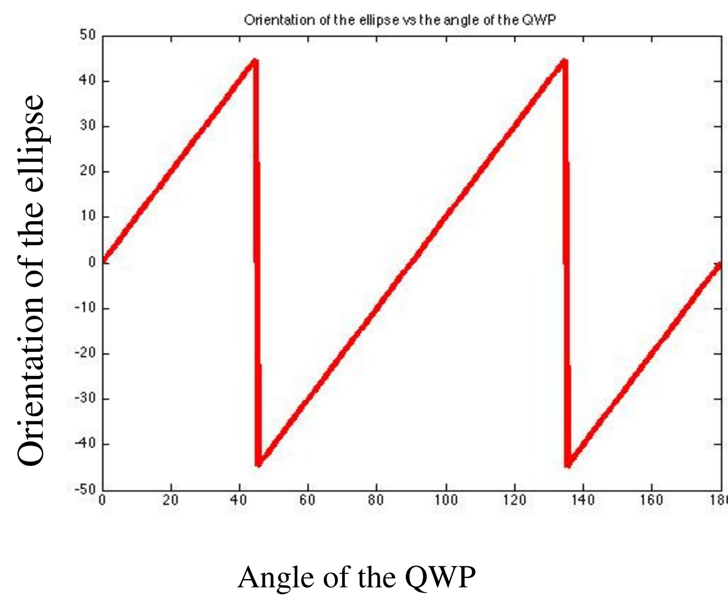
Polarization effect on phase modulation and macroscopic properties of filament





Final state of polarization

$$\begin{bmatrix} E \\ F \end{bmatrix} = \begin{bmatrix} cos^2(\theta) \\ sin(\theta)cos(\theta) \end{bmatrix}$$



Sources of polarization modification

Non resonant electronic Kerr

$$P_i = \epsilon_0 A(E.E^*)E_i + \frac{1}{2}\epsilon_0 B(E.E)E_i^*$$

$$\Delta n = n_+ - n_- = \frac{B}{2n_0}(|E_-|^2 - |E_+|^2)$$

$$\frac{|\ E_m\ |}{|\ E_M\ |} = e_p$$

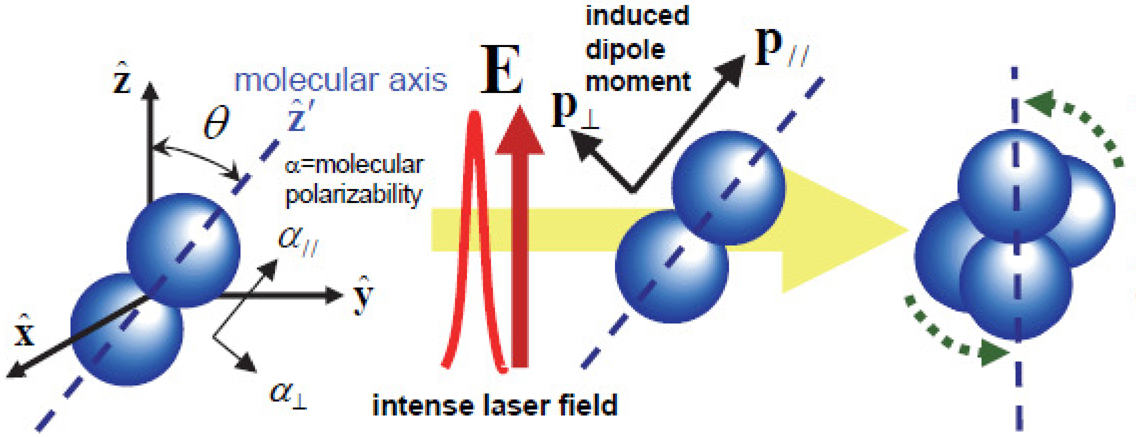
$$\theta = 1/2\Delta nkz$$

Molecular Kerr

$$\delta n_{ii} = \frac{2\pi N}{n_o}\left(\langle\alpha_{ii}\rangle - \bar{\alpha}\right)$$

$$\begin{aligned}
\langle\alpha_{xx}\rangle &= \bar{\alpha} + \Delta\alpha\left(\langle\sin^2\theta\cos^2\phi\rangle - 1/3\right) \\
\langle\alpha_{yy}\rangle &= \bar{\alpha} + \Delta\alpha\left(\langle\sin^2\theta\sin^2\phi\rangle - 1/3\right) \\
\langle\alpha_{zz}\rangle &= \bar{\alpha} + \Delta\alpha\left(\langle\cos^2\theta\rangle - 1/3\right)
\end{aligned}$$

Molecular and electronic Kerr

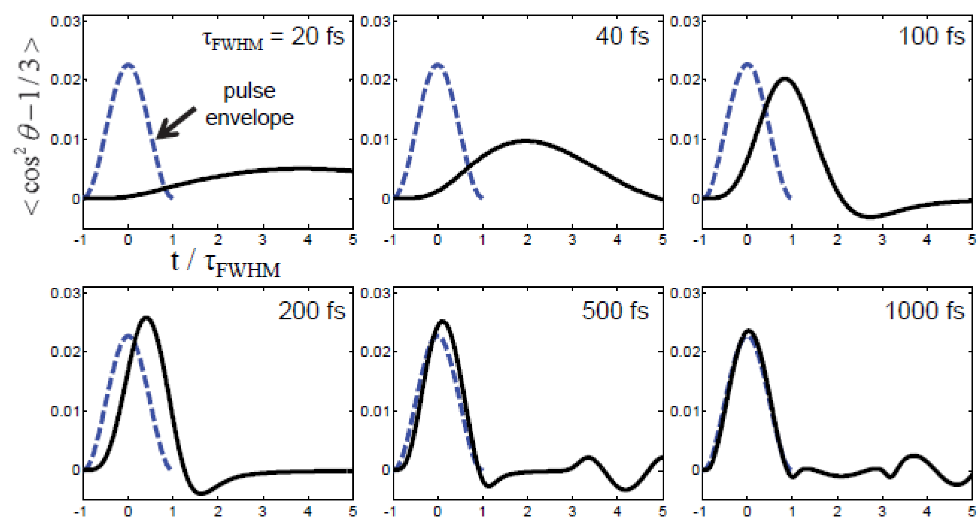


Molecule	$\alpha_{\parallel}$ [Å^3]	$\alpha_{\perp}$ [Å^3]
N_2	2.58	1.58
N_2^+	2.43	1.49
O_2	2.36	1.22
O_2^+	1.02	0.54

$$\Delta n_{delayed}(t) = \frac{2\pi N}{n_0}\Delta\alpha\left(<\cos^2\theta>_t - \frac{1}{3}\right) \propto (\Delta\alpha)^2$$

degree of alignment

Peak power 10TW/cm^2



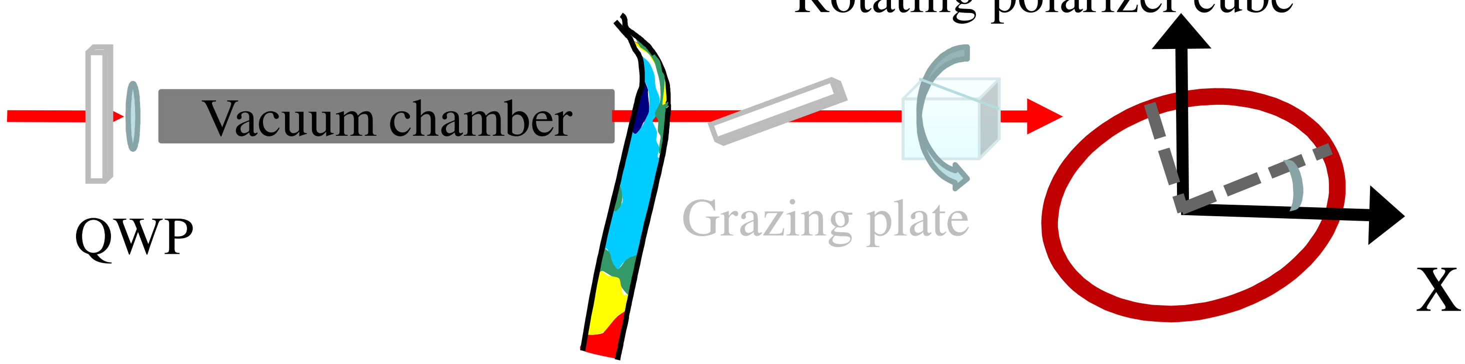
Electronic Kerr

$$\Delta n_{\mathrm{Kerr},X}(r,t) = 2n_2 I_{\mathrm{pump}}(r,t)$$

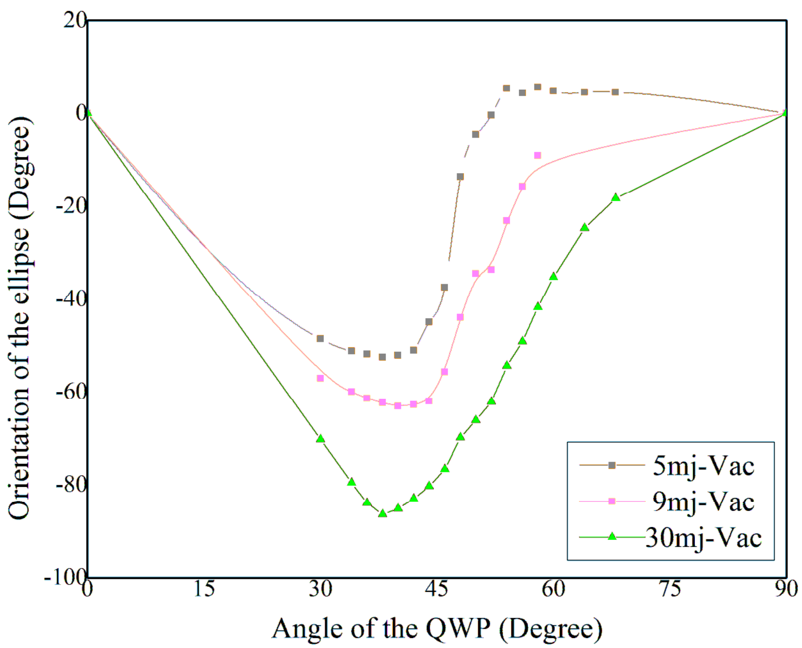
$$\Delta n_{\mathrm{Kerr},Y}(r,t) = \frac{2}{3}n_2 I_{\mathrm{pump}}(r,t)$$

$$n_2 = \frac{12\pi^2}{n_0^2 c_0}\chi^{(3)}_{xxxx}$$

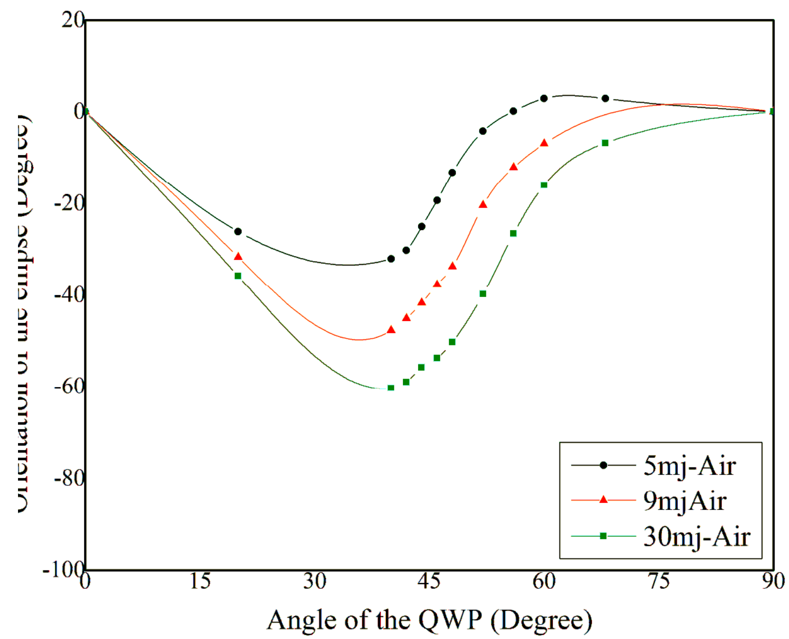
Angle of the ellipse at focus prior to the filamentation



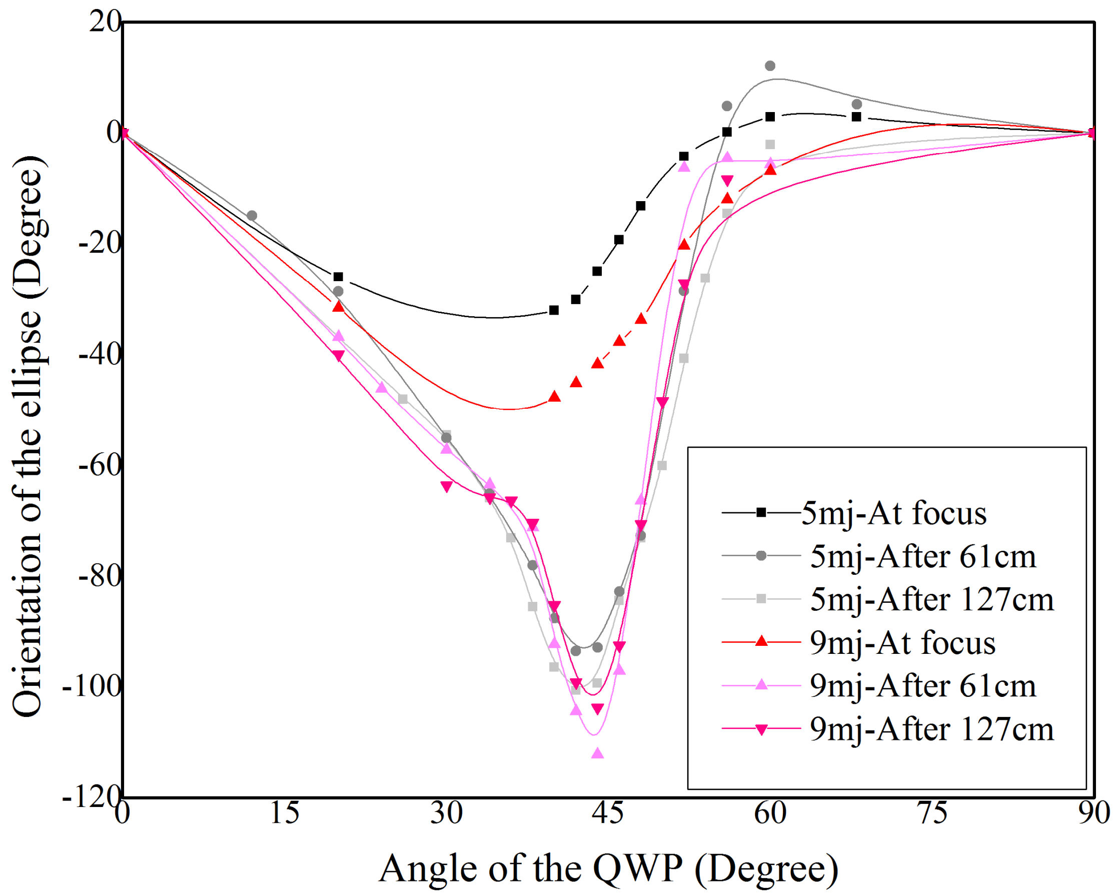
Focusing in vacuum



Focusing in air



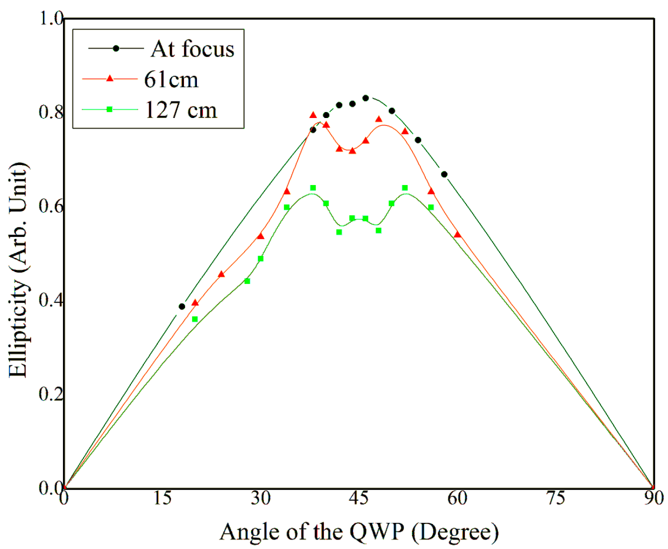
Angle of the ellipse after filament



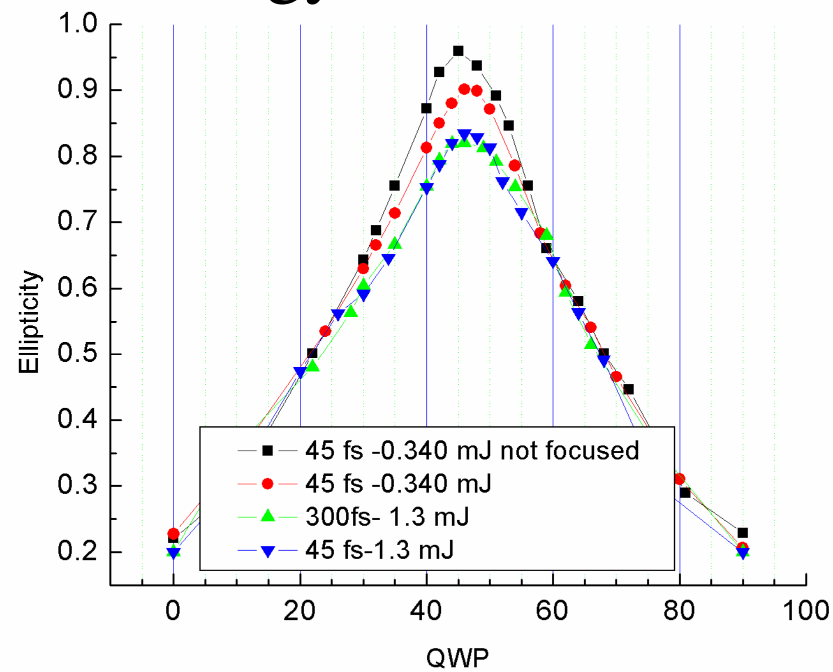
Polarization study of the focused beam in air

Ellipticity

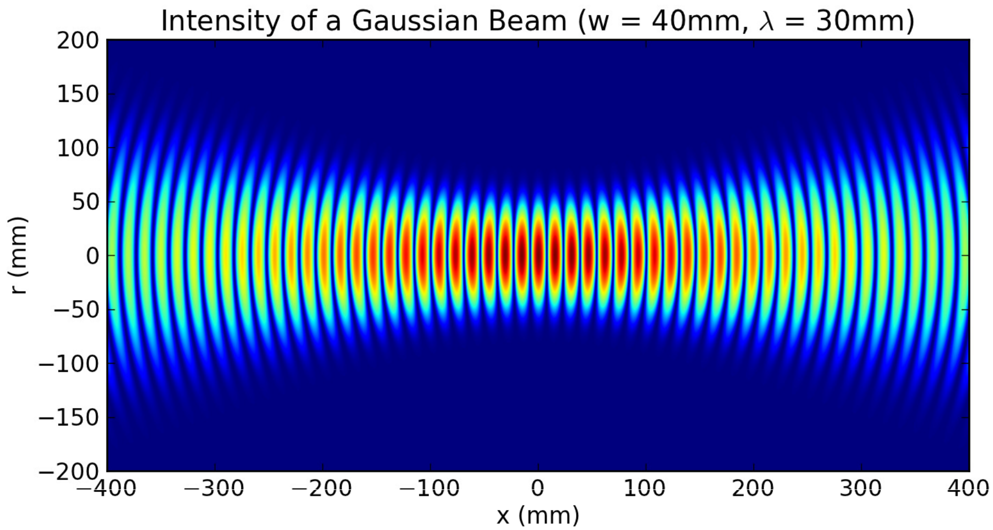
9mJ -60fs-filament in air



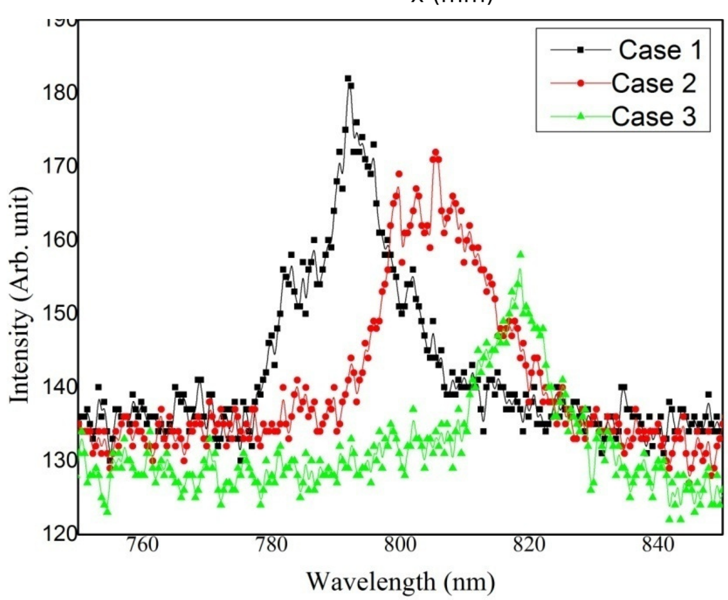
Ellipticity change at focus vs energy

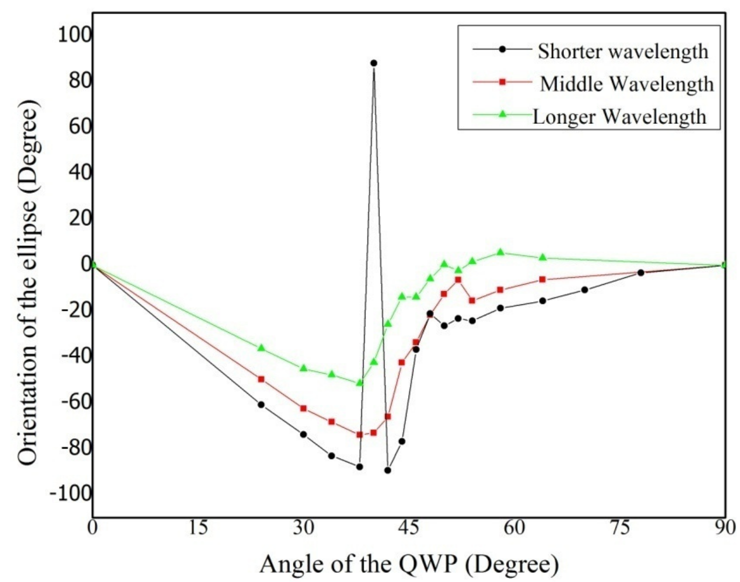


Spatial profile of the polarization



The polarization evolution varies across the beam profile due to the intensity distribution. Measuring polarization profile of the beam provides an insight to nonlinear interaction within a light filament





Angle of ellipse for selected colors of the beam perifery

Tunnel ionization

L. V. Keldysh, Sov. Phys. JETP 20, 1307 (1965).

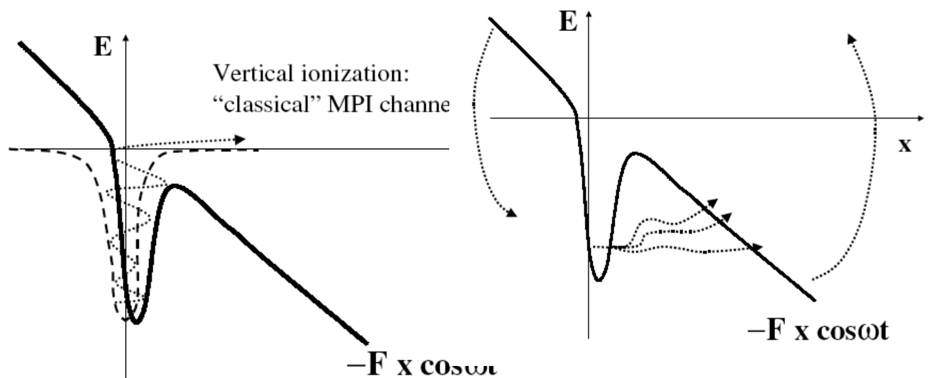
"Ionization in the field of a strong electromagnetic wave"

if γ<1, multiphoton ionization can be approximated as tunnelling.

$$\gamma^2 = IP / 2U_P$$

where

$$U_p = q^2 E_0^{\ 2} / (4m\omega^2)$$



Multi Photon

Tunneling

U_p energy of the classical-like motion of an electron in IR field

U_p=6 eV for λ=800nm; I=10^{14} W/cm^2

Electron ionization -- linear polarization

$$E(t) = E_0 \mathrm{Cos}(\omega t)$$

$$qE_0 \mathrm{Cos}(\omega t) = m\frac{dv}{dt}$$

$$v(t) = \frac{qE_0}{m\omega}\mathrm{Sin}(\omega t) + \mathrm{v_d}$$

Strong Field Approximation

Applying that $v(t') = 0$

$$v(t) = \frac{qE_0}{m\omega}\left[\mathrm{Sin}(\omega t) - \mathrm{Sin}(\omega t')\right]$$

The electron oscillates just like an electron initially at rest

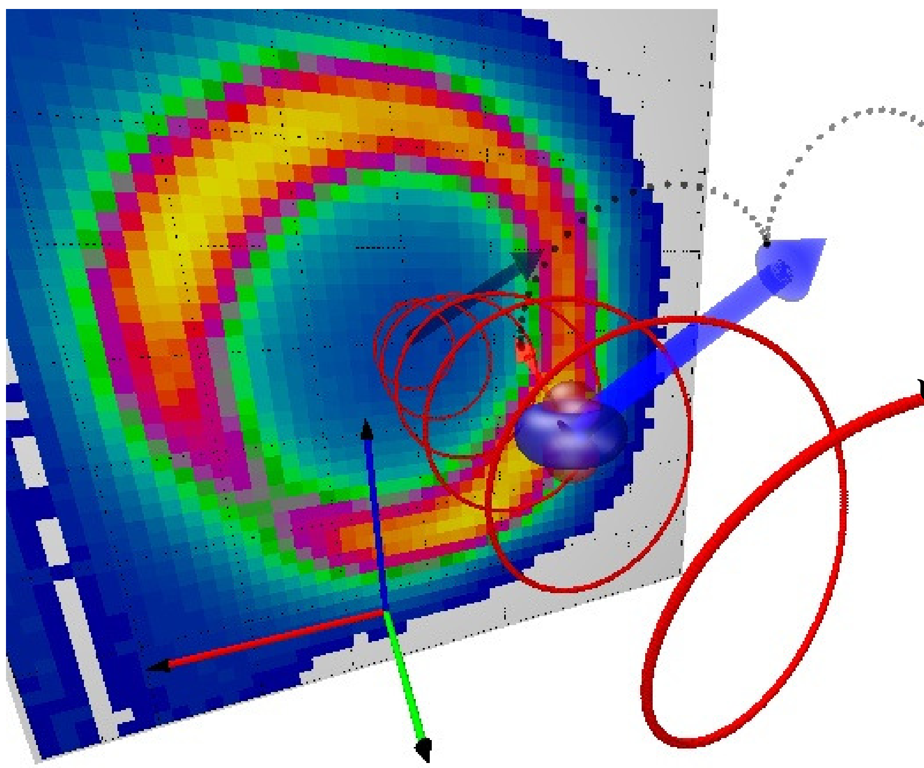
with an average oscillating energy $U_p = \dfrac{q^2 E_0^2}{4m\omega^2}$

and drifts with velocity $\mathrm{v_d} = \dfrac{\mathrm{qE_0}}{\mathrm{m}\omega}\mathrm{Sin}(\omega t')$

tunneling determines the probability of each t'

Electron ionization -- Circular polarization

In tunneling with circularly polarized light the field is always on. The velocity distribution of electrons has a donut distribution where the radius of the donut is defined by drift velocity and the thickness by quantum tunneling width.



$$E(t) = E_0 \mathrm{Cos}(\omega t)\hat{x} + \varepsilon \quad E_0 \mathrm{Sin}(\omega t)\hat{y}$$

$$v_d = \frac{qE_0}{m\omega}$$

$$\Psi_c(\theta) \propto \langle p_\perp | \Psi \rangle \exp\left[-\frac{\sqrt{I_P(\theta)}}{\sqrt{2}E(t)} p_\perp^2 \right]$$

L.Arissian PRL ,**105**, 133002 (2010)

For 800nm light and I~10^{14} W/cm^2, $v_d \approx c/100$

Is electron density enough for knowing the index?

Equation of motion

$$m\frac{d^2r}{dt^2} = -\omega_0^2 mr - \frac{m}{\tau}\frac{dr}{dt} - eE$$

$$r = \frac{-e/m}{\omega_0^2 - \omega^2 + i\omega/\tau}$$

$$\Delta E = P = -Ne\delta r$$

Free electron

$$r = \frac{eE}{m\omega^2}$$

Bond electron

$$r = \frac{-eE}{m\omega_0^{\,2}}$$

Drude model

$$\omega_p^2 = \frac{Ne^2}{\varepsilon m_e}$$

$$\Delta n = \frac{-\omega_p^2}{2\omega^2}$$

Traditional index

motion

$$\frac{d^2\partial r}{dt^2} + 2\gamma\frac{d\partial r}{dt} + \omega_{res}^2\,\delta r = \frac{-e}{m_e}\mathrm{E}\,\mathrm{e}^{\mathrm{i}\omega t}$$

ω_p ω_0

response

$$\Delta E = P = -Ne\,\delta r$$

$$\Delta \times H = J_f + \frac{\delta D}{\partial t} = J + \varepsilon_0\frac{\partial E}{\partial t}$$

$$\frac{\partial \varepsilon E}{\partial t} = \varepsilon\frac{\partial E}{\partial t} = -Nev + \varepsilon_0\frac{\partial E}{\partial t}$$

$$\Delta E = P = (\varepsilon - \varepsilon_0)E$$

propagation

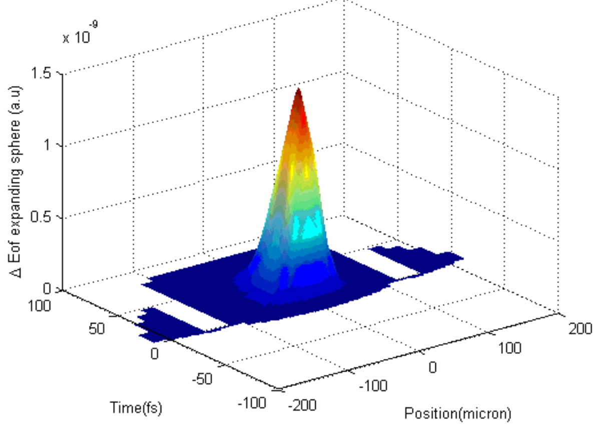
$$\frac{\partial E}{\partial z} = -ik\Delta E$$

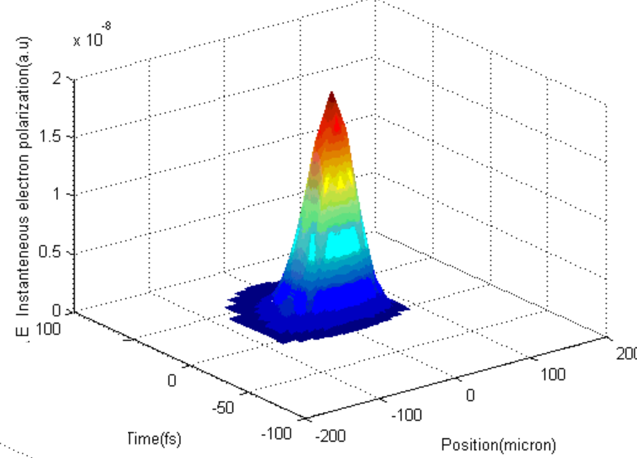
Radiation of expanding bobble

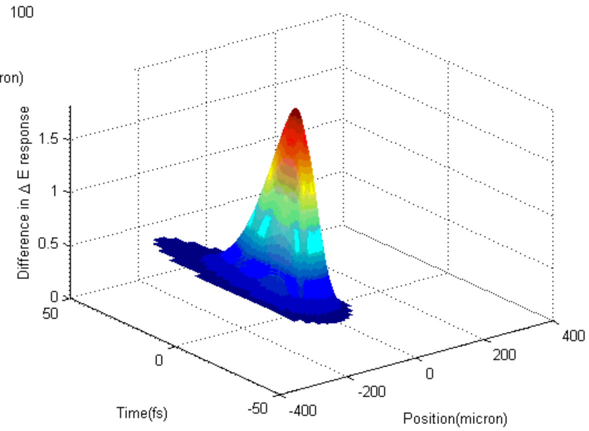
L. C Bahiana. *Electromagnetic induction on an expanding conducting sphere.* PhD thesis, Massachusetts Institute of Technology, 1964.

$$E = -\frac{\mu_0}{c^2}\frac{3Hv^3}{(1-v/c)^2(1+2v/c)}\left[\frac{T}{rc}+\frac{T^2}{2r^2}\right]$$

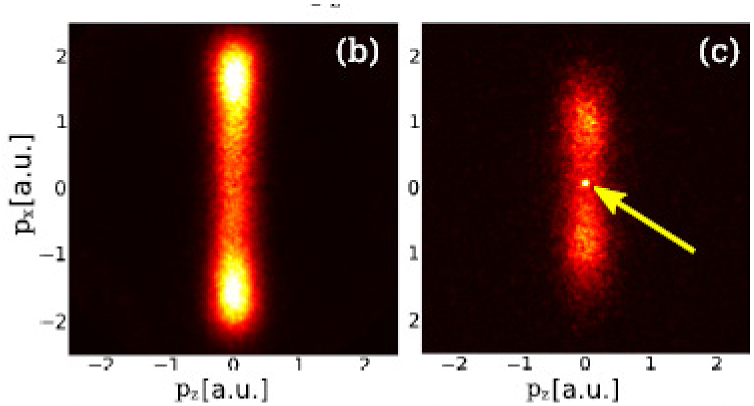
$$T = t - r/c$$

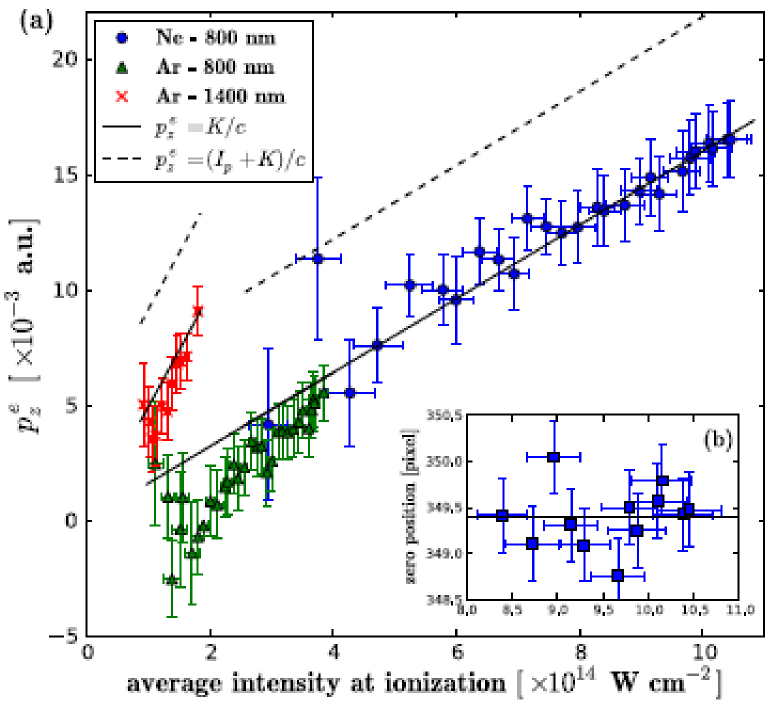






Partition of momentum in strong field ionization





C.Smeenk,L.Arissian PRL ,**106**, 193002 (2011)

Conservation of momentum and energy

$$N\hbar\omega = I_p + K + U_p$$

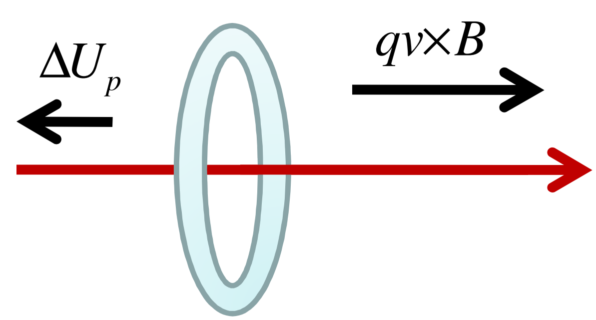
$$N\hbar k = p_z^{ion} + p_z^{electron} + p_z^{light}$$

$$F = qE + qv\times B$$

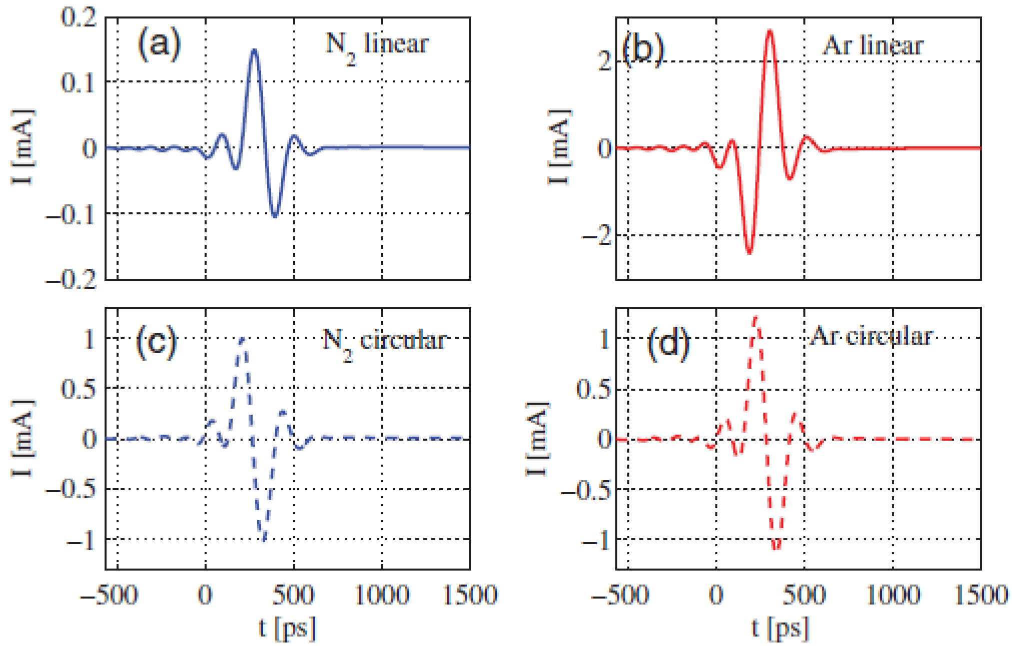
$$U_p = \frac{qE_0^2}{4m\omega^2}$$

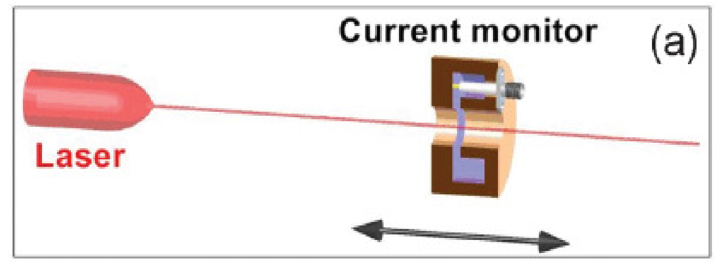
ΔU_p Pondermotive gradient

$$p_{\parallel,\infty} = \frac{U_{p,0}}{c}\begin{cases} 2\sin^2\phi_0 & \text{for linear polarization,} \\ 2 & \text{for circular polarization,} \end{cases}$$



Polarization dependent current in a plasma channel

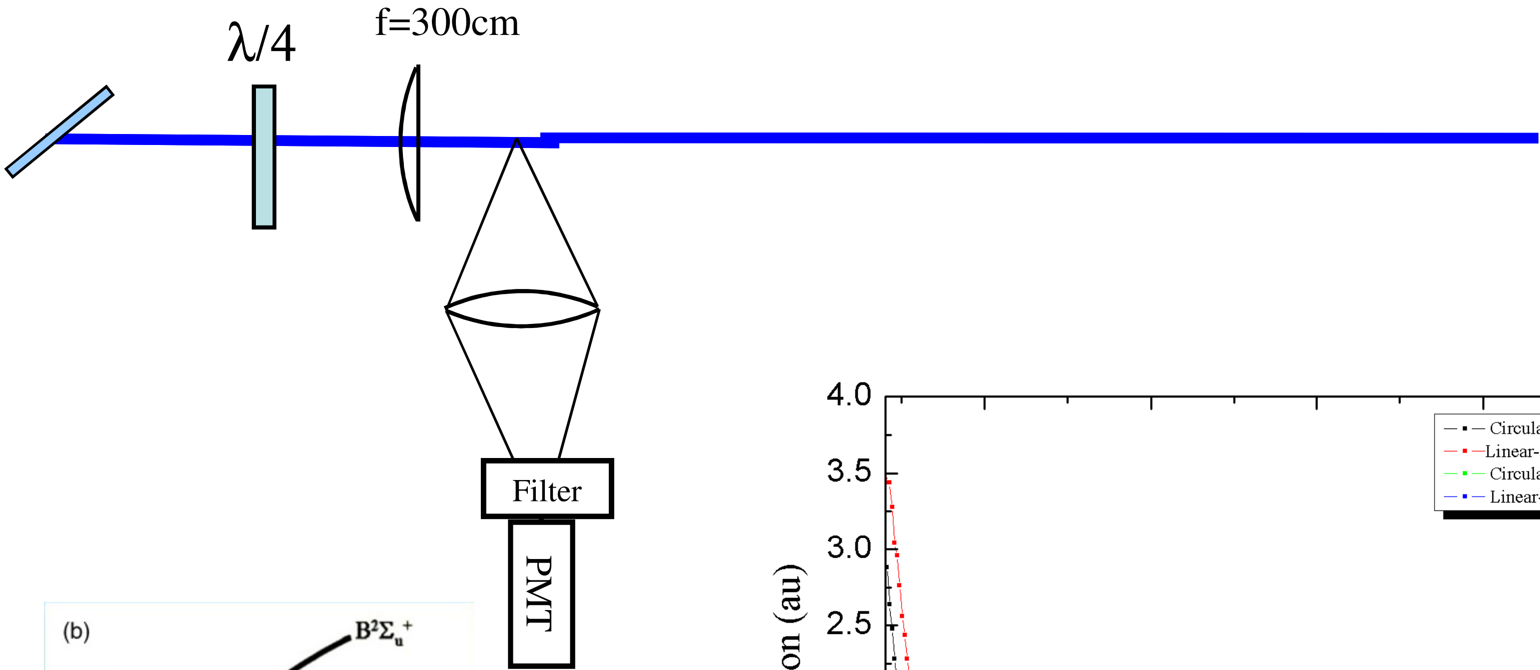


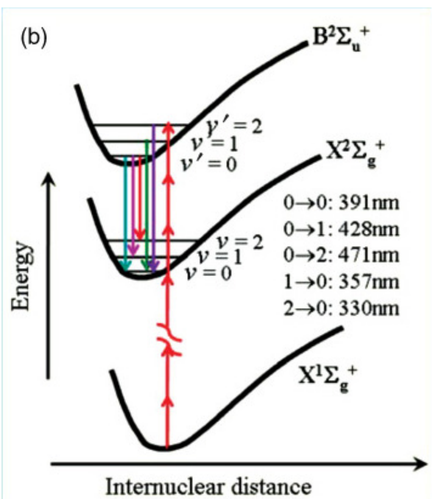


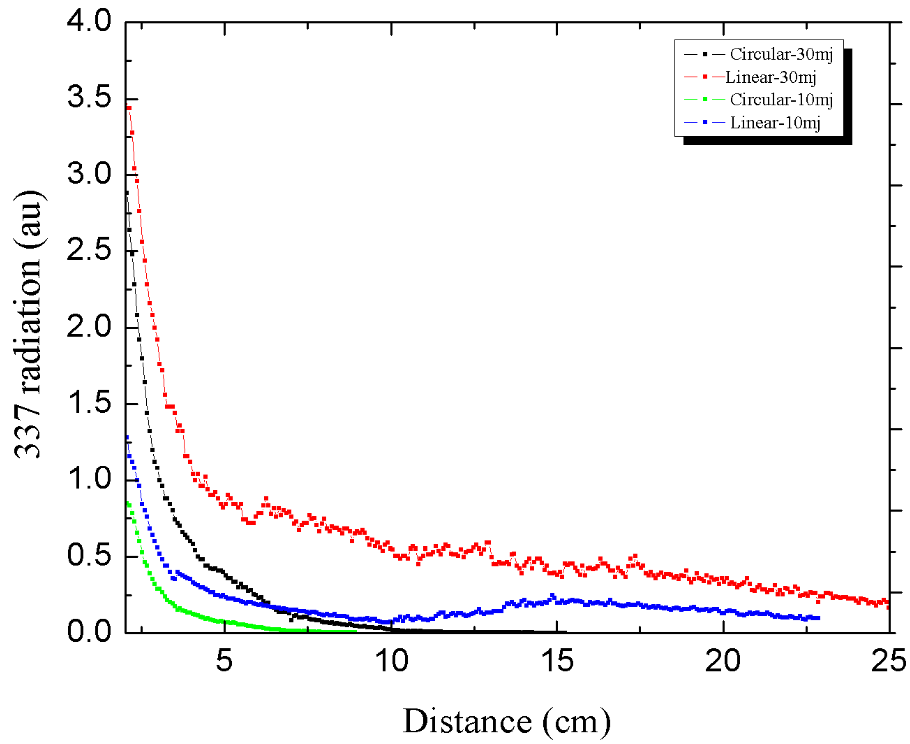
- Change of sign in Ar current ….circular versus linear
- Amplitude of the signal in N2, ten time higher circular versus linear
- No change in circular radiation with pressure for both Ar and N_2
- Competition between laser force and Coulomb wake force is more observed in linear light and Ar, for its lower cross section (5-10 times)

B Zhao…,L.Arissian PRL ,**106**, 255002 (2011)

Fluorescence 337 as a function of polarization



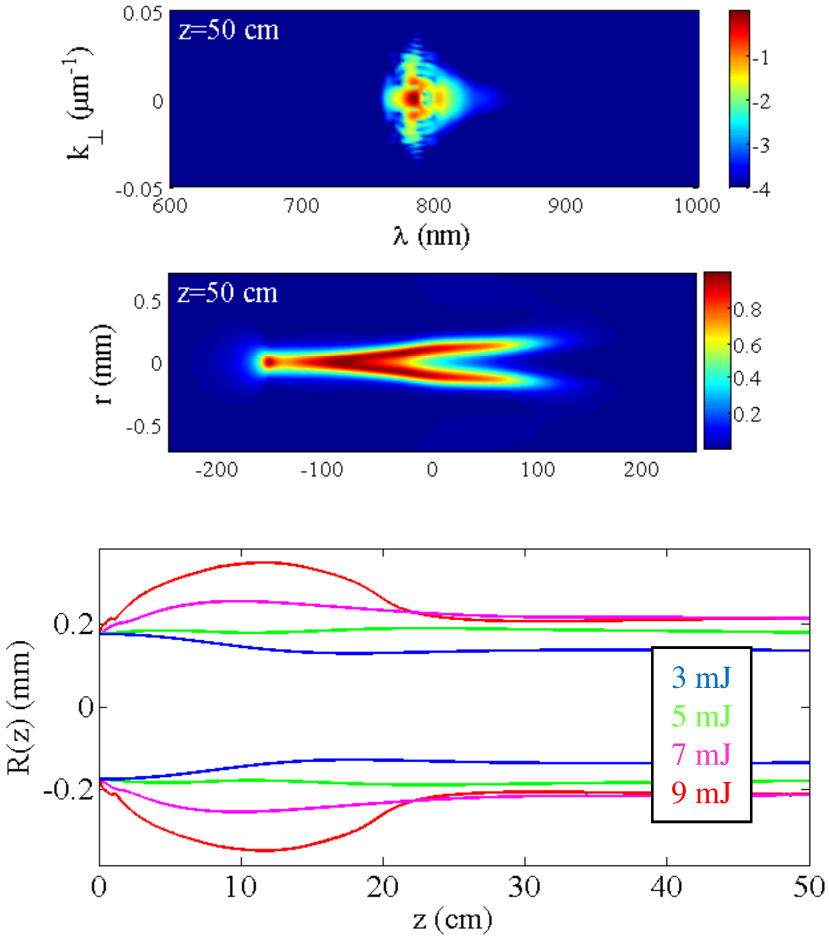




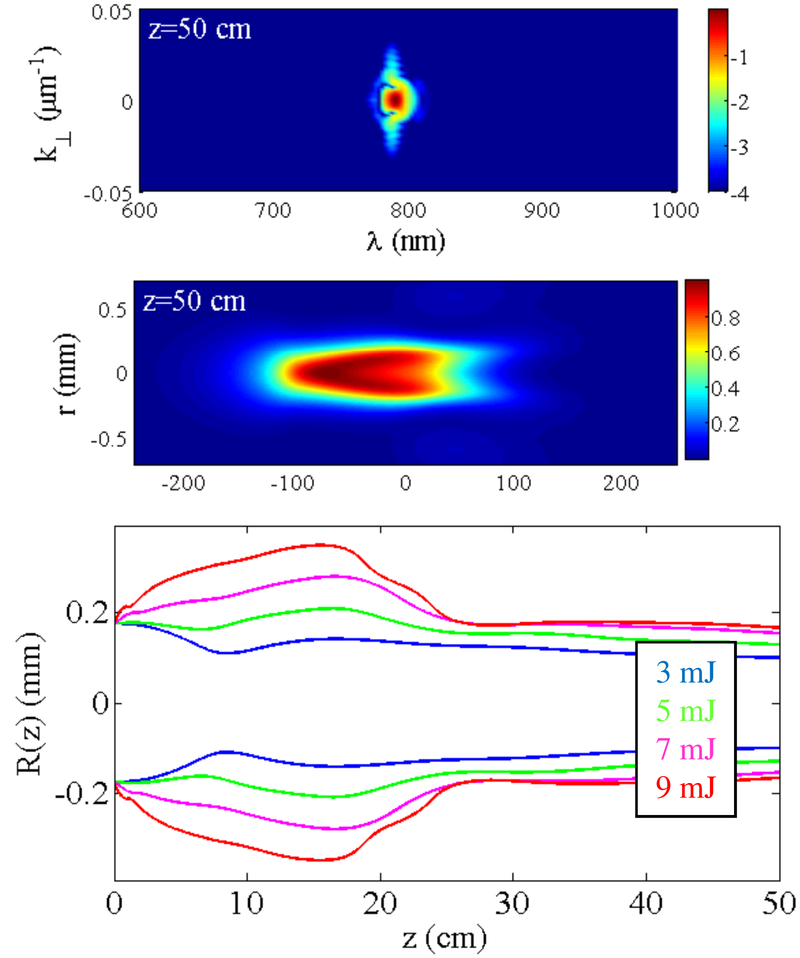
Simulation of nonlinear pulse **propagation**

A.Couarion

Linear



Circular



Conclusion

- Filamentation at its core is a strong field ionization process
- Polarization evolution can be used to explore the nonlinear interaction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