DeLLight : Modifying the speed of light in a vacuum with intense laser pulses

Journée du LABEX P2IO

30^{th} November 2022

Speed of light in vacuum

- Speed of light and optical index (n=1) are constants:

$$\left.\begin{aligned} \vec{D} &= \epsilon_0\,\vec{E} \\ \vec{B} &= \mu_0\,\vec{H} \end{aligned}\right\} \Rightarrow c = \frac{1}{\sqrt{\epsilon_0\mu_0}} \text{ with } \epsilon_0 \text{ and } \mu_0 \text{ constant}$$

Speed of light in dielectric medium

- Optical index depends on external field B, E:

$$\left.\begin{aligned} \vec{D} &= \epsilon_0\,\vec{E} + \vec{P}(\vec{E},\vec{B}) \\ \vec{B} &= \mu_0\,\vec{H} + \vec{M}(\vec{E},\vec{B}) \end{aligned}\right\} \Rightarrow v = \frac{1}{\sqrt{\epsilon(E,B)\mu(E,B)}}$$

Well known example is the **Kerr Effect** where the optical index n depends on I:

$$n = n_0 + n_2 I \tag{1}$$

- **Heisenberg & Euler** (1936):

$$\begin{cases} \vec{D} = \epsilon_0 \vec{E} \\ \vec{B} = \mu_0 \vec{H} \end{cases} \longrightarrow \begin{cases} \vec{D} = \epsilon_0 \vec{E} + \vec{P}(\vec{E}, \vec{B}) \\ \vec{B} = \mu_0 \vec{H} + \mu_0 \vec{M}(\vec{E}, \vec{B}) \end{cases}$$

Classical electrodynamic in vacuum

take into account electron-position vacuum fluctuation

with

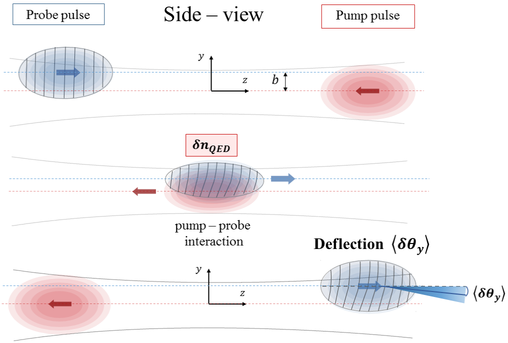
$$\begin{cases} P = \xi\epsilon_0^2[2(E^2 - c^2B^2)\vec{E} + 7c^2(\vec{E}.\vec{B})\vec{B}] \\ M = -\xi\epsilon_0^2[2(E^2 - c^2B^2)\vec{B} + 7(\vec{E}.\vec{B})\vec{E}] \end{cases}$$

- **Schwinger** (1951) : Derived later the H-E result within the QED frame.

QED predicts that the optical index of the vacuum is modified by an external field.

Has this ever been observed?

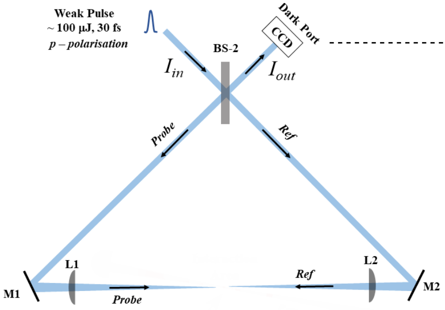
Dellight principle - pump/prob interaction



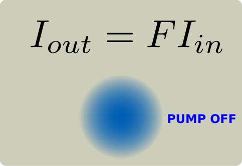
LASERIX specifications:

$$\left.\begin{array}{l} E_{pump} = 2.5 \text{ J} \\ \Delta\tau = 30 \quad \text{fs} \\ W_0^{pump} = w_0^{prob} = 5\mu\text{m} \end{array}\right\} \Rightarrow \boxed{\begin{array}{l} \delta n_{QED} = 2 \times 10^{-13} \\ <\delta\theta_y> = 0.1 \quad \text{prad} \end{array}}$$

Deflection measured with a Sagnac interferometer



What we observe on the CCD



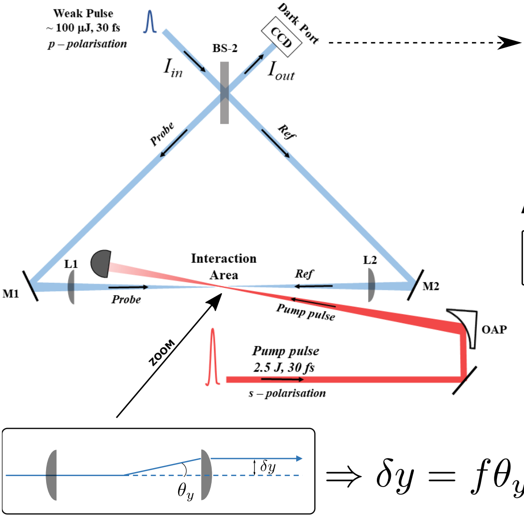
Extinction Factor F:

$$F = \frac{I_{out}}{I_{in}} = (\delta a)^2$$

BS coefficient:

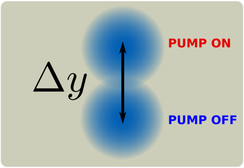
$$\begin{cases} T = \frac{1}{2}(1 + \delta a) \\ R = \frac{1}{2}(1 - \delta a) \end{cases}$$

Deflection measured with a Sagnac interferometer



$$\Rightarrow \delta y = f\theta_y$$

What we observe on the CCD



Amplified transveral shift:

$$\Delta y = \frac{1}{2\sqrt{F}} \times \delta y = G\delta y$$

Expected sensitivity

3-D numerical simulations developped by Scott Robertson:

$$\left.\begin{array}{l} E_{pump} = 2.5\ \text{J} \\ F = 0.4 \times 10^{-5}\ \text{(extinction)} \\ f = 50\ \ \text{cm (focal length)} \\ W_0^{pump} = w_0^{prob} = 5\mu\text{m} \quad \text{(waist at focus)} \end{array}\right\} \Rightarrow \boxed{\Delta y = 0.015\ \text{nm}}$$

With N_{mes} measurements collected, the sensitivity (number of standard deviations N_{sig}) is : $N_{sig} = \frac{\Delta y}{\sigma_y \sqrt{N_{mes}}}$

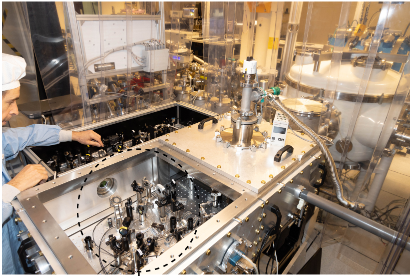
- Spatial resolution expected : $\sigma_y = 10$ nm
- Laser repetition rate : 10 Hz

$$\Rightarrow \boxed{N_{sig} = 3\sigma \ \ \text{in} \sim 9\ \text{day}}$$

Implementation of a prototype in air in order to characterize the limiting experimental parameters.

Objectives:

- Obtain an extinction factor F such $\boxed{F = 0.4 \times 10^{-5}}$
  $\Rightarrow$ see S. Robertson et al., Phys. Rev. A 103, 023524 (2021)
- **TODAY:** Observation with the DeLLight prototype of the deflection induced by the Kerr effect in air at low energy.

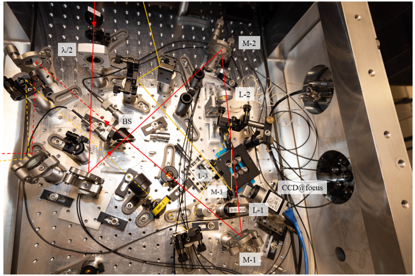


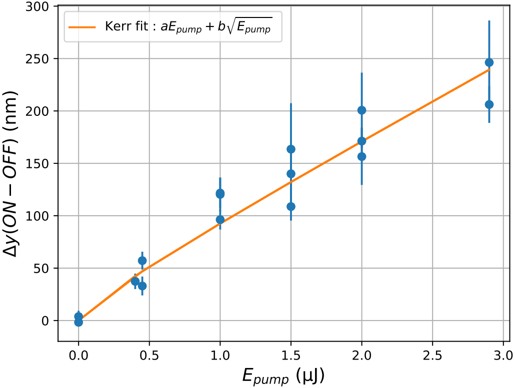
DeLLight goal in vacuum :

$$\omega_0 \text{ @ focus } 5\mu\text{m}$$
$$f = 500 \text{ mm}$$
$$E_{pump} = 2.5 \text{ J}$$

DeLLight prototype in air :

$$\omega = 1 \text{ mm}$$
$$\omega_0 \text{ @ focus } 35\mu\text{m}$$
$$f = 100 \text{ mm}$$
$$E_{pump} \sim \mu \text{ J}$$





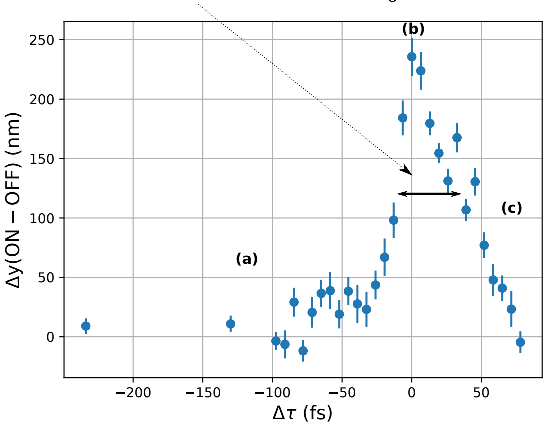
- Signal $\Delta y(ON - OFF)$ proportional to E_{pump}, as excepted for the Kerr effect
- Simulation agreement: factor 1.8 @ $E_{pump} = 3\mu J$:

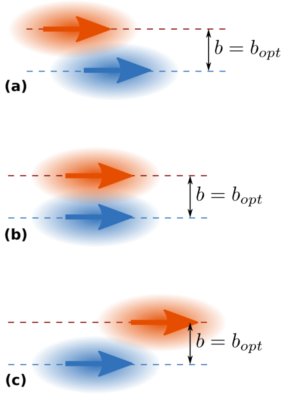
$$\Rightarrow \begin{array}{|l|} \Delta Y^{exp} = 250 \text{ nm} \\ \Delta Y^{sim} = 450 \text{ nm} \end{array}$$

justified by the uncertainty regarding n_{air}^{Kerr}

Deflection as function as ΔT

$$\Delta\tau^{FWHM} \sim 50fs$$



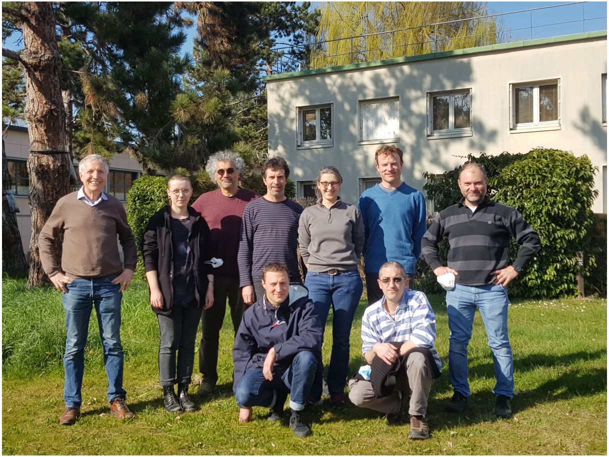


Summury:

- We are able to observe the deflection induced by the Kerr effect in the air when the pump and the probe are propagating in the same direction.

Next step:

- Observation of the Kerr effect in the air: the pump and the probe propagate in opposite directions.
- Reduce the mechanical noise to improve the resolution in the high amplification regime with $\Rightarrow \sigma_y = 10$ nm.
- Start measure in vacuum



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Thank you for your attention !

State of Art

At high energy regime $\hbar\omega \gg m_e c^2$: perturbation of the vacuum induce:

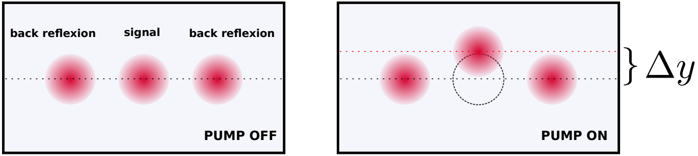
- Light by light scattering $\rightarrow$ **Observed** [1,2,3]
- Vacuum magnetic birefringence $\rightarrow$ **Observed** [4]

At low energy regime $\hbar\omega \ll m_e c^2$ with high occupation number (10^{19} photons): modification of the fundamental constant as c,ϵ_0 and μ_0.

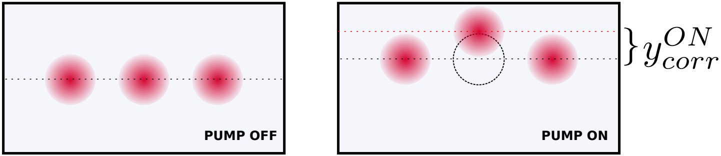
[1] : M. Aaboud et al. (ATLAS Collaboration), Nat. Phys 13 (2017)
[2] : G. Aad et al. (ATLAS Collaboration), Phys. Rev. Lett. 123 (2019)
[3] : A.M. Siruyan et al. (CMS Collaboration), Phys. Lett. B 797 (2019)
[4] R.P. Mignani et al., Mon. Not. R. Astron. Soc. 465 (2016)

Displacement extraction from data

- **Without beam pointing fluctuations:** $\Delta y = y_{sig}^{ON} - y_{sig}^{OFF}$



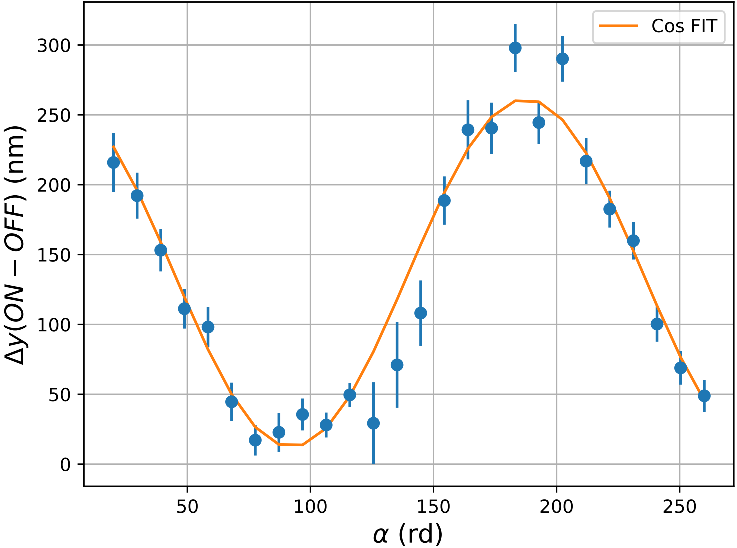
- **With beam pointing fluctuations:** $\Delta y = y_{corr}^{ON} - y_{corr}^{OFF}$



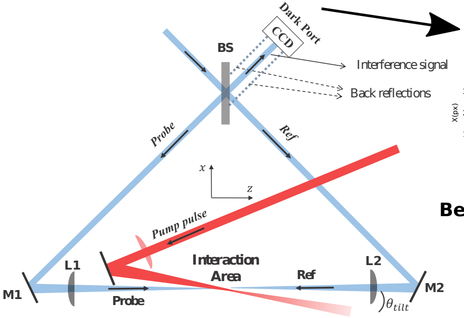
$y_{corr}^{OFF} = y_{signal}^{OFF} - y_{ref}^{OFF}$ $\quad$ $y_{corr}^{ON} = y_{signal}^{ON} - y_{ref}^{ON}$

Beam pointing fluctuations corrected from the back reflexion

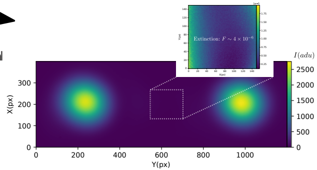
α : polarization angle between the pump and the probe



Extinction and Amplification



Example of signal on CCD



Beam splitter @ 45 °:

$$R = T = 50\% \pm 0.1$$

$$\Rightarrow G \sim 250$$
$$\Rightarrow F \sim 4 \times 10^{-6}$$

THE EXPECTED AMPLIFICATION !!!

- We obtain the expected amplification $G = 250$ with $F = 0.4 \times 10^{-5}$