DeLLight

(Deflection of Light by Light in vacuum)

with LASERIX @ IJCLab

Slowing down the light in vacuum with intense laser pulses

Slow down the speed of light in vacuum

- **Classical electrodynamics: Maxwell's equations are « linear » in vacuum**

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} \end{cases} \qquad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \qquad \Rightarrow$$

c, ε_0 and μ_0 are universal constants

- **Quantum Electrodynamics : vacuum is filled of virtual e+/e- pairs**

Nonlinear interaction between the electromagnetic fields, through the e+/e- pairs

$\Rightarrow$ Nonlinear optical polarization and magnetisation of the vacuum

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}(\mathbf{E}^2,\mathbf{B}^2) = \varepsilon\,(\mathbf{E}^2,\mathbf{B}^2).\mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}(\mathbf{E}^2,\mathbf{B}^2) = \mu\,(\mathbf{E},\mathbf{B}).\mathbf{H} \end{cases}$$

Heisenberg and Euler, Z. Phys. 98, 714 (1936)

J. Schwinger, Phys. Rev. 82, 664 (1951)]

with
$$\begin{cases} \mathbf{P} = \xi \varepsilon_0^2 [(E^2 - c^2 B^2)\mathbf{E} + 7c^2(\mathbf{E}.\mathbf{B})\mathbf{B}] \\ \mathbf{M} = -\xi \varepsilon_0^2 c^2 [(E^2 - c^2 B^2)\mathbf{B} - 7(\mathbf{E}.\mathbf{B})\mathbf{E}] \end{cases} \qquad \xi^{-1} = \frac{45 m_e^4 c^5}{2\alpha^2 \hbar^3} \approx 3\ 10^{29}\ \mathrm{J/m^3}$$

$\Rightarrow$ Vacuum optical index and speed of light depend on external fields E,B

Slow down the speed of light in vacuum

- The vacuum should behave as a nonlinear optical medium: **The speed of light in vacuum should be reduced at macroscopic scale, in the classical (optical) sense, when vacuum is stressed by intense e.m. fields**

- It has never been observed

- So far, search for vacuum birefringence using standard magnetic field (few Tesla)

  Sensitivity limited by the intensity of the field

- The advent of ultra-intense laser pulses, delivering ultra-intense electromagnetic fields in laboratory, opens a new promising window to observe the optical non linearity of vacuum : this is the goal of the DeLLight project

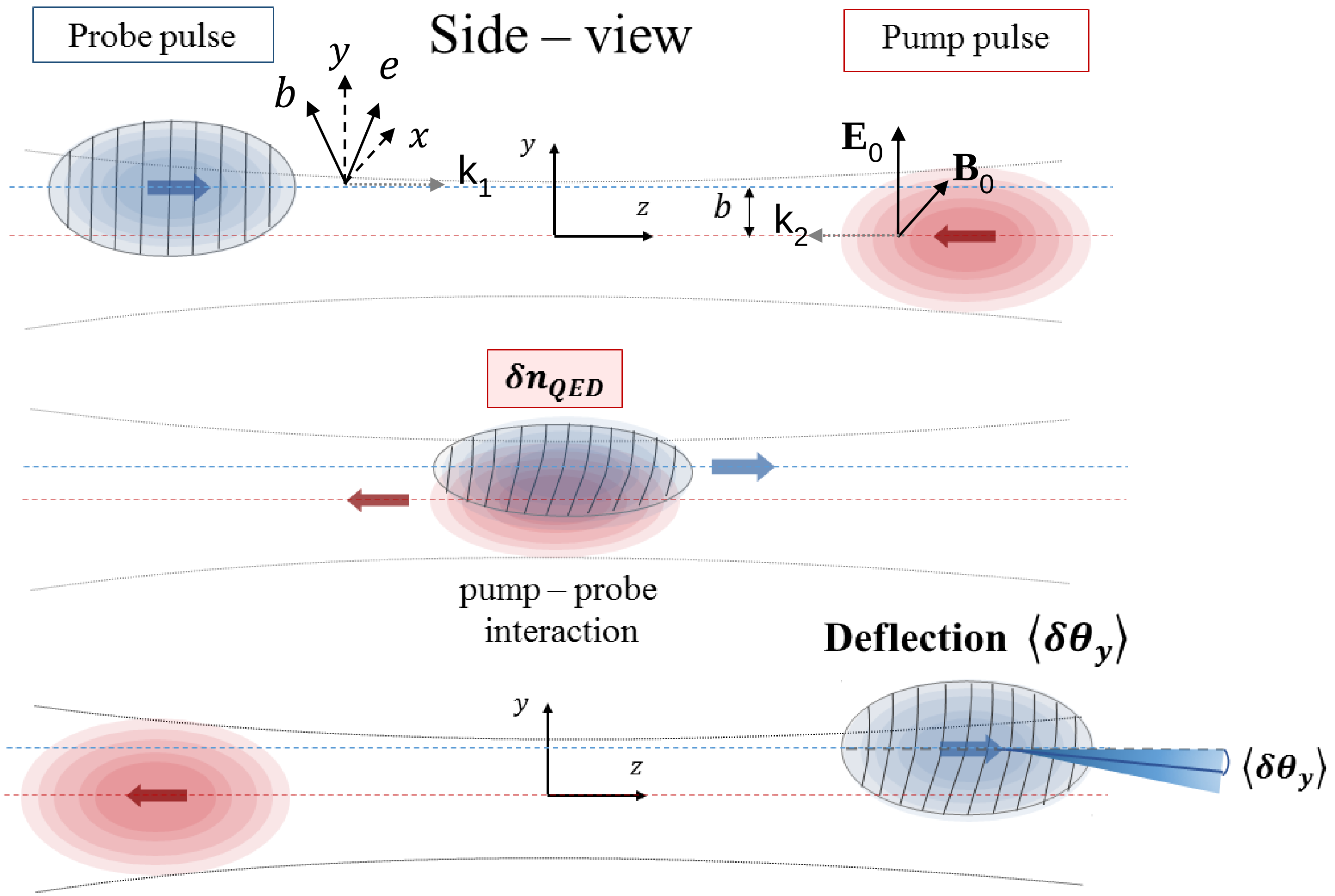
➡ DeLLight with intense laser field produced by LASERIX

2.5 J, 30 fs, w_0=5µm ⇒ I ~ 2×10^{20} W/cm^2

⇒ $\boldsymbol{E \sim 3 \times 10^{13} V/m,\ B \sim 10^5\ T}$

DeLLight with intense laser fields @LASERIX

Use highly focused laser pulses to achieve strong fields



Pump specifications (*LASERIX*)

- ✓ **Energy ≈ 2.5 Joules**
- ✓ Duration ≈ 50 fs
- ✓ **Waist @ focus ≈ 5 µm**

$\Rightarrow I_{pump} \sim 2 \times 10^{20}$ W/cm^2

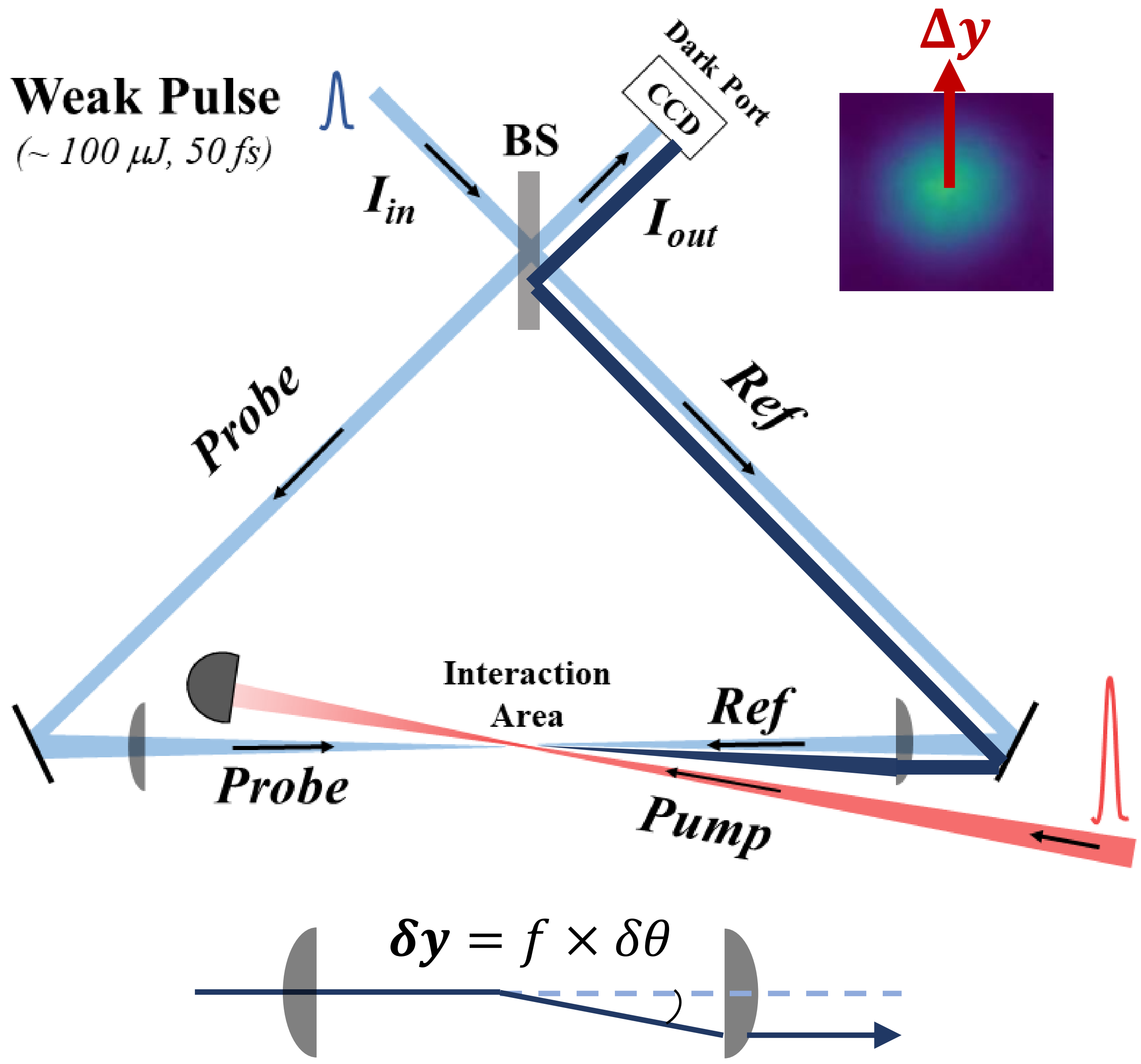
$\Rightarrow B \sim 10^5$ T

$\Rightarrow E \sim 3 \times 10^{13}$ V/m

$\delta n \sim 3 \times 10^{-13}$

$\delta\theta \sim 0.1$ prad

Refraction measured with a Sagnac Interferometer



- Extinction factor in the dark output

$$\Rightarrow \quad \boldsymbol{\mathcal{F}} = \frac{I_{out}}{I_{in}}$$

- $\boldsymbol{\delta y}$ = Direct vertical shift of the probe inside the Sagnac
- $\boldsymbol{\Delta y}$ = Vertical shift of the interference intensity profile is **amplified** in the dark output (*Weak Value Amplification*)

$$\Rightarrow \quad \Delta \boldsymbol{y} = \mathcal{A} \times \boldsymbol{\delta y}$$

- Amplification factor $\mathcal{A} = \pm \frac{1}{2\sqrt{\mathcal{F}}}$

- « *ON – OFF* » measurements @ 5 Hz

Expected signal and sensitivity

Expected signal: $$\Delta y = 2.7\ \text{nm}\ \times \frac{E(Joule) \times f(m)}{\left(w_0^2 + W_0^2\ (\mu\text{m})\right)^{3/2} \times \sqrt{\mathcal{F}/10^{-5}}}$$ (with $\theta_{tilt} \sim 15°$)

- ✓ **Energy $E = \mathbf{2.5}$ J @ LASERIX (10 Hz repetition)**
- ✓ **Extinction** $\mathcal{F} = 4 \times 10^{-6}$ ($\mathcal{A} = 250$) (best extinction measured)
- ✓ **Waist at focus** $w_0 = W_0 = 5\ \mu\text{m}$ (typical achievable value)
- ✓ **Spatial resolution** $\sigma_y = 10$ nm (CCD shot noise resolution)

➡ $\Delta y \sim 15$ pm

➡ ON-OFF measurements @ 5 Hz

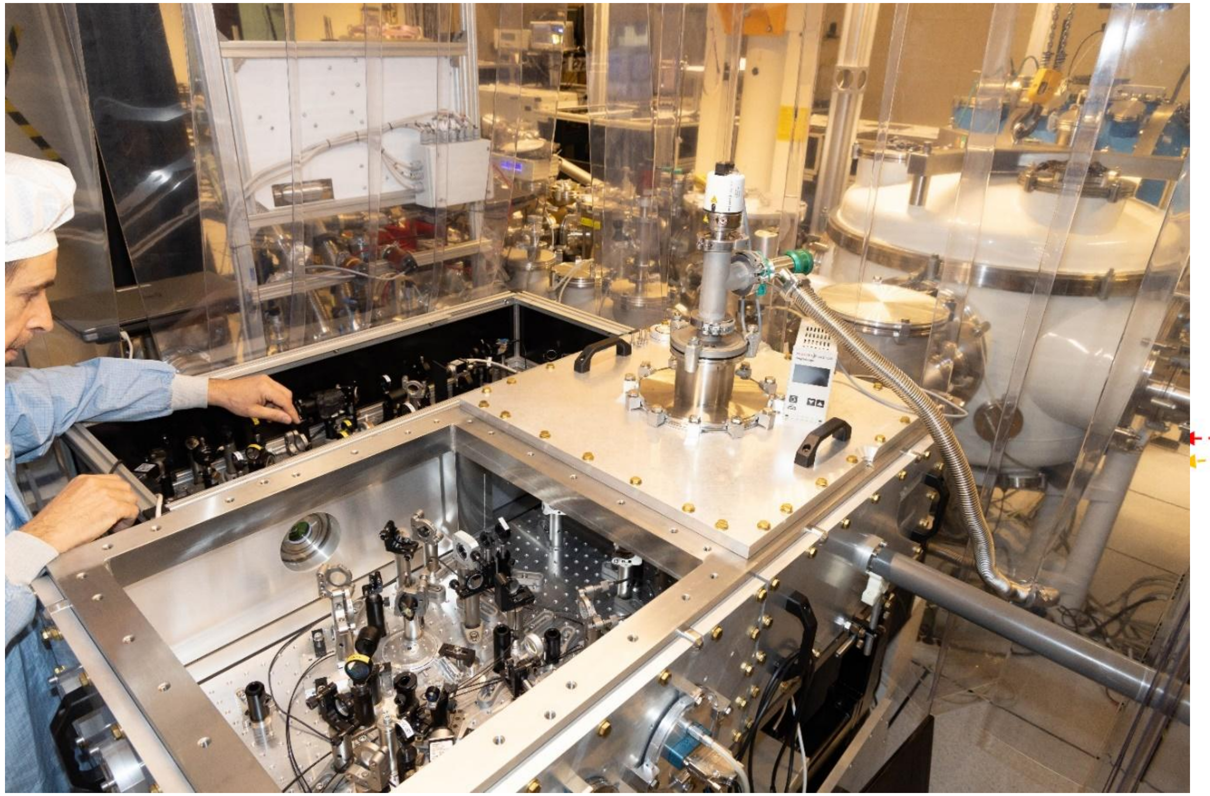
Statistical sensitivity (without bias) : 1 sigma sensitivity within ~ 4 days with LASERIX

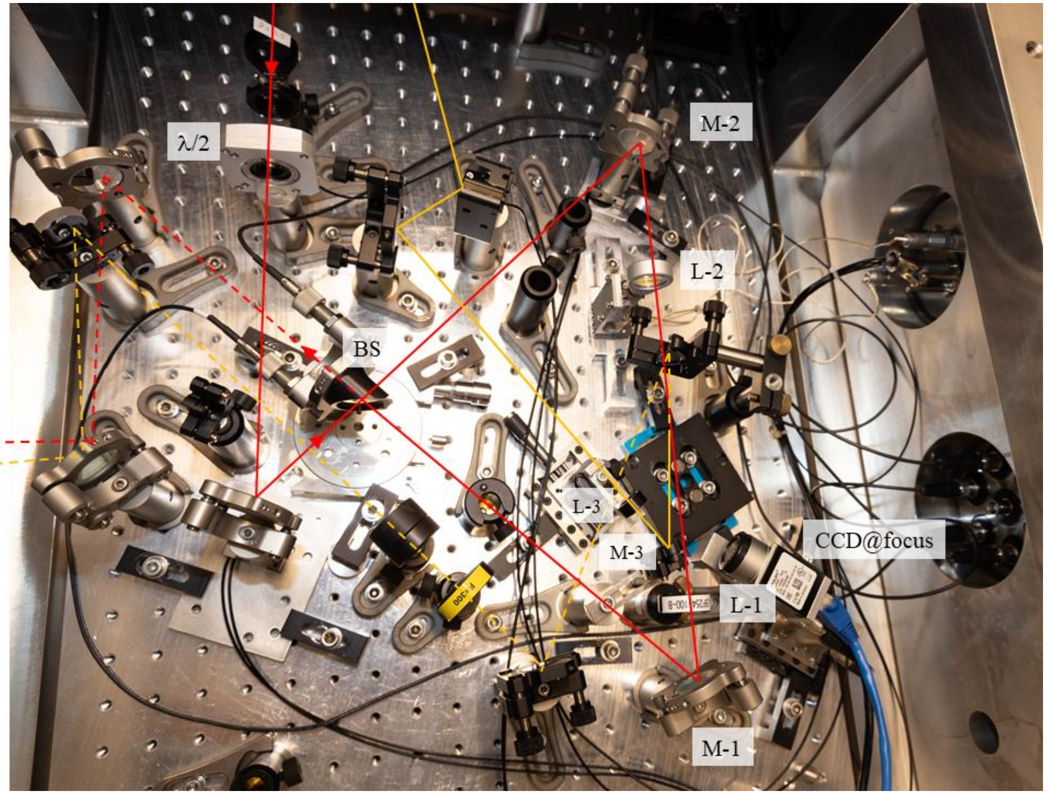
The DeLLight pilot experiment

Pilot experiment in vacuum chamber

Sagnac interferometer with focus of the probe and pump beams

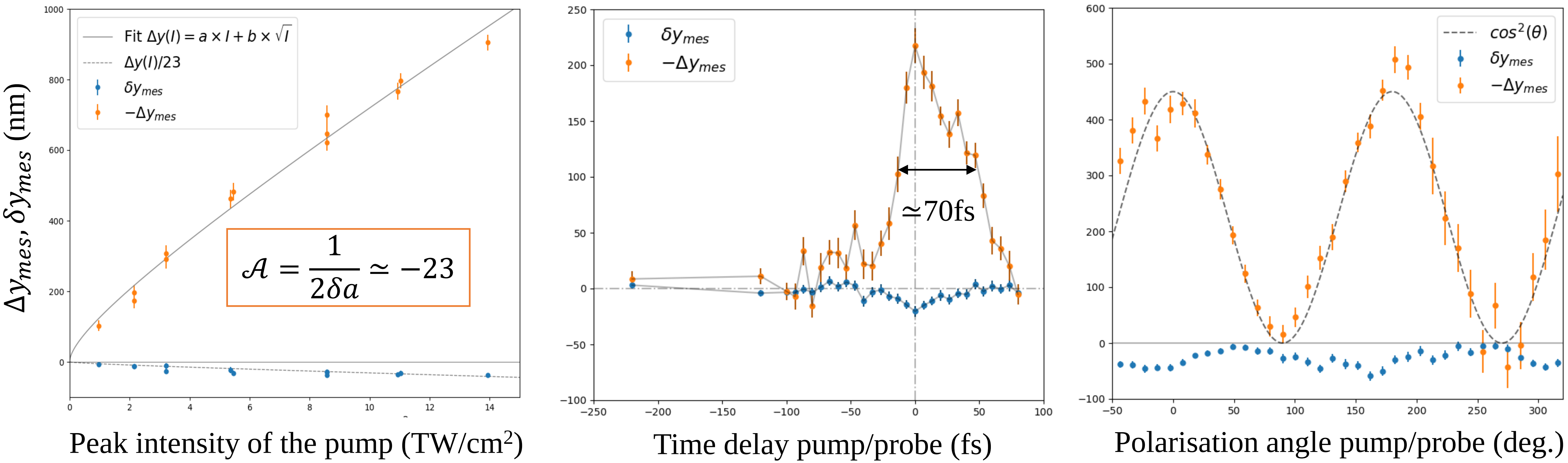
→ DeLLight deflection measured in air with a low pump energy





Measurement of the DeLLight signal in air

$\Delta y = f(\text{Intensity})$ $\Delta y = f(\text{time delay})$ $\Delta y = f(\text{polarisation})$

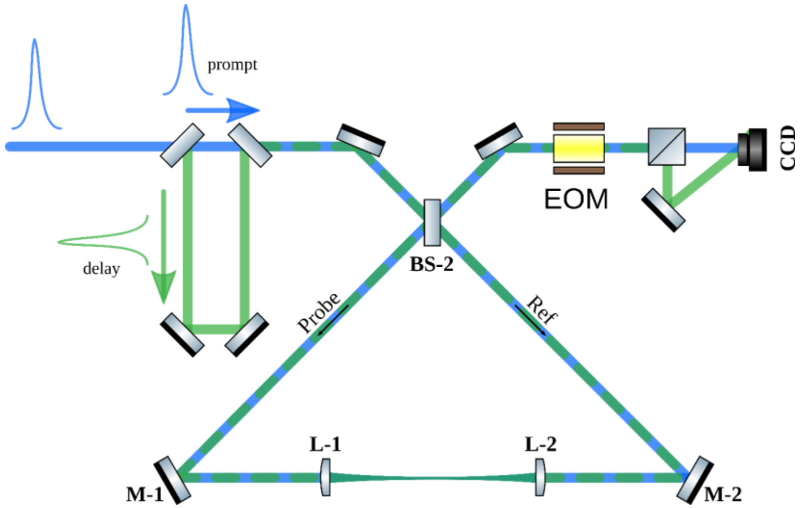


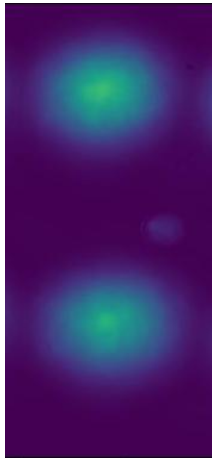
Validation of the DeLLight experimental method based on interferometric amplification !

More details in A. Kraych *et al*, Physical Review A 109.5 (2024)

Spatial resolution: the quantum noise limit

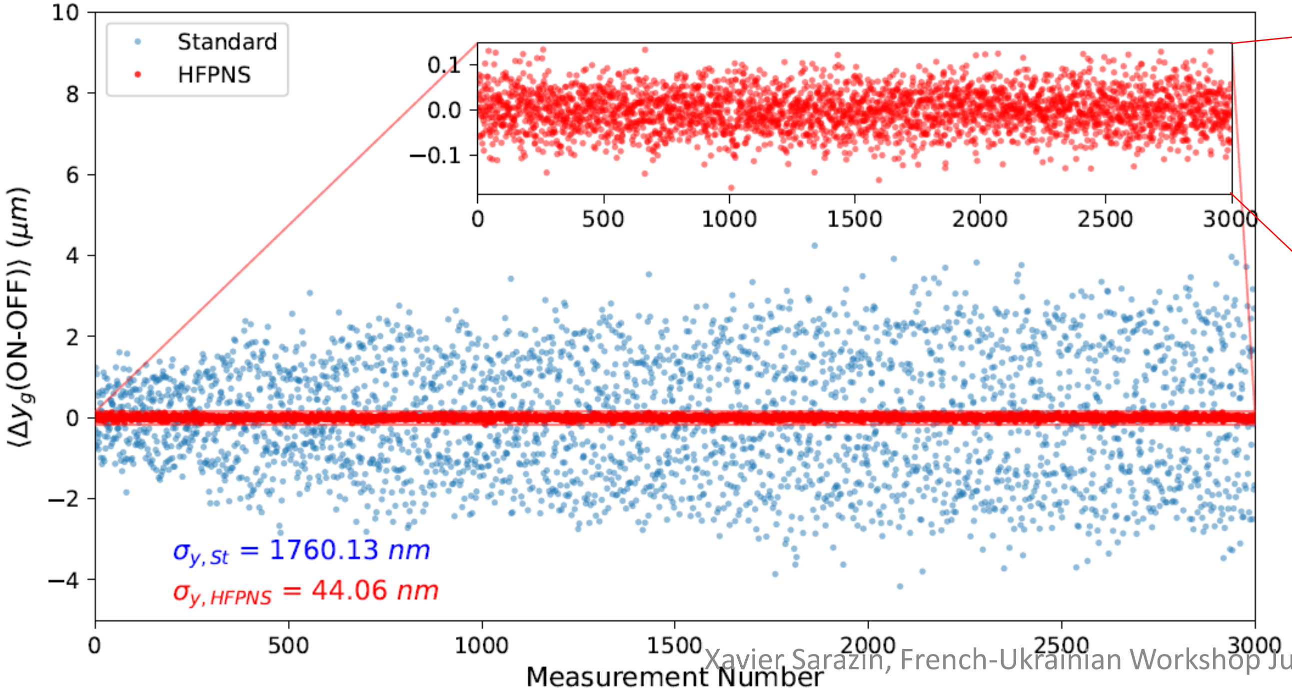
- Measurement and supression of the vibration-induced interferometric phase noise using a delayed (High Frequency) pulse
- The ultimate quantum noise-limited special resolution has been achieved (Ali Aras's thesis)

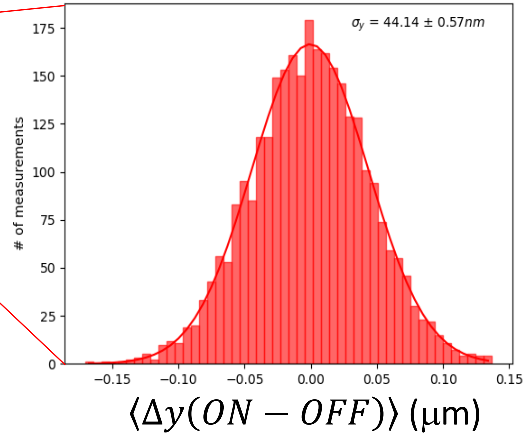




Prompt

Delay





Standard: σ_y = 1760 nm
After HFPNS: σ_y = 44 nm
Quantum noise: $\sigma_y \cong$ 40 nm

What next

- Installation of the DeLLight Phase-1 (High energy LASERIX pulses in vacuum) currently in progress in a new dedicated experimental room

- First measurements in vacuum with intense fields expected end of 2026

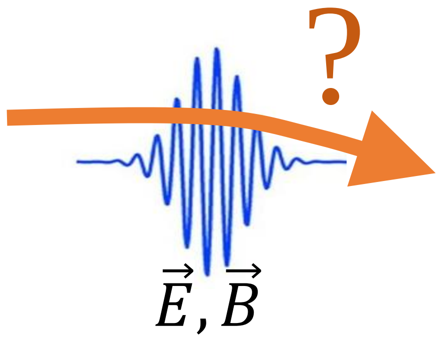
- DeLLight Phase-2 using new generation intense lasers with high repetition rate
  - LAPLACE-HC@LOA (1-5 J, 100Hz)
  - KALDERA@DESY (5J, 1kHz)

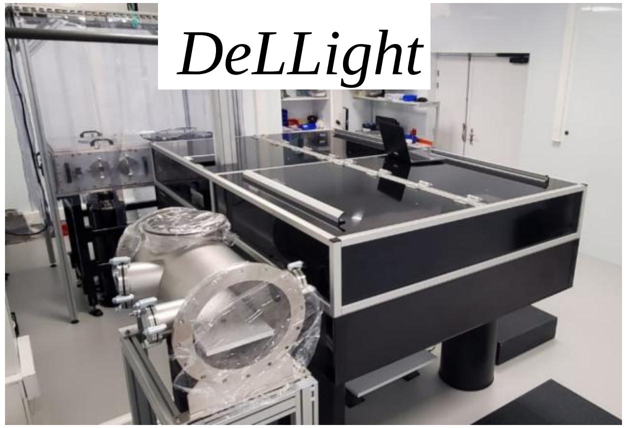
  $\Rightarrow$ 3σ sensitivity in few hours !

Conclusions

- A positive measurement would demonstrate that the speed of light in vacuum can be reduced, in the classical sense on a macroscopic scale, in the presence of external e.m. fields.

Electromagnetic Lensing





Gravitational Lensing