Modification of the vacuum refractive index with intense laser pulses:

Deflection of Light by Light

The DeLLight Project on LASERIX

F. Couchot, A. Mailliet (student), S. Robertson (post-doc LAL, theory), X. Sarazin, M. Urban

E. Baynard, J. Demailly, O. Guilbaud, S. Kazamias, B. Lucas, M. Pittman

A. Djannati-Ataï

Presented by F. Couchot **(most slides prepared by Xavier Sarazin) -** LAL, CNRS-IN2P3 / Univ. Paris-Saclay

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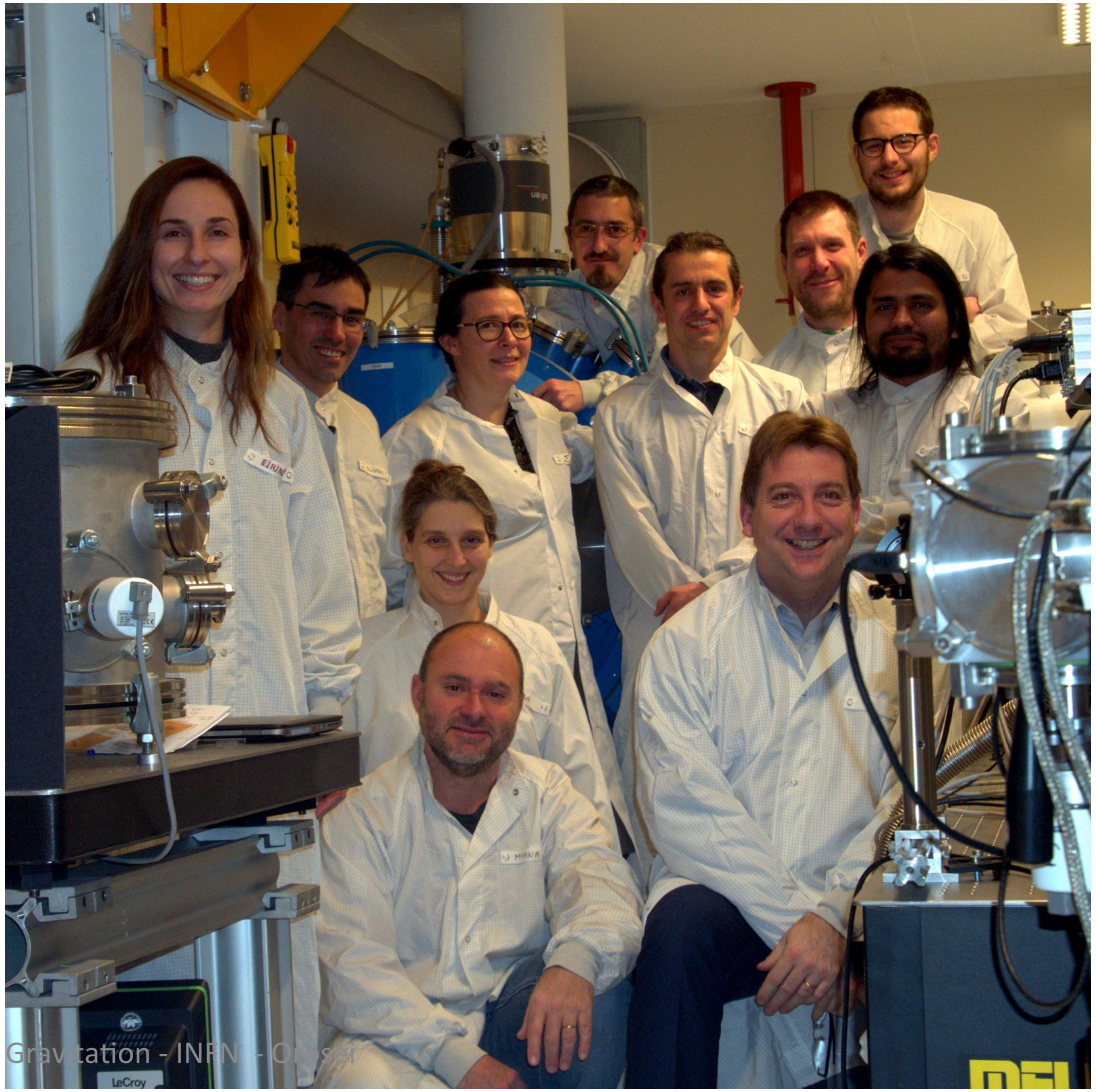
Most work presented here made by

Thanks to LASERIX

- Installed at LAL since a few years
- 30 fs, 2.5 J pulses @ 10 Hz
- $\lambda \sim 800$ nm
- $\sim 1\mu$m position jitter at focus
- Dedicated to
  - X-ray laser pulses production
  - Laser-plasma acceleration tests
  - Others…

- http://hebergement.u-psud.fr/laserix/en/



Maxwell equations in continuous media

- Maxwell's equations are « linear » in vacuum

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

➡ ε_0 and μ_0 are CONSTANT
Optical index (n=1) is constant
Do not depend on external fields

- Maxwell's equations are not linear in medium

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}(\mathbf{E},\mathbf{B}) = \varepsilon(\mathbf{E},\mathbf{B}).\mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}(\mathbf{E},\mathbf{B}) = \mu(\mathbf{E},\mathbf{B}).\mathbf{H} \end{cases} \qquad v = \frac{1}{\sqrt{\varepsilon(E,B)\mu(E,B)}}$$

➡ Optical index is not constant but depends on external fields E,B $\Rightarrow$ ***n*(E,B)**

There is a non linear interaction between the electromagnetic fields, through the medium

n(B) : Birefringence induced by an external magnetic field, first measured by **Faraday** (1845)

n(E) : Refractive index increased by an electric field, first measured by **Kerr** (1875)

What kind of medium is the vacuum w.r.t. electromagnetic waves?

« Euler-Heisenberg Lagrangian » & non linear QED

Euler-Heisenberg (1935) : nonlinearity induced by the coupling of the field with the e^+/e^- virtual pairs in vacuum

Beautifully hand-calculated from 1927 Dirac equation

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

$$\begin{cases} \boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}(\boldsymbol{E},\boldsymbol{B}) \\ \boldsymbol{B} = \mu_0 \boldsymbol{H} + \mu_0 \boldsymbol{M}(\boldsymbol{E},\boldsymbol{B}) \end{cases} \quad \begin{cases} \boldsymbol{P} = \xi \varepsilon_0^2 [2(E^2 - c^2B^2)\boldsymbol{E} + 7c^2(\boldsymbol{E}.\boldsymbol{B})\boldsymbol{B}] \\ \boldsymbol{M} = -\xi \varepsilon_0^2 [2(E^2 - c^2B^2)\boldsymbol{B} - 7(\boldsymbol{E}.\boldsymbol{B})\boldsymbol{E}] \end{cases} \quad \xi^{-1} = \frac{45 m_e^4 c^5}{4\alpha^2 \hbar^3} \approx 3\ 10^{29}\ \mathrm{J/m^3}$$

chiral

⇒ Modification of the Maxwell's equations in vacuum ⇒ Vacuum is a non linear medium

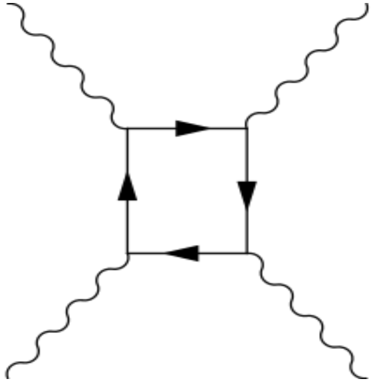
The vacuum refractive index is not an absolute constant $n \neq 1$

It can be **modified on large scale** (low energy) when it is stressed by intense e.m. fields

This result has been derived later by Schwinger with the QED frame

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

Schwinger critical field :
$$\begin{cases} E_{cr} = \dfrac{m_e^2 c^3}{e\hbar} = 1.3 \times 10^{18}\ \mathrm{V/m} \\ B_{cr} = E_{cr}/c = 4.4 \times 10^9\ \mathrm{T} \end{cases}$$



Remarks

- A single wave propagates linearly (E=cB, E.B=0 – no extra term)
- For 2 same linearly polarized counterpropagating waves one has in some places

$$\mathbf{P} = \xi \epsilon_0^2 2E^2 \mathbf{E} = \epsilon_0 \epsilon_r \mathbf{E}$$

- The electrostatic energy density can be seen as extra virtual pairs trapped in the field:

$$\epsilon_r = 4\xi \frac{\epsilon_0 \mathbf{E}^2}{2} = \epsilon_0 \times 4\xi \times 2m_e c^2 \rho_{e^+e^-} \approx \frac{\rho_{e^+e^-}}{5 \times 10^{41} \mathrm{pair}/m^3}$$

which pictures the vacuum filled with about one pair per (12 fm)^3

- Several experiments are trying to measure these effects since decades:
    - Mesoscale electrodynamics at low photon energy with very high occupation number. Collective effects.

Jone's experiment in 1960…

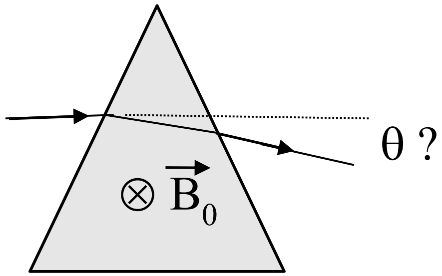
- Variation of the vacuum refractive index, independentely of the polarization, has been tested only once, by R.V. Jones in … 1960 !

Described in **R Battesti and C Rizzo , Magnetic and electric properties of a quantum vacuum**, Rep. Prog. Phys. **76** (2013) 016401

- **Jones's experiment (1960)** : Magnetic prism in vacuum with a static external field **B = 1 Tesla**

  Theoretical expected signal $\Delta\theta_{\mathrm{QED}} \cong 10^{-23}$ rad

  Sensitivity ≅ 0.5 picorad (!)



$$\Delta\theta_{\mathrm{QED}} \propto B^2$$

DeLLight with intense laser field produced by LASERIX

2.5 J, 30 fs, w_0=5μm ⇒ ~ 3×10^{20} W/cm² ⇒ $\boldsymbol{E} \sim \mathbf{3 \times 10^{13} V/m}$, $\boldsymbol{B} \sim \mathbf{10^5\ T}$

$$(\mathbf{E}_{\mathrm{LaseriX}}, \mathbf{B}_{\mathrm{LaseriX}}) \approx 10^{-5} \times (\mathbf{E_c}, \mathbf{B_c})$$

The DeLLight experiment …triggered by the Battesti & Rizzo 2013 report

Xavier Sarazin <sarazin@lal.in2p3.fr> arch14juildéc 2 juillet 2014 à 11:43

Une idée de manip pour tester QED non linéaire en mesurant la déflection d'une impulsion laser Détails

XS

À : carlo rizzo <carlo.rizzo@lncmi.cnrs.fr>, Cc : François COUCHOT <couchot@lal.in2p3.fr>

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Bonjour Carlo

tu trouveras en pièce jointe une note résumant une proposition de manip qu'on aimerait démarrer prochainement avec LASERIX au LAL.
On propose de tester QED non linéaire en faisant contre-croiser deux impulsions laser et en cherchant à observer la déflection de l'une par l'autre.

Cette idée nous est venue grâce à la lecture de ton article ("Magnetic and electric properties of a quantum vacuum", écrit avec Rémy Battesti), dans lequel vous mentionnez l'effet de la variation apparente de l'indice du vide en fonction de l'intensité du champ externe et l'effet de déflection attendue.

Dans cette note, on a essayé d'estimer l'effet avec LASERIX et on a commencé à définir un possible setup.

On aimerait bien avoir un avis de ta part sur cette idée.

Merci beaucoup et bonne journée

xavier sarazin

Principle published: X. Sarazin et al., **Refraction of light by light in vacuum,** Eur. Phys. J. D, 70 1 (2016) 13

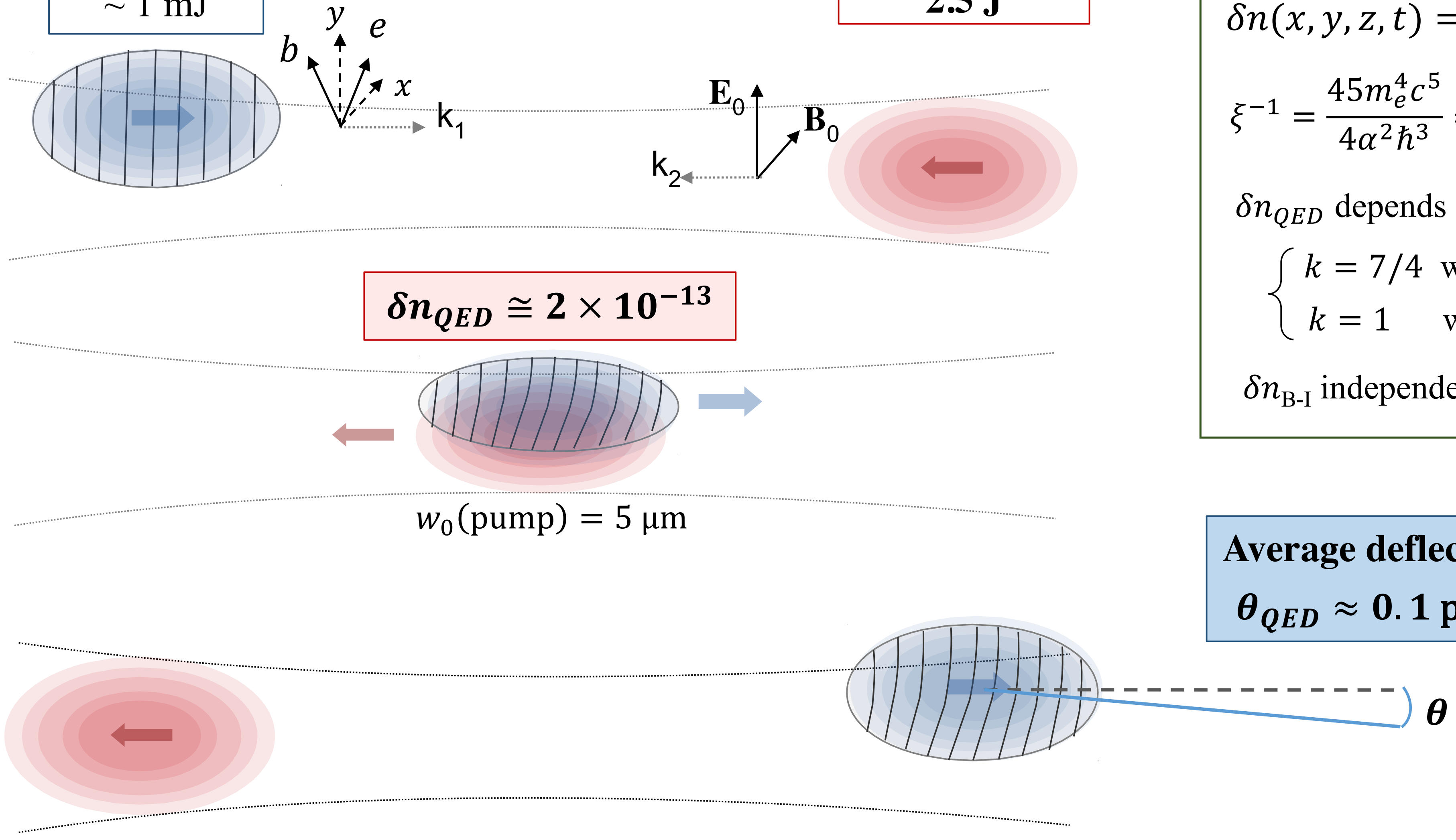
Now consolidated by Scott J. Robertson's theory work, to be presented at the **2019 World of Photonics Congress**, Munich 2019

Pump-Probe interaction

Recent calculations done by Scott Robertson, post-doc LAL & LPT (R. Parentani)

Probe pulse
~ 1 mJ

Pump pulses
2.5 J



$$\delta n(x,y,z,t) = k \times \xi 4 \varepsilon_0 E_0^2$$

$$\xi^{-1} = \frac{45 m_e^4 c^5}{4 \alpha^2 \hbar^3} \approx 3\ 10^{29}\ \text{J/m}^3$$

δn_{QED} depends on the polarisation

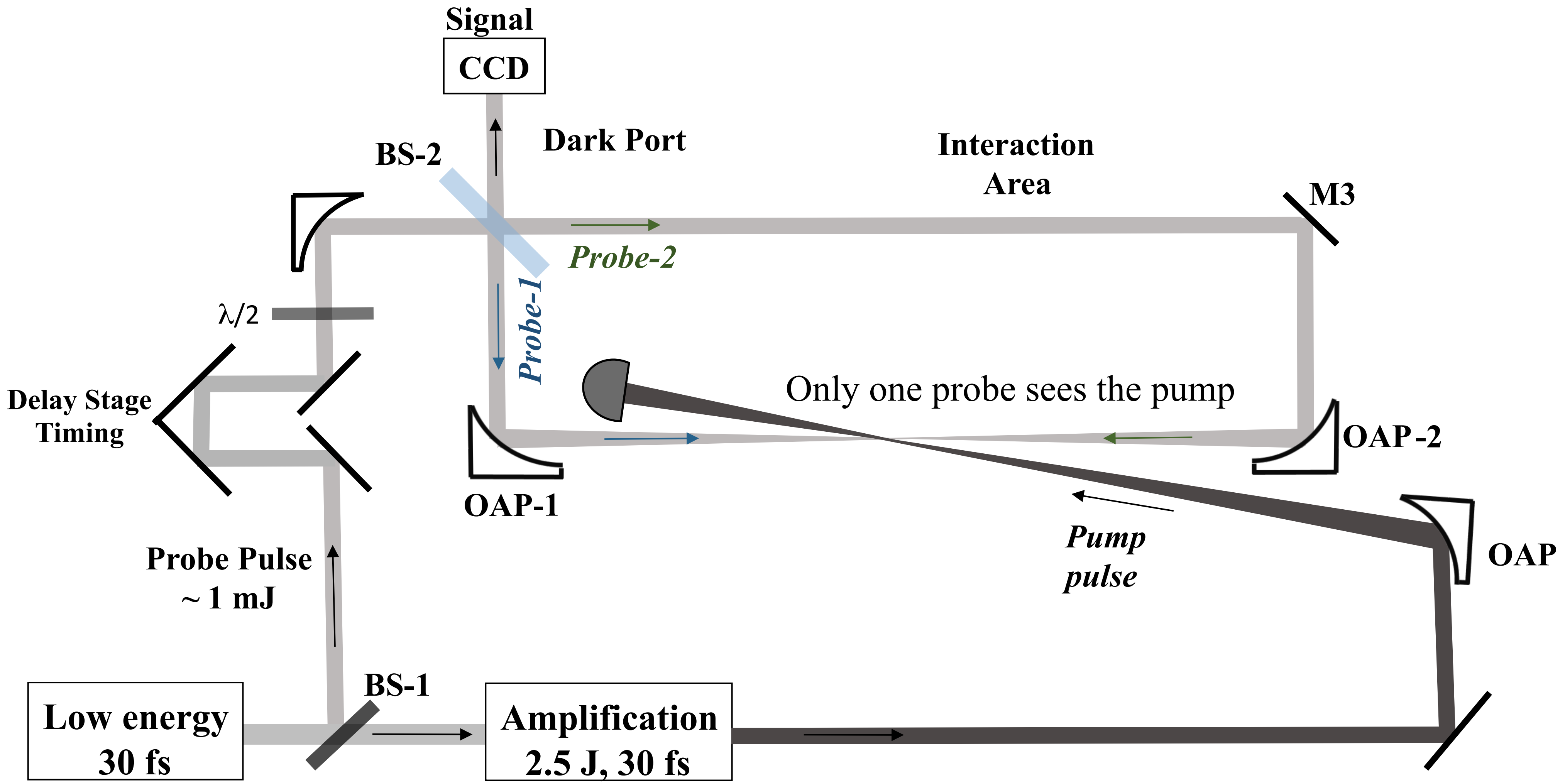
$$\begin{cases} k = 7/4 & \text{when } e_y = 0 \\ k = 1 & \text{when } e_x = 0 \end{cases}$$

$\delta n_{\text{B-I}}$ independent of the polarisation

Average deflection
$\boldsymbol{\theta_{QED} \approx 0.1}$ **prad**

Refraction measured with a Sagnac Interferometer

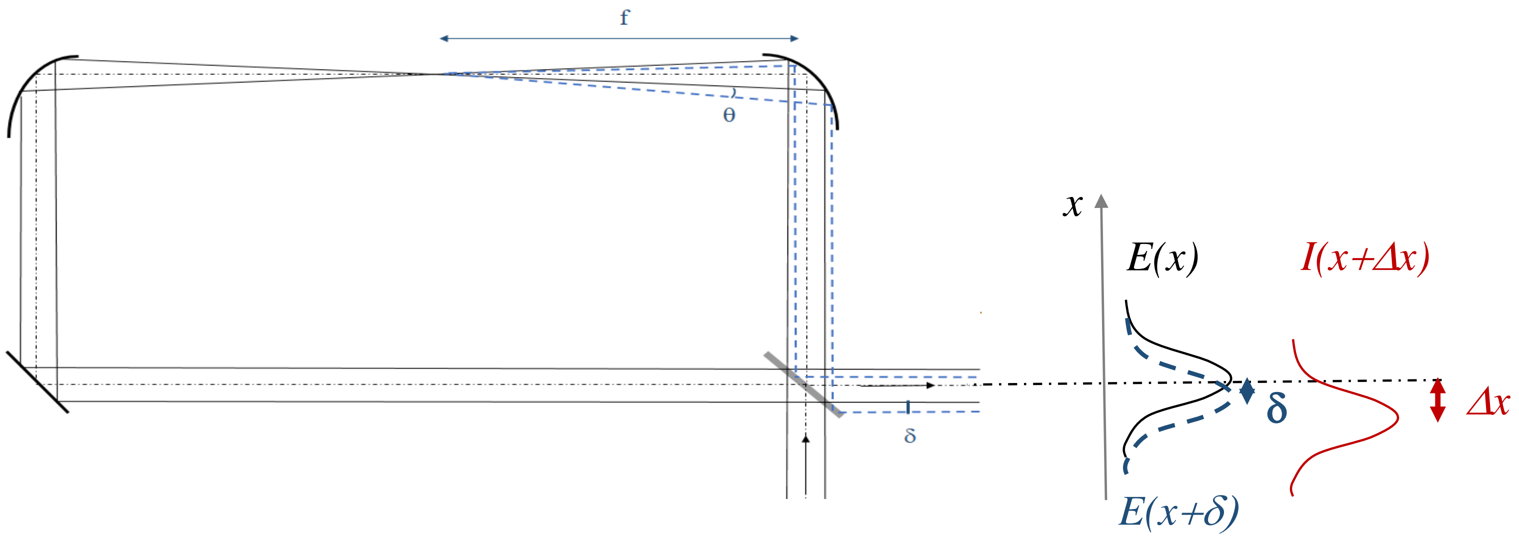
Refraction of the probe pulse ⇒ **Transversal shift *Δx*** of the interference intensity profile



Refraction measured with a Sagnac Interferometer

Generic method described in:
*P. Ben Dixon et al., **Ultrasensitive Beam Deflection Measurement via Interferometric Weak Value Amplification**, PRL**102**, 173601 (2009)*

- Refraction of the probe pulse $\Rightarrow$ **Transversal shift Δx of the interference intensity profile**



- Interference $\Rightarrow$ **Amplification factor $\mathcal{F}$** compared to standard pointing method (with transversal shift δ)

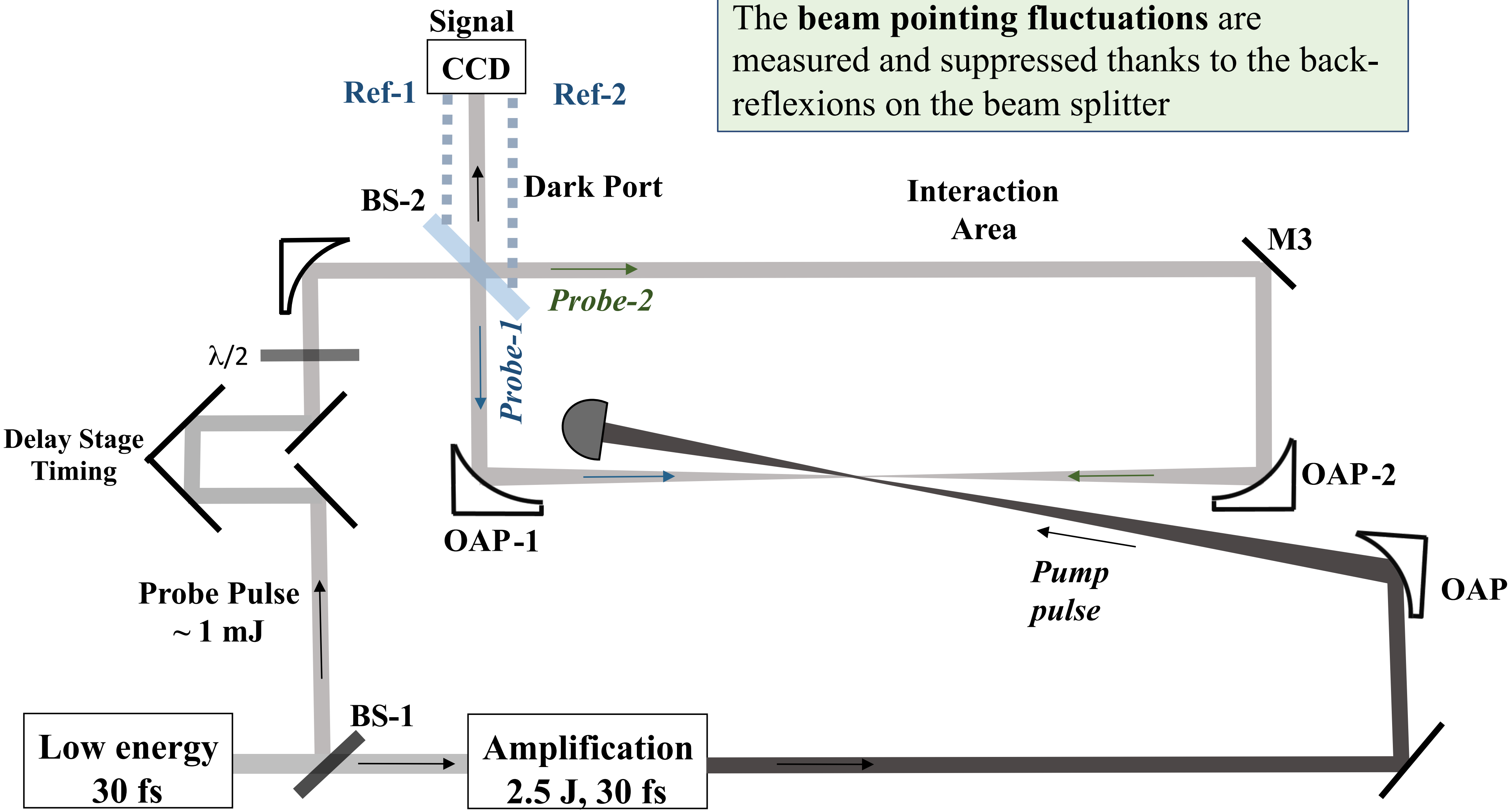
$$\mathcal{F} = \frac{\Delta x}{\delta} = \frac{1}{2\sqrt{Extinction}}$$ where $Extinction = \frac{I_{out}}{I_{in}} = 4\epsilon^2$ and ϵ = asymetry in intensity of the beam splitter)

$$\boxed{\boldsymbol{\epsilon = 10^{-3} \Rightarrow Extinction = 0.4\,10^{-5} \Rightarrow \mathcal{F} = 250}}$$

Refraction measured with a Sagnac Interferometer

Refraction of the probe pulse ⇒ **Transversal shift *Δx*** of the interference intensity profile

The **beam pointing fluctuations** are measured and suppressed thanks to the back-reflexions on the beam splitter



Numerical Simulations - Scott

3-d (x,z) numerical simulation:

- **Two pulses** (30 fs, 800 nm) with ortogonal polarisation are counter-propagating (along z) and focused
- **Transversal profiles of the beams are gaussian:** $\boldsymbol{\mathcal{E}(x,z) = A_0 e^{(-x^2/w_0^2)}}$
- Energy pump pulse **E=2.5 J**; Energy probe pulse is negligible (1 mJ)
- Minimum waist at focus: $\boldsymbol{w_o(\mathrm{probe}) = 2 \times w_o(\mathrm{pump})}$
- Probe beam is shifted transversally by a distance δ_p
- Vacuum refractive index is calculated in the interaction : $\delta n_{QED}(x,z,t) = 7\xi\varepsilon_0 c^2 E^2(x,z,t)$

  $\Rightarrow$ After interaction, the probe pulse is refracted by a phase $\varphi_{QED}(x,z) = \int \frac{2\pi c}{\lambda} \delta n_{QED}(x,z,t)dt$
- Gaussian propagation of the refracted and unrefracted probe pulses to a **distance D**, where they interfer

  $\Rightarrow$ Interference with an **extinction** $\boldsymbol{\mathcal{F} = 4\epsilon^2}$ (ϵ = assymetry of the beam splitter)

Effect of impact parameter, and tilt angle

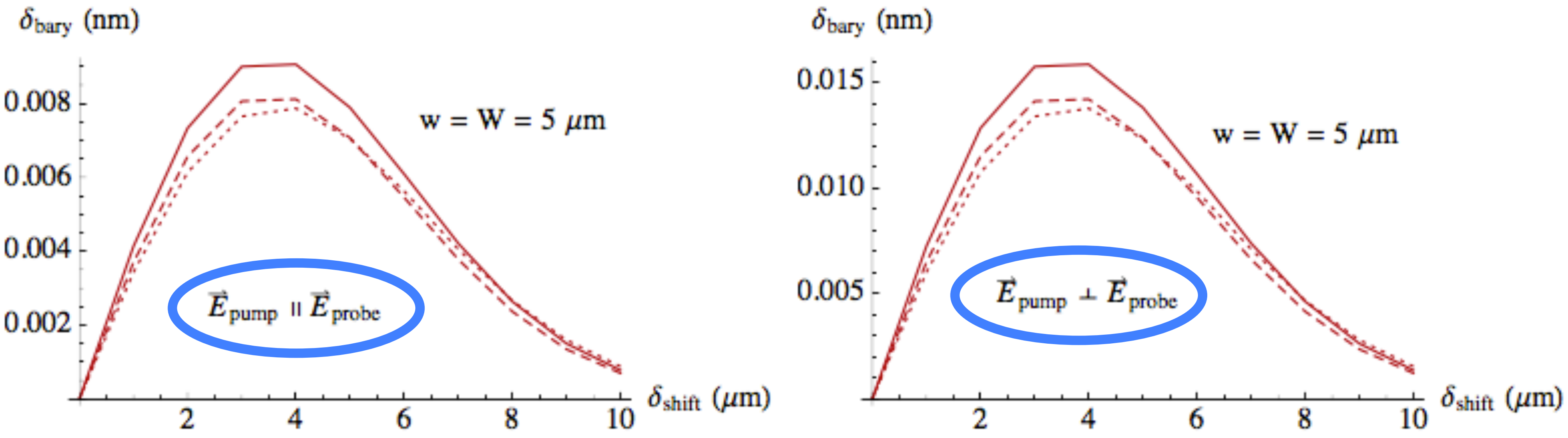


Figure 5. Shift of the barycentre at the output of the Sagnac interferometer after introducing a tilt angle of 30°. The pump energy is fixed at 2.5 J, and the waists of the pump and probe at $W = w = 5\,\mu$m. We also assume a focal length $f = 50$ cm and a beamsplitter asymmetry $\epsilon = 10^{-3}$, exactly as in Figs. 3 and 4. The solid curve reproduces the result with no tilt angle (that on the right panel is exactly the same as the red curves in Fig. 4), while the dashed and dotted curves show results for a tilt angle of 30°. If the pump and probe propagate in the (x, z)-plane, then the dashed curve shows the results when the relative shift between the two pulses is in the y-direction, i.e. perpendicular to the plane in which they propagate. The dotted curve instead shows the results when the relative shift is in the x-direction, i.e. in the same plane in which the two pulses propagate. As indicated on the plots, the left panel is for the case of equal polarization of pump and probe, while the right panel is for the case of opposite polarization; the two are related by a factor of 7/4.

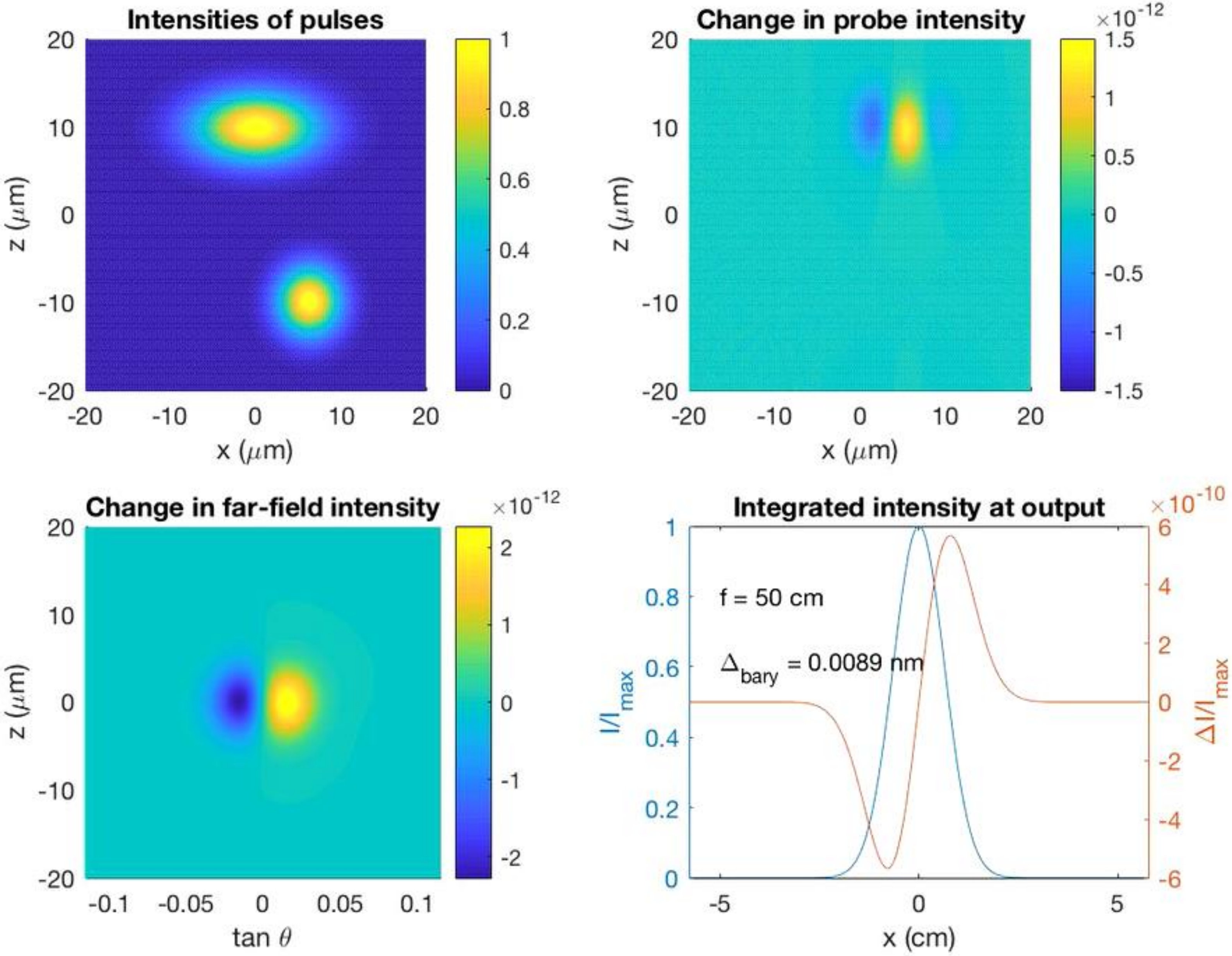
Numerical Simulations

- E = 2.5 J,
- Extinction = 0.4 10^{-5} ($\epsilon = 10^{-3}$)
- D = 50 cm *(limited by the beam divergence)*
- w_0(pump) = 5 μm, w_0(probe) = 10 μm
- $\delta_p = w_0/2$

$\boldsymbol{\Delta x \approx 0.01\, nm}$

Signal Δx reduced by ~20% if jitter pump ±2.5μm

$$\Delta x \cong 6.10^{-10}\ \text{m} \times \frac{E(Joule) \times D(m)}{\left(w_0(\mu\text{m})\right)^3 \times \sqrt{\mathcal{F}/10^{-5}}}$$



Expected sensitivity

- Switch ON & OFF alternatively the pump beam (laser repetition rate = 10 Hz):

  $\Rightarrow$ Barycenters of the intensity profile : $\bar{x}_k^{ON}$ and $\bar{x}_k^{OFF}$

  $\Rightarrow$ Signal (ON-OFF) for the measurement k : $\Delta x_k = \bar{x}_k^{ON} - \bar{x}_k^{OFF}$

- N_{mes} measurements collected $\Rightarrow$ Average signal $= \overline{\Delta x} \pm \sigma_x/\sqrt{N_{mes}}$

  where $\boldsymbol{\sigma_x}$ **is the ON-OFF spatial resolution, including systematics**

- The sensitivity (number of standard deviations N_{sig}) is :

$$\boxed{\boldsymbol{N_{sig}} = \frac{\overline{\Delta x}}{\sigma_x/\sqrt{N_{mes}}} \cong 500 \times \frac{\sqrt{\boldsymbol{T_{obs}}(\text{days})}}{\left(\boldsymbol{w_{0,pump}}(\mu\text{m})\right)^3 \times \sqrt{\boldsymbol{\mathcal{F}}/10^{-5}} \times \boldsymbol{\sigma_x}(\text{nm})}}$$

$$\left\{\begin{array}{l} \text{Extinction } \mathcal{F} = 0.4\ 10^{-5}\ \ (\epsilon = 10^{-3}) \\ \sigma_x = 10\text{ nm} \\ w_0\text{ (pump)} = 5\ \mu\text{m} \end{array}\right. \Rightarrow N_{sig} \cong 0.6\sqrt{T_{obs}(\text{days})} \Rightarrow \boxed{\text{3 sigma discovery in 25 days}}$$

$$\left\{\begin{array}{l} T_{obs} \propto w_{0,pump}^6 \\ T_{obs} \propto \sigma_x^2 \end{array}\right.$$

With w_0 (pump) = 20 µm $\Rightarrow N_{sig} \cong 0.1$ with 100 days of collected data (same as PVLAS birefringence sensitivity)

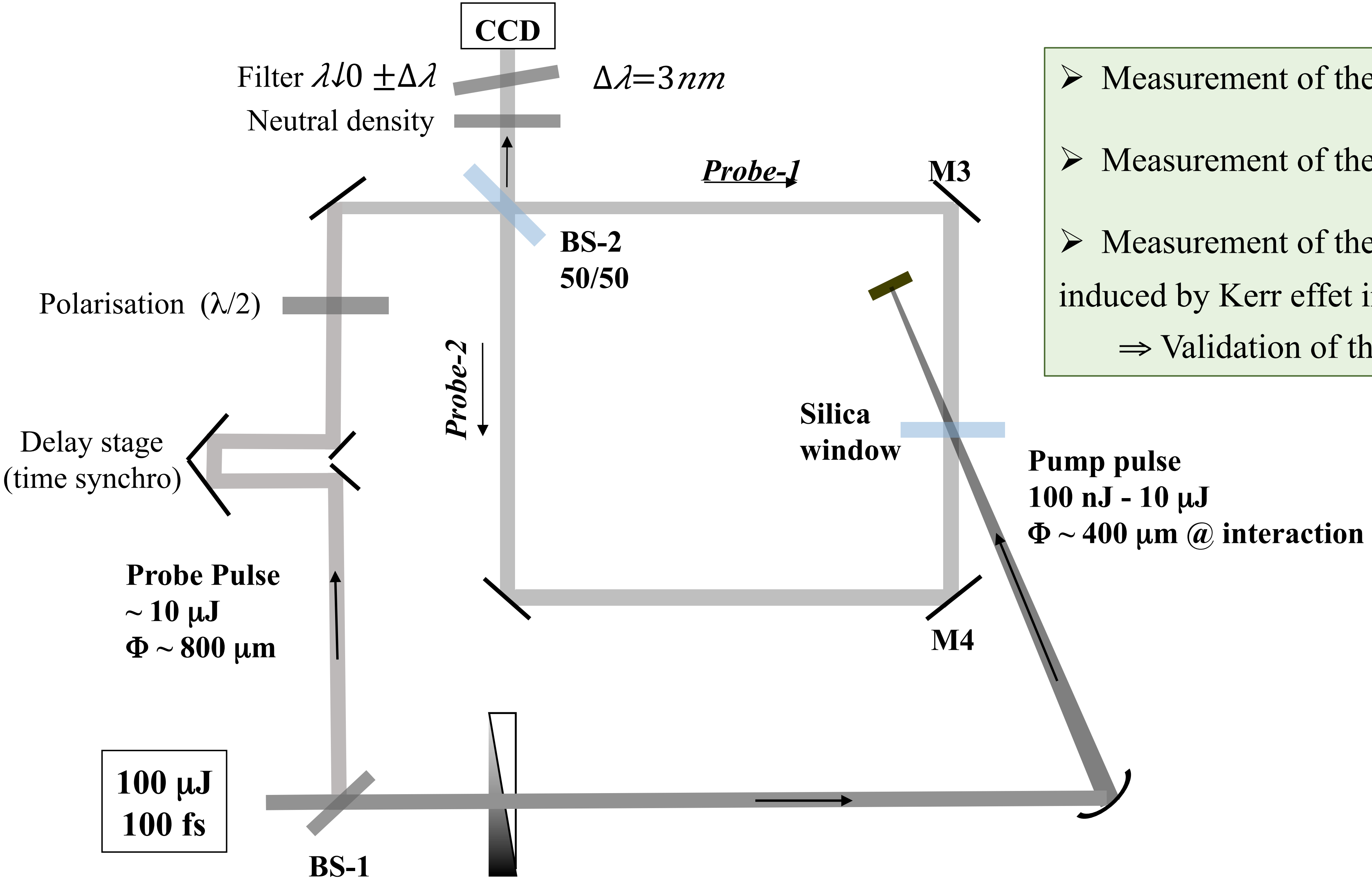
Experimental challenges

- ✓ Extinction: $\mathcal{F} = 0.4\ \ 10^{-5}\ \ (\epsilon = 10^{-3})$
- ✓ Spatial resolution: $\sigma_x = 10$ nm
- ✓ Waist at focus as low as possible

  + stability of the pump-probe overlap

DeLLight-0 prototype

DeLLight-0 prototype

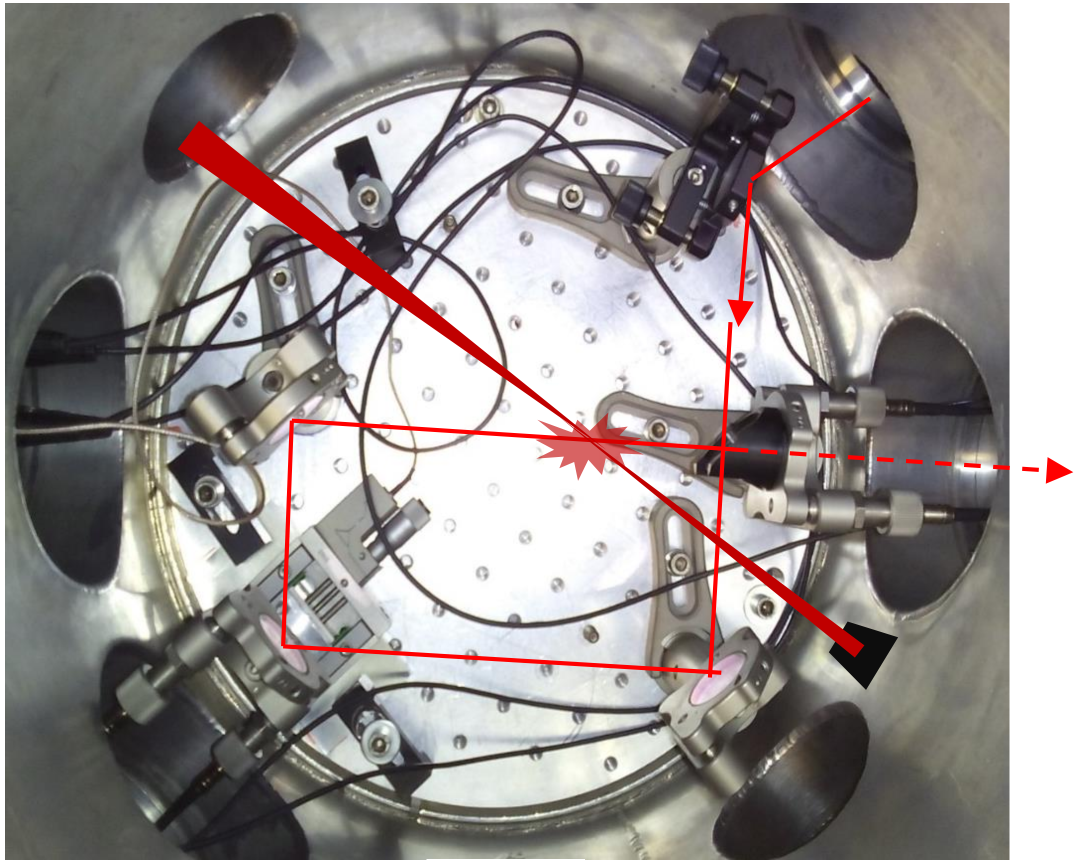


- Measurement of the extinction factor
- Measurement of the spatial resolution
- Measurement of the index gradient

induced by Kerr effet in silica window and in gas

⇒ Validation of the methode

DeLLight-0 demonstrator



← 20 cm →

- ✓ Beam Splitter 50/50 *Semrock ™* (3mm thick)
- ✓ Flat silver mirror standard (λ/10)
- ✓ BS and opposite mirror controled with piezo adjuster
  POLARIS® K1S2P 5 nrad/mV
- ✓ Dark Output:
  - Filter $\Delta\lambda$ = 3 nm @ 800 nm
  - CCD camera *BASLER ™ acA1300-60gm*
    1260x1080 pixels
    pixel size = 5.3 μm
    saturation $\cong 10^4$ electrons/pixel
- ✓ Fused silica window (6mm thick)

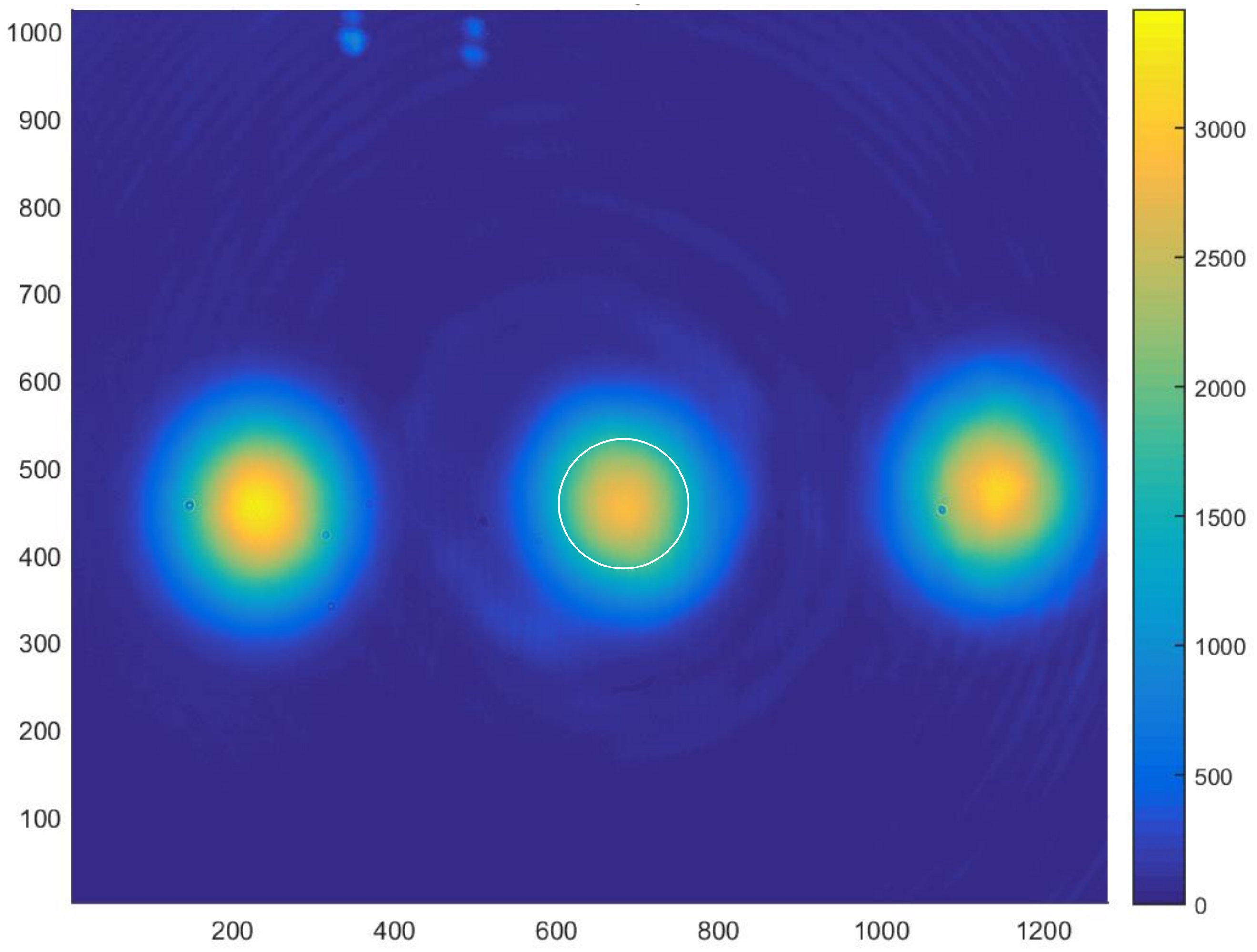
Extinction of the interferometer

Rotation of the polarization $\Rightarrow$ Extinction $\sim 10^{-3}$

Extinction = $4\varepsilon^2$

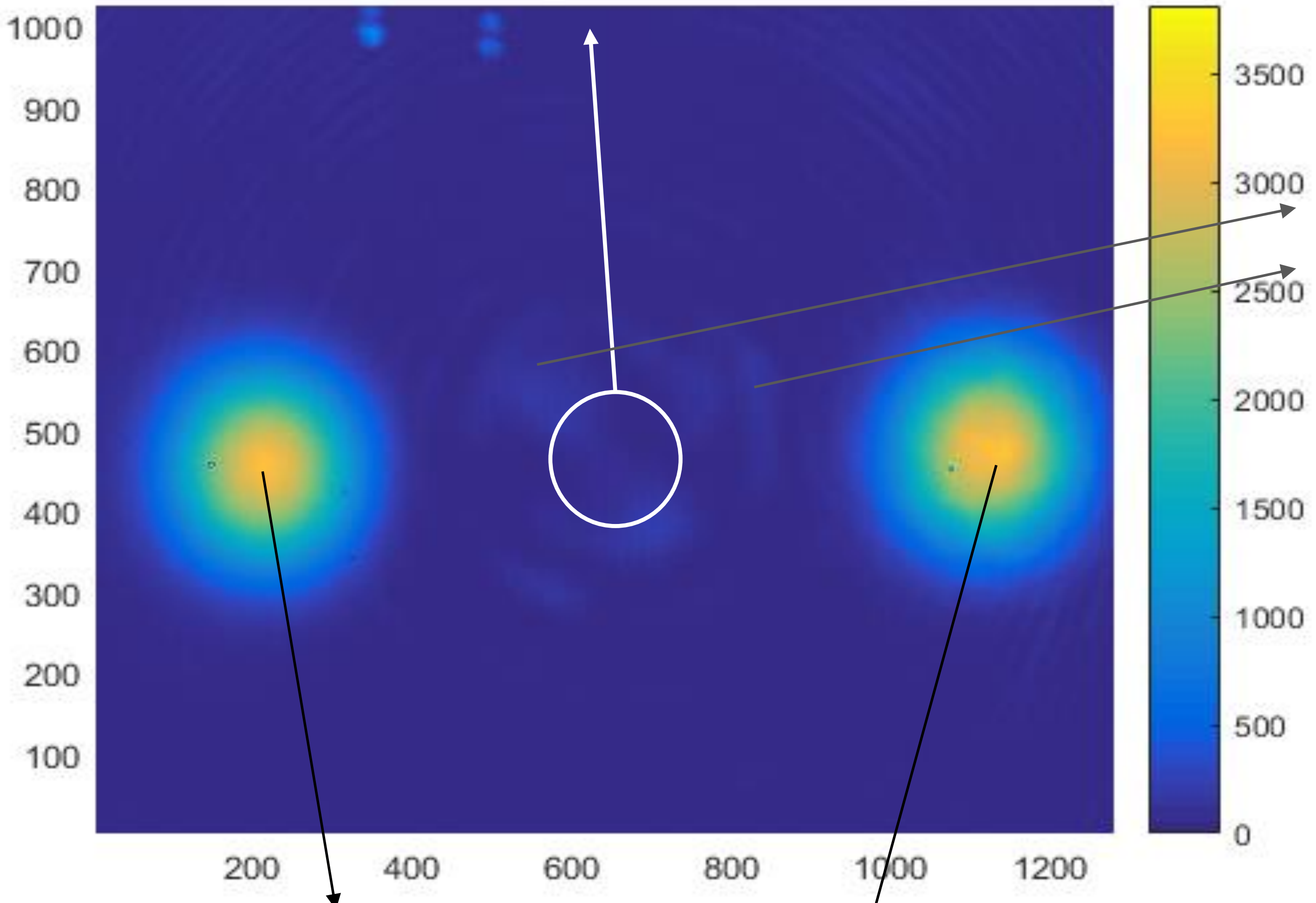
$\varepsilon = I_t/I_r =$ Asymetry (intensity) of the beam splitter

ε depends upon the polarization



Extinction of the interferometer

Signal : Extinction ~ 10^{-5}



Hot spots :

Surface defects on mirors inside the Sagnac

Back reflection (~ 10^{-3})

Spatial resolution

Expected resolution limited by the photon statistic:

$$\Rightarrow \sigma_x \propto \frac{d_{pix}}{\sqrt{N_{e-}^{max}}}$$

- Monte-Carlo: CCD (*BASLER ™ acA1300-60gm)*
  - Pixel size d_{pix}: 5.4×5.4 μm^2
  - Charge saturation $N_{e-}^{max} \cong 10^4$ e$^-$/pixel

$$\boxed{\Rightarrow \ \boldsymbol{\sigma_x \cong 33\ \mathrm{nm}}}$$

- With better CCD *BASLER ™* (*acA4024-29um*):
  - Pixel size d_{pix}: 1.8×1.8 μm^2
  - Charge saturation $N_{e-}^{max} \cong 10^4$ e$^-$/pixel

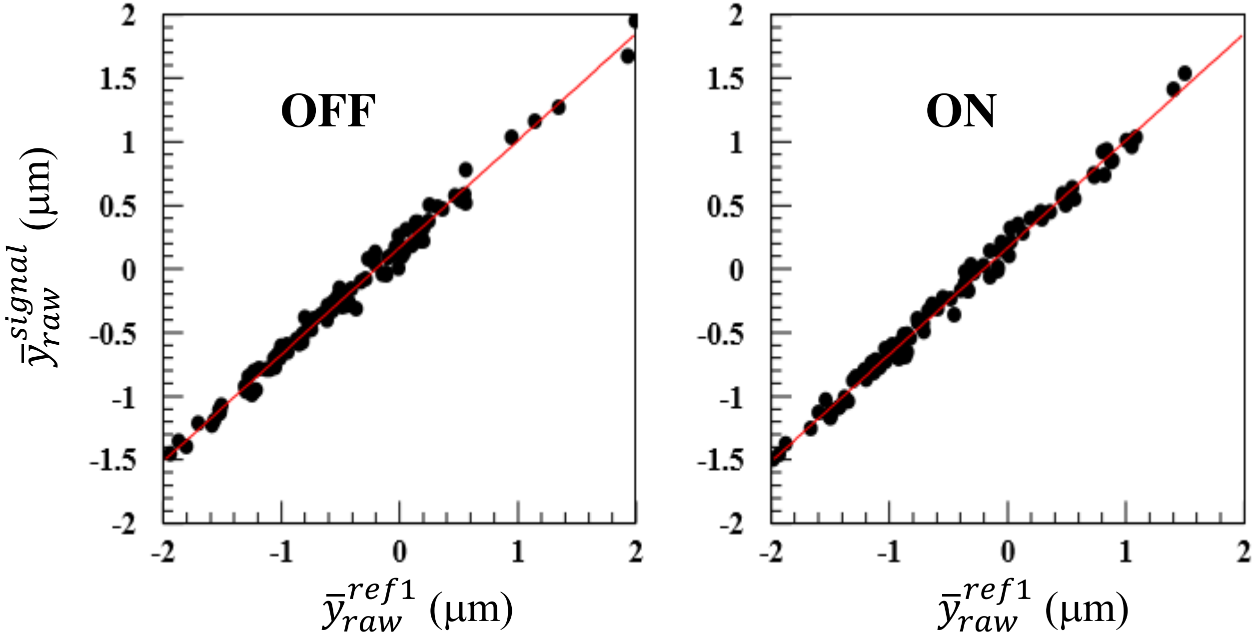
$$\boxed{\Rightarrow \ \boldsymbol{\sigma_x \cong 10\ \mathrm{nm}}}$$

Beam pointing fluctuation correction

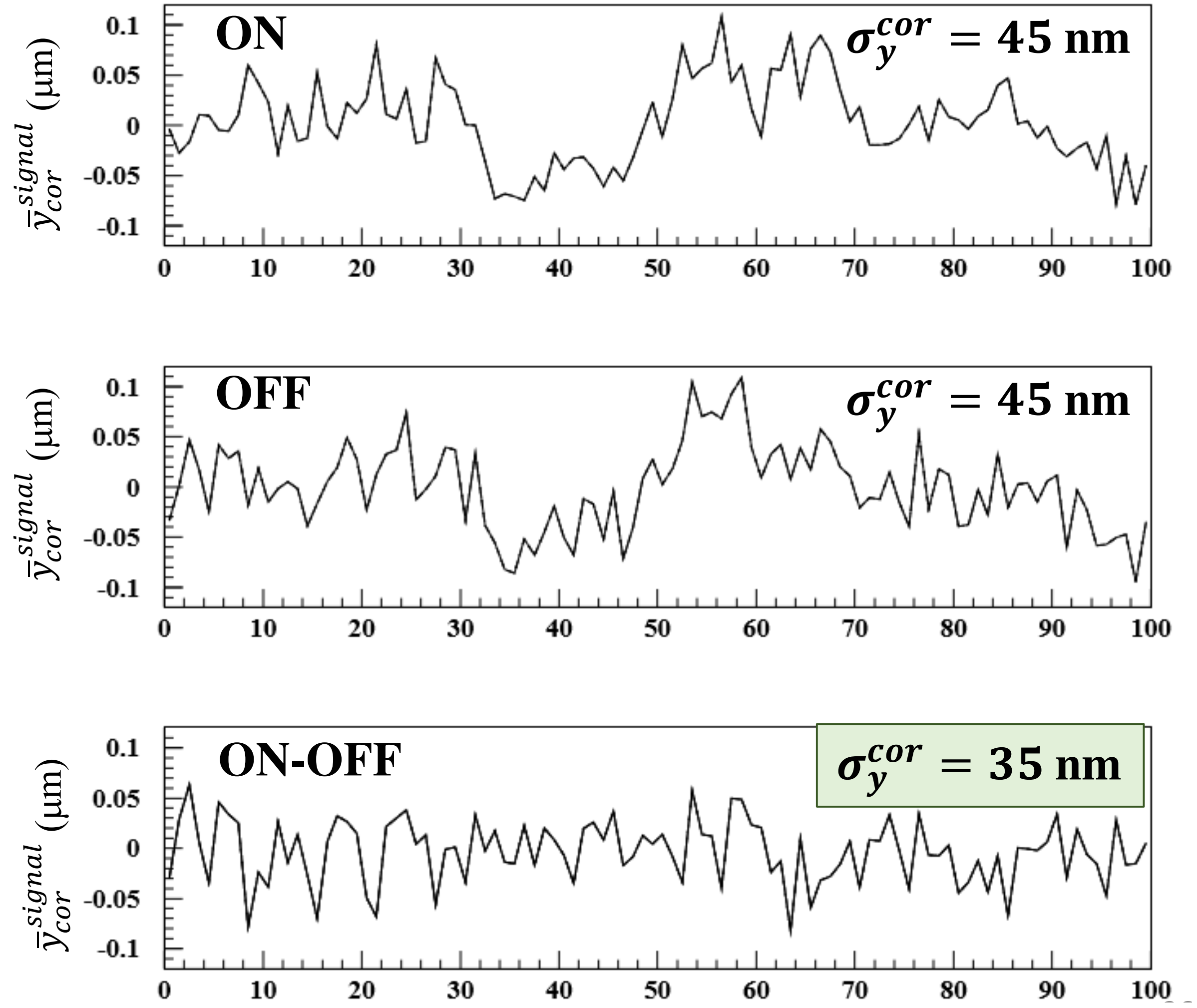
Spatial resolution

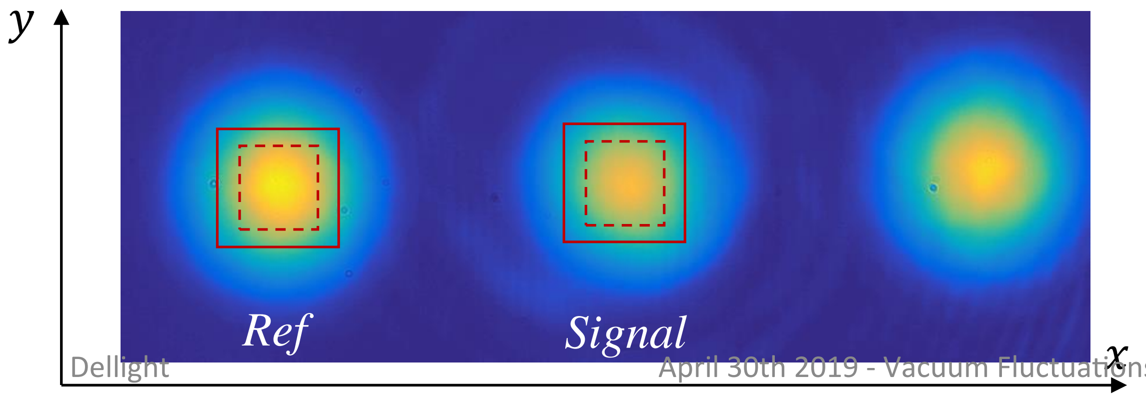
Preliminary analysis based on a barycenter calculation in a simple square analysis window (RoI)

Beam pointing fluctuations are well measured by the back-reflections on BS



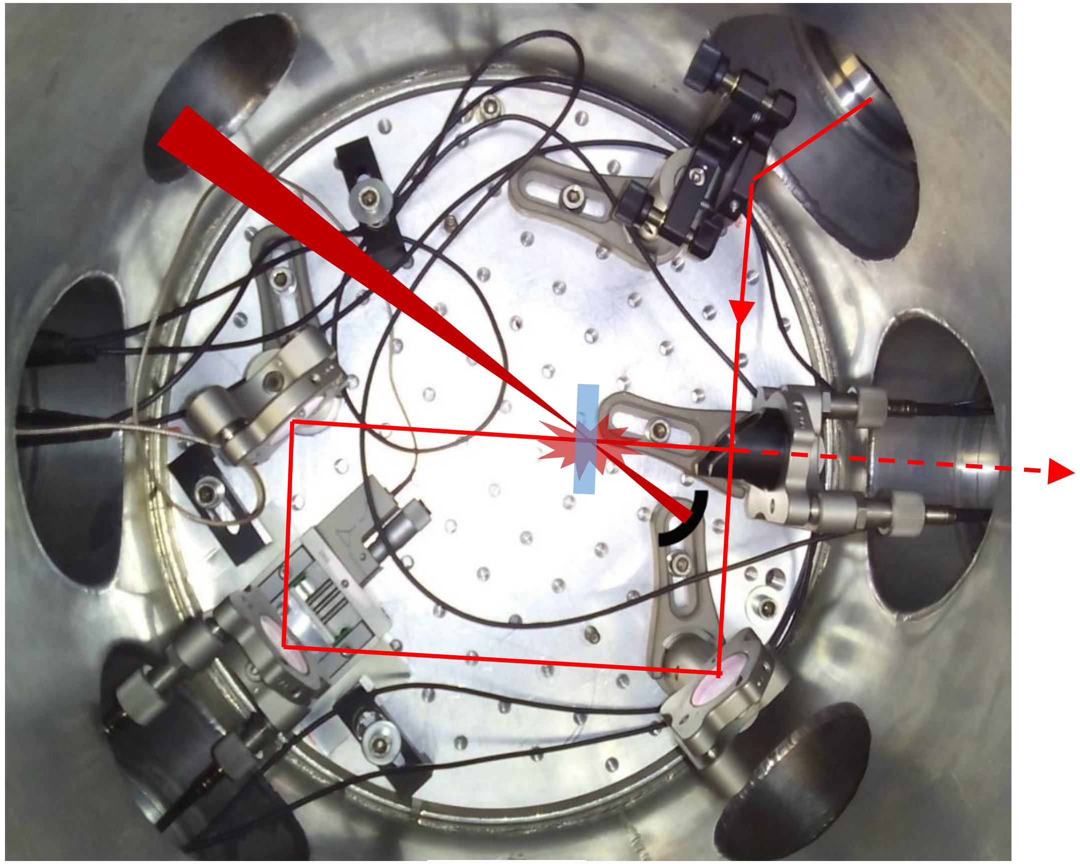
After beam pointing correction
⇒ low frequency drift supressed by ON-OFF subtraction





Observation of the non linear Kerr effect

Kerr effect induced in a fused silica window (6mm thick)



$\longleftarrow$ 20 cm $\longrightarrow$

$$n(I) = n_0 + n_2 \times I(\mathrm{W/cm^2})$$
$$n_2(\mathrm{Silica}) \approx 3 \times 10^{-16}\ \mathrm{cm^2/W}$$

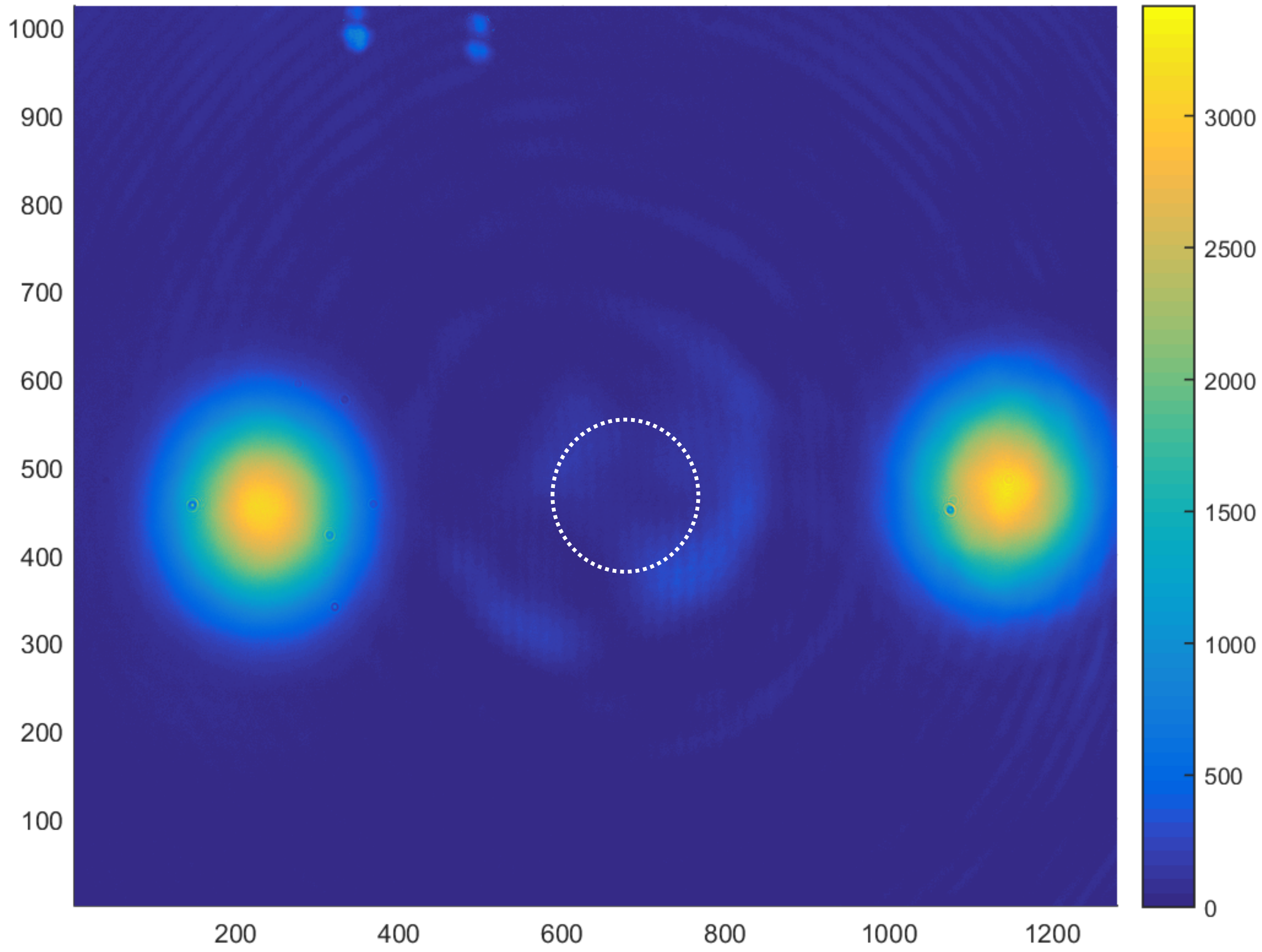
Data taken in June & July 2018

- Φ(probe) $\cong$ 800 μm (fwhm)
- Φ(pump) $\cong$ 400 μm (fwhm)
- Duration of the pulses Δt ~ 50 – 100 fs
- Energy Pump varies from ~12 μJ down to ~300 nJ

Measurement of the Kerr signal in SiO_2

Maximal extinction

Without pump



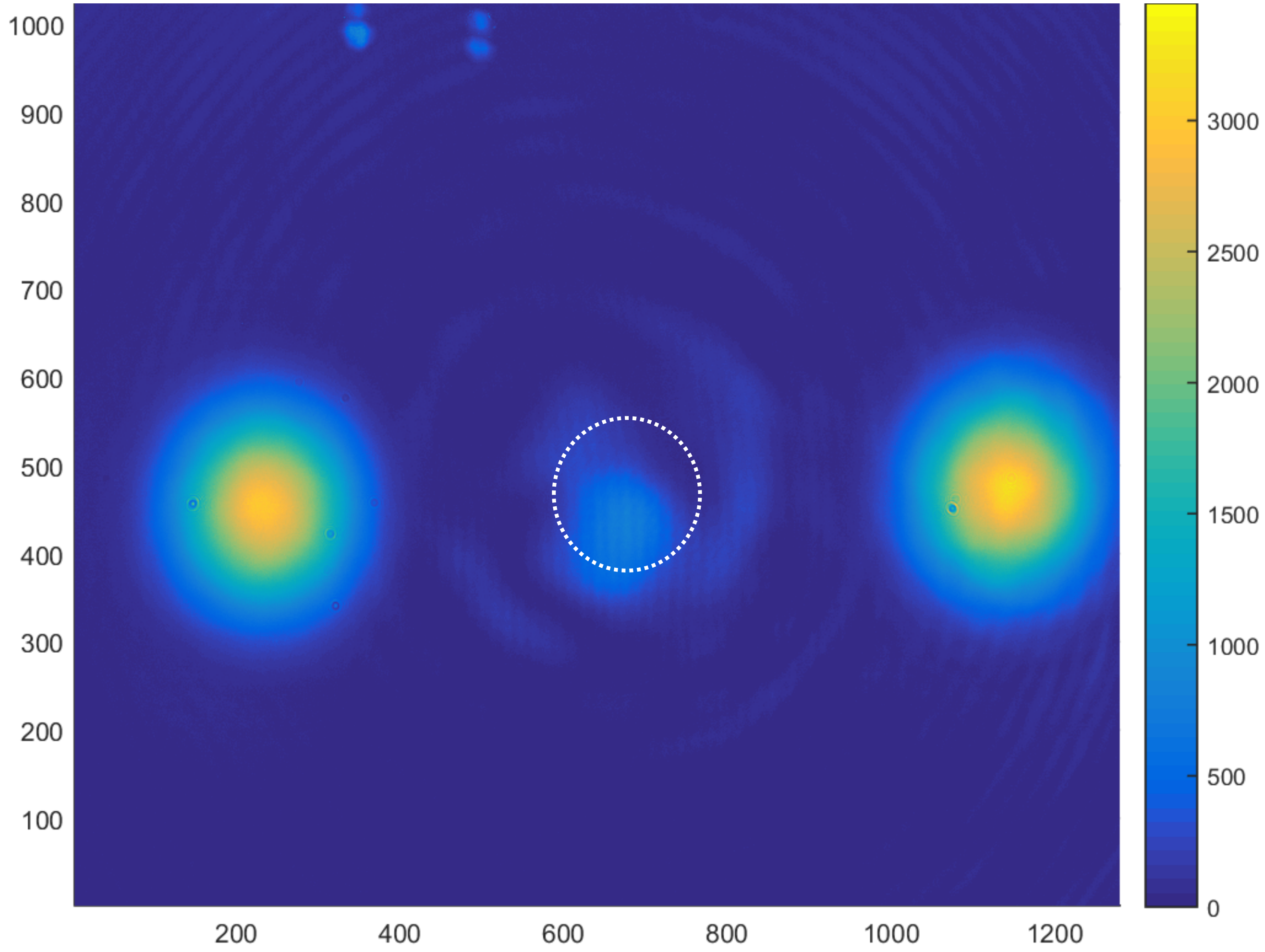
Intensity profiles in the dark output
of the Sagnac interferometer

Measurement of the Kerr signal in SiO_2

Maximal extinction

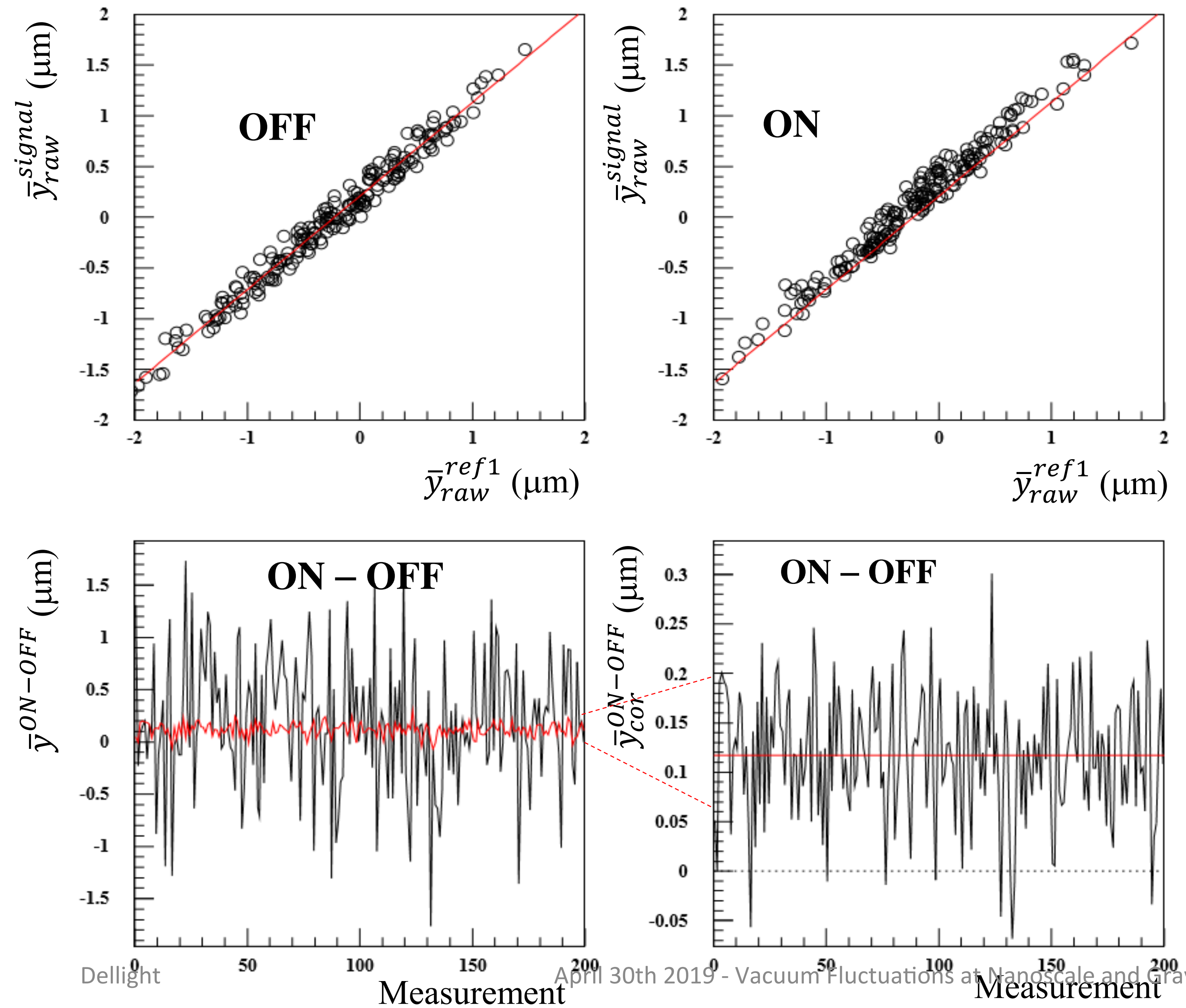
With pump $I \sim 10^{11}$ W/cm^2

Energy pump ~ 20 μJ



Intensity profiles in the dark output
of the Sagnac interferometer

Measurement of the Kerr signal in SiO_2



Energy pump ~ 300 nJ

Δt ~ 50 – 100 fs

Φ(pump) ~ 400 μm

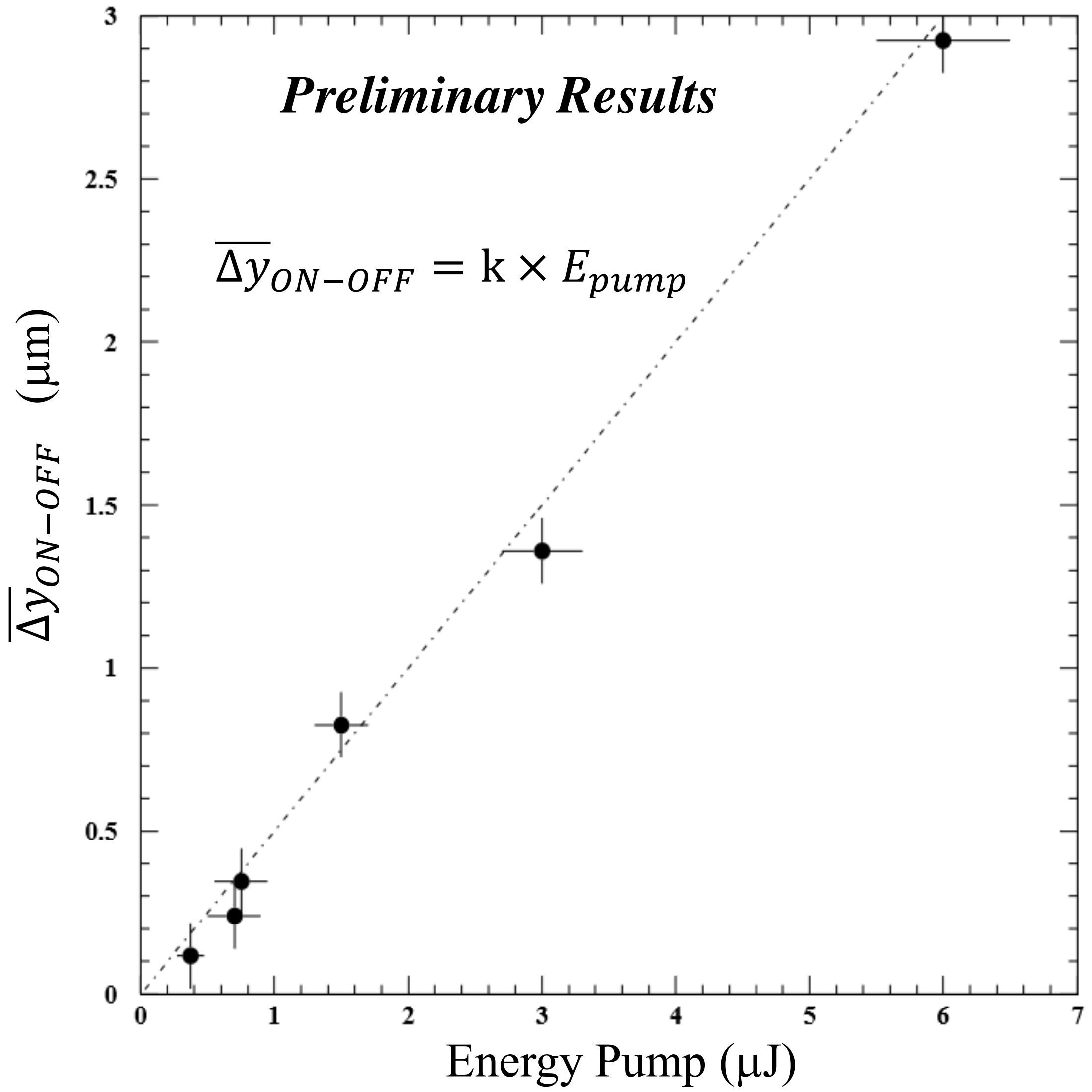
➡ I ~ 10^9 W/cm^2

➡ $\boldsymbol{\Delta n/n \approx 5 \times 10^{-7}}$

$\boldsymbol{\Delta y = 117.0 \pm 4.5}$ **nm**

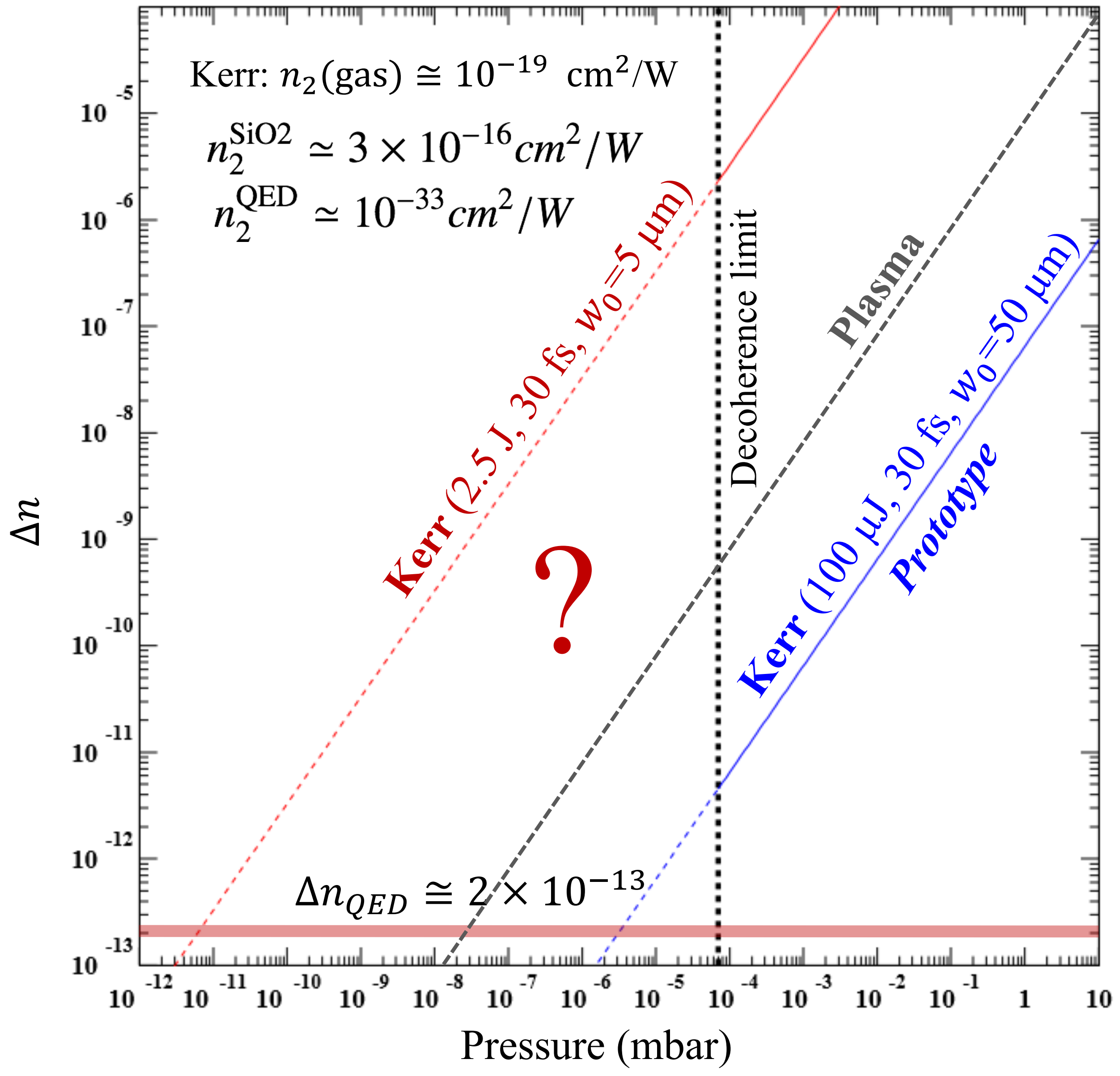
(200 meas. ON-OFF; 40 sec.)

Measurement of the Kerr signal in SiO_2



- ✓ Signal $\overline{\Delta y}_{ON-OFF}$ is proportional to the energy of the pump, as expected for the Kerr effect
- ✓ Preliminary results, work in progress...
  - Simulations of the Kerr effect
  - Influence of the polarization
  - ….
- ✓ Next step: measure Kerr effect in gas

Kerr effect and plasma in residual gas

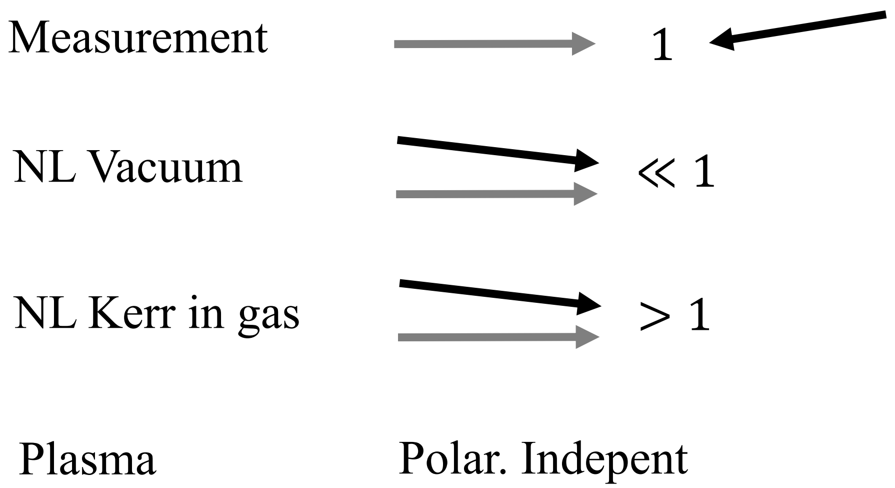


- **Kerr effect in gas: Decoherence limit ?**

$p \cong 7 \times 10^{-5}$ mbar $\Rightarrow$ distance between atoms $\cong \lambda_{laser}$

- **Plasma**: $\Delta n_{plasma} \cong \Delta n_{QED}$ for $p = 2 \times 10^{-8}$ mbar

- Beam polarisation & orientation used to distinguish the processes



DeLLight for the next 3 years

Funded (~310 keuros) by ANR Oct. 2018 – Oct. 2021

2/3 Equipement

1/3 2-years post-doc (starting spring 2019)

Partners: LAL, LPGP, LUMAT, APC

Program:

1. DeLLight-0 (2019):
   - Kerr effect inside Silica window ⇒ $\delta n \approx 10^{-8}$
   - Kerr effect & plasma inside low pressure gas ⇒ $\delta n \approx 10^{-11}$
2. DeLLight Phase 1 (2019-2020): Measure in vacuum with 2 Joules & focus $w_0 = 10 – 20$ µm
3. DeLLight Phase 2 (2020-2021): Measure in vacuum with focus $w_0 = 5$µm ⇒ $\delta n \approx 2 \times 10^{-13}$

Thank you ☺