DeLLight
(Deflection of Light by Light)
with LASERIX @ IJCLab

Modification of the light velocity in vacuum with intense laser pulses

Core DeLLight group : F. Couchot, A. Klaych (upcoming postdoc Nov. 2021), A. Mailliet (PhD), S. Robertson (former postdoc until Aug. 2021), X. Sarazin
Laserix : E. Baynard, J. Demailly, M. Pittman,
Other members : A. DjannaL-Atai (APC, upcoming visitor), M. Urban (emerite)

DeLLight experiment to observe an optically induced change of the vacuum index,
Phys. Rev. A 103, 023524 (2021), arXiv:2011.13889

Project currently funded by ANR: Nov. 2018 → April 2022

Is the vacuum optical index constant ?

- ***Maxwell's equations are linear in vacuum***

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

➡ ε_0 and μ_0 are CONSTANT
$\Rightarrow$ Speed of light (optical index) is constant

- ***Maxwell's equations are not linear in dielectric media***

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

➡ Optical index depends on external fields E,B
Nonlinear interaction between the e.m. fields through the medium

➡ Nonlinear optical **Kerr effect** with intense laser: $n = n_0 + n_2 \times I(\mathrm{W/cm^2})$ $\quad n_2(Air) \cong 10^{-19}\ \mathrm{cm^2/W}$

- **QED** : ***nonlinearity in vacuum*** induced by the coupling of the fields with the e^+/e^- virtual pairs

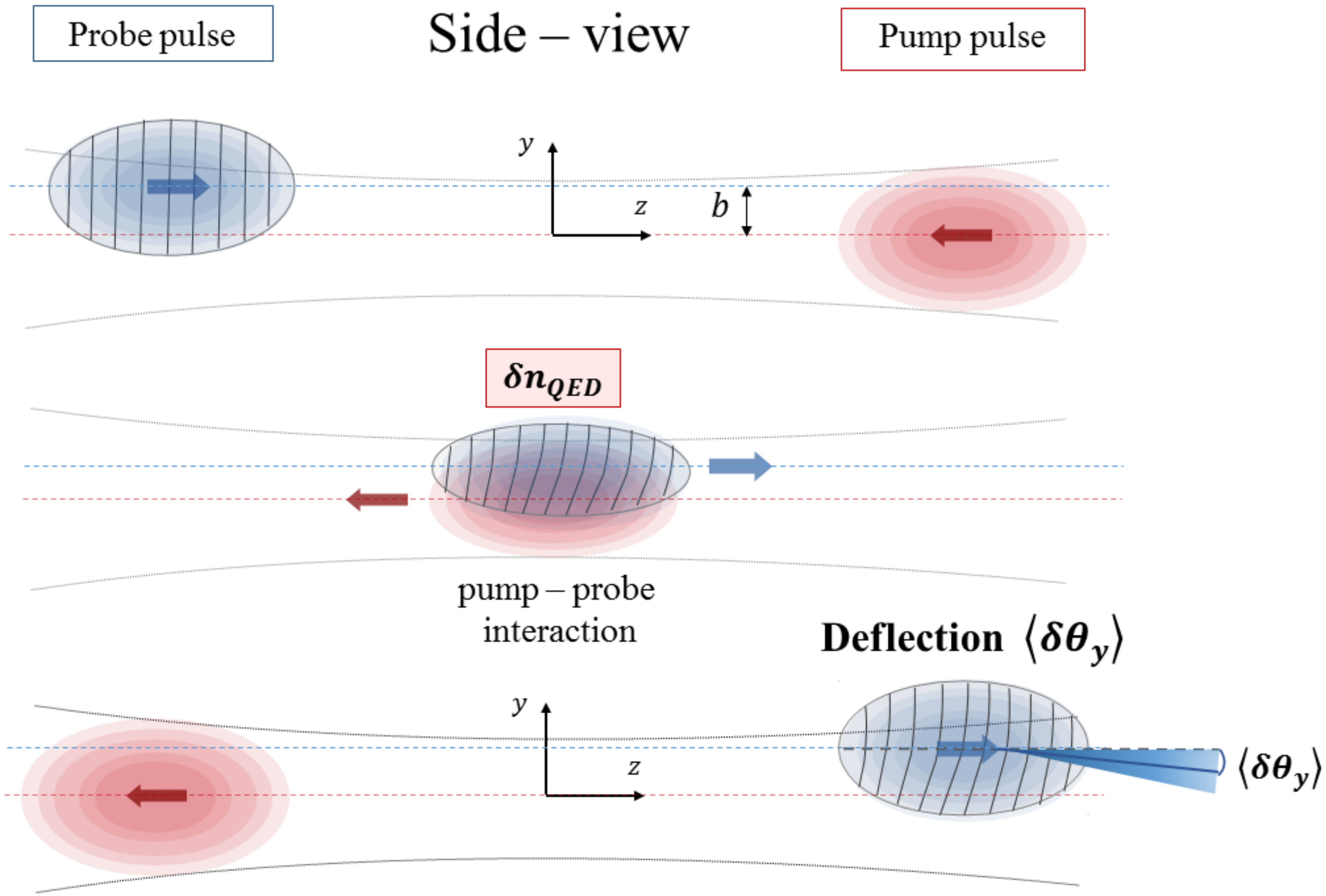
Heisenberg and Euler, Z. Phys. 98, 714 (1936)

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

➡ **Optical Kerr effect in vacuum ?** $\boldsymbol{n_2 = 1.6 \times 10^{-33}\ \mathrm{W/cm^2}}$

S. Robertson et al. Phys. Rev. A 100, 063831 (2019)
arXiv:1908.00896

Pump-Probe interaction



Use highly focused laser pulses to achieve strong fields

- $\boldsymbol{I_{pump} \gg I_{probe}}$
- Pump unaffected by probe
- Probe refracted by δn_{QED} induced by pump

Pump specifications (with *LASERIX*)

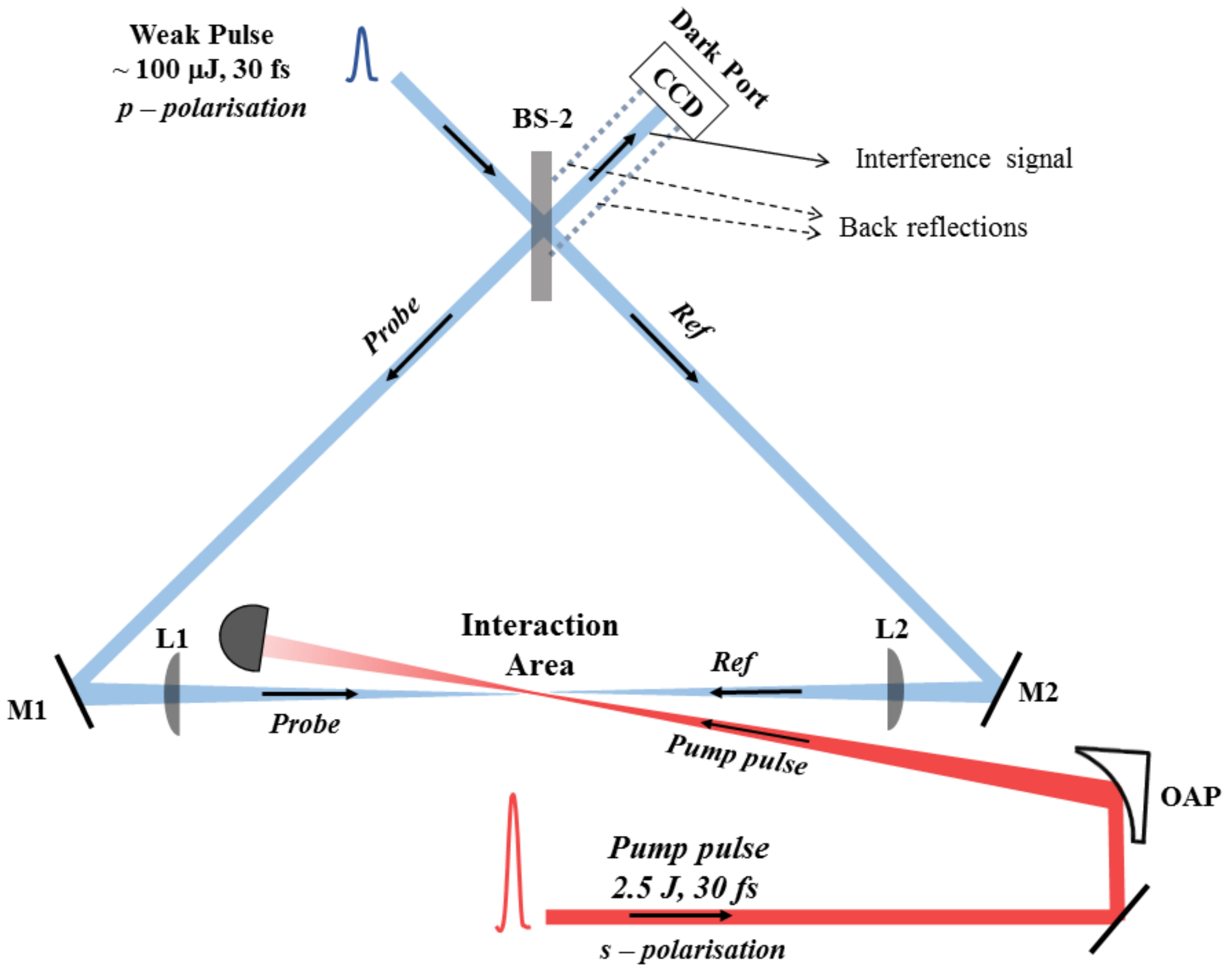
- Energy ≈ 2.5 Joules
- Duration ≈ 30 fs
- Waist @ focus ≈ 5 μm

$\Rightarrow I_{pump} \sim 3 \times 10^{20}$ W/cm^2

$\Rightarrow B \sim 10^5$ T

$\Rightarrow \boldsymbol{\delta\theta \sim 10^{-13}}$ **rad**

Refraction measured with a Sagnac Interferometer



Amplificaton of expected signal

- Extinction factor : $\mathcal{F} = I_{out}/I_{in} \sim 10^{-5}$
- Focal length of lenses : $f \sim$ 50cm

$\Rightarrow$ Observed shift of intensity profile in the dark output **$\Delta y \sim$ 0.01 nm**

$$\Delta y = 2.7 \text{ nm} \times \frac{E(Joule) \times f(m)}{\left(w_0^2 + W_0^2\ (\mu\text{m})\right)^{3/2} \times \sqrt{\mathcal{F}/10^{-5}}}$$

Requirements :

	Target
Extinction $\mathcal{F}$ as high as possible	$\boldsymbol{\mathcal{F} = 10^{-5}}$
Waist at focus w_0 as small as possible (keeping a high focal length)	$\boldsymbol{w_0 = 5\ \mu m}$
Good spatial resolution for the position of the intensity profile in the dark output	$\boldsymbol{\sigma_y = 10\ nm}$

Back reflections at beamsplitter allow monitoring and suppression of beam poin'ng fluctua'ons

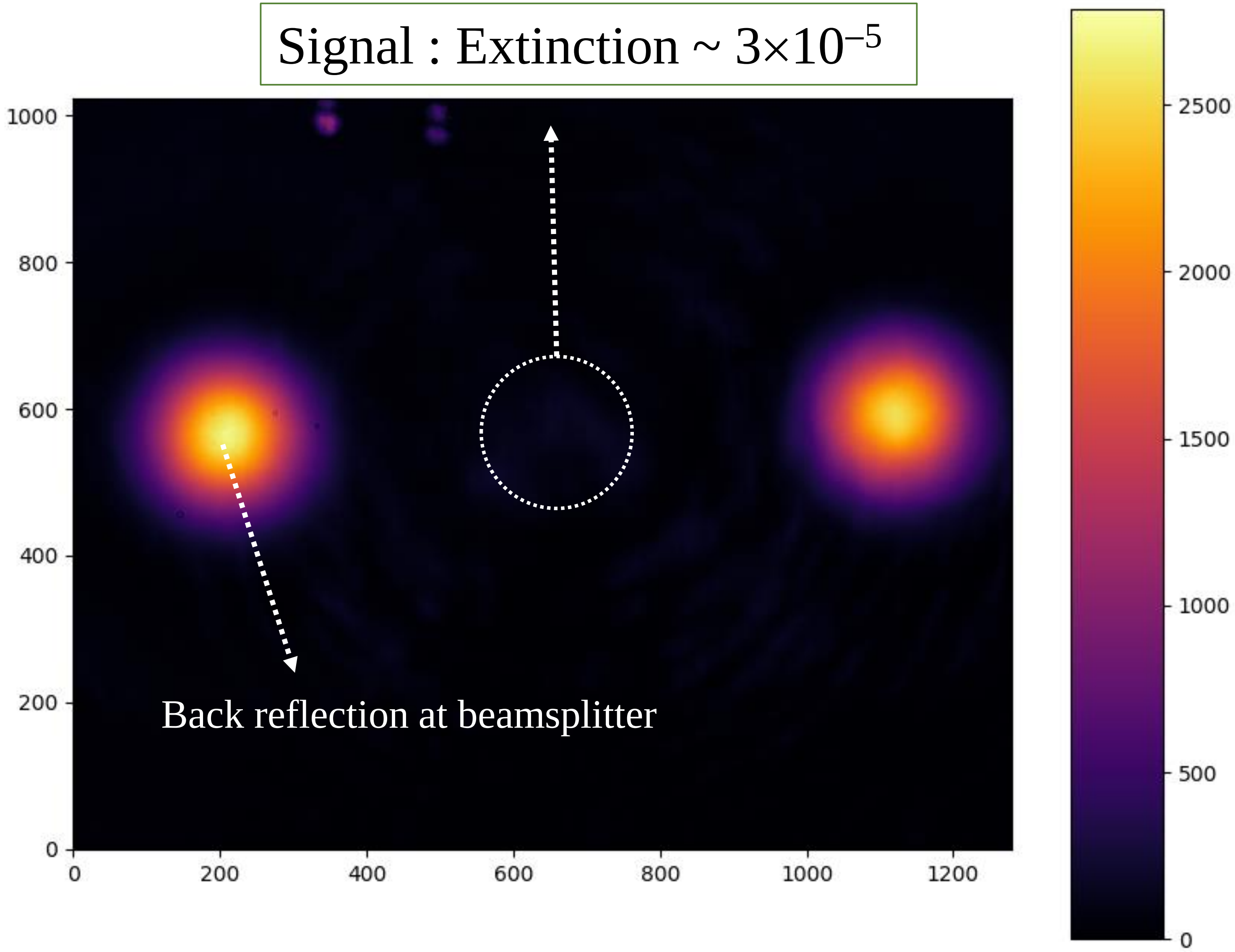
QED signal : 1 sigma sensitivity per $\sqrt{T_{obs}(days)}$

Extinction of the interferometer

Signal : Extinction ~ 3×10^{-5}

Extinction = $4\varepsilon^2$

ε = Asymetry (intensity) of the beam splitter

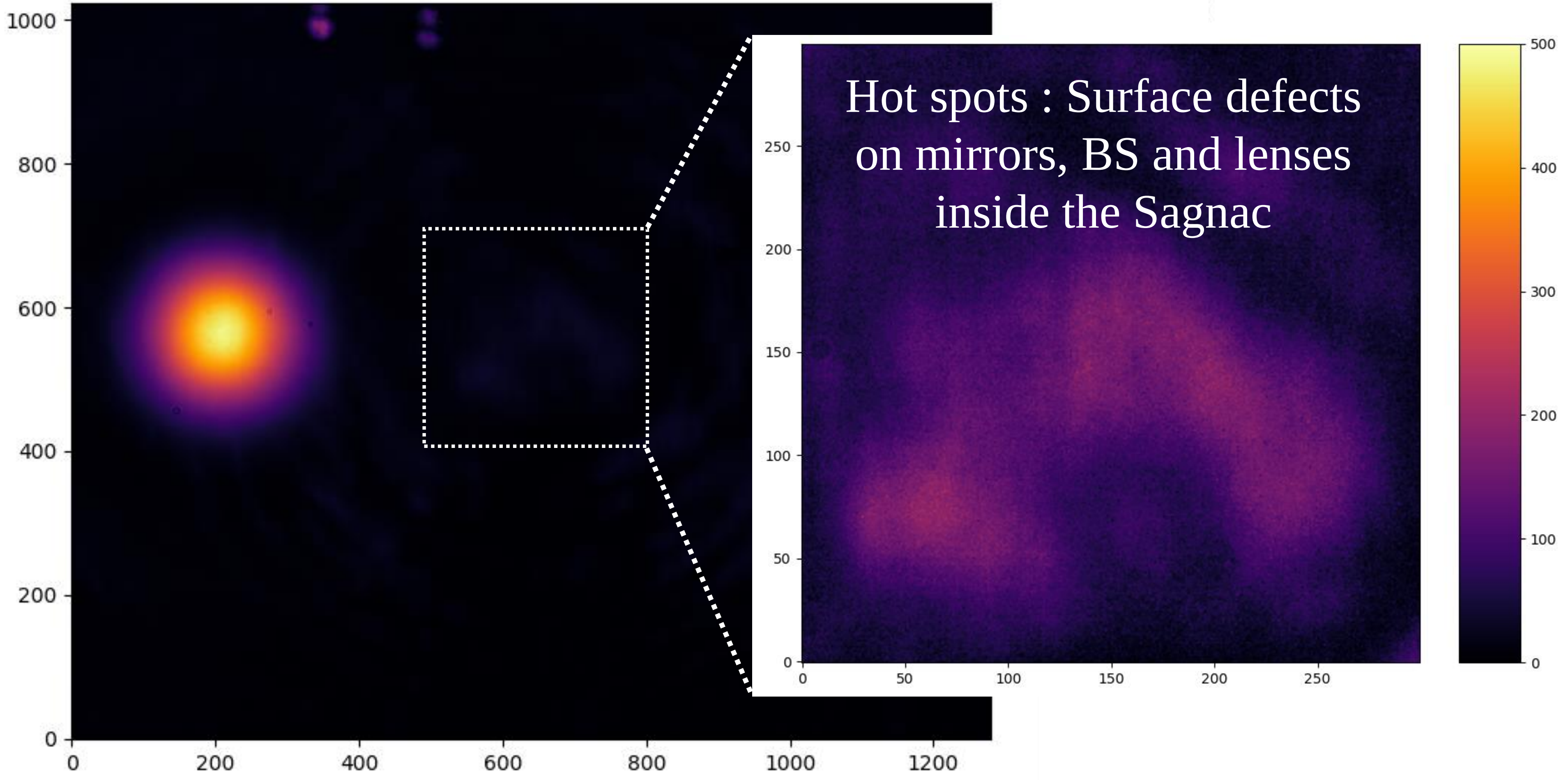


Extinction of the interferometer

Signal : Extinction ~ 3×10^{-5}

Extinction = $4\varepsilon^2$

ε = Asymetry (intensity) of the beam splitter



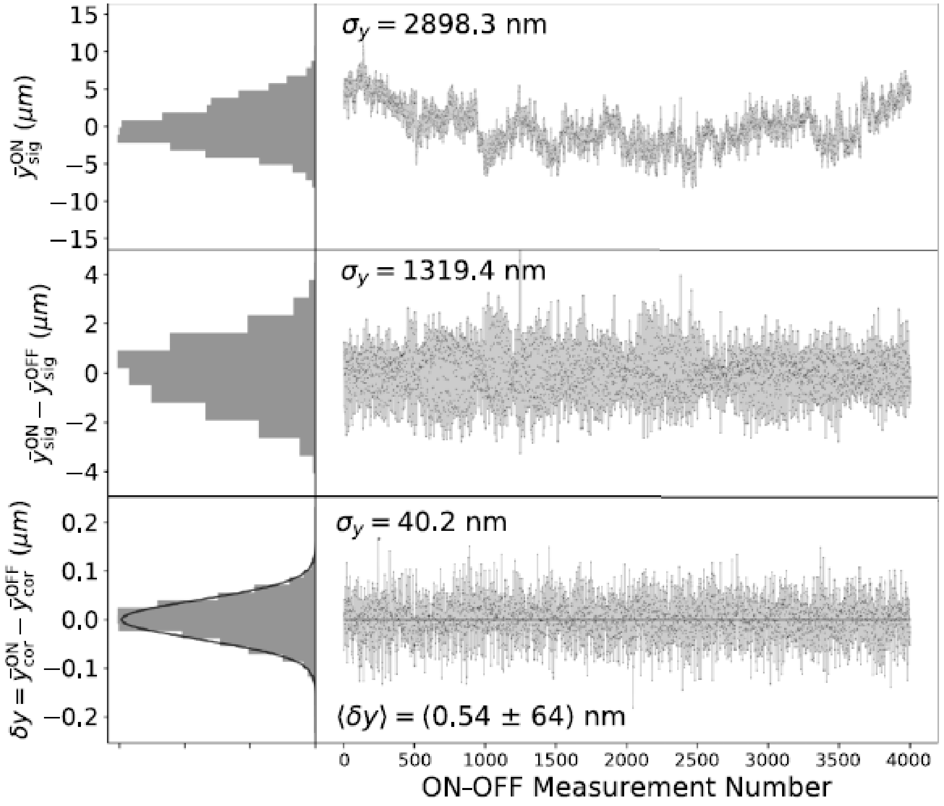
Spatial resolution

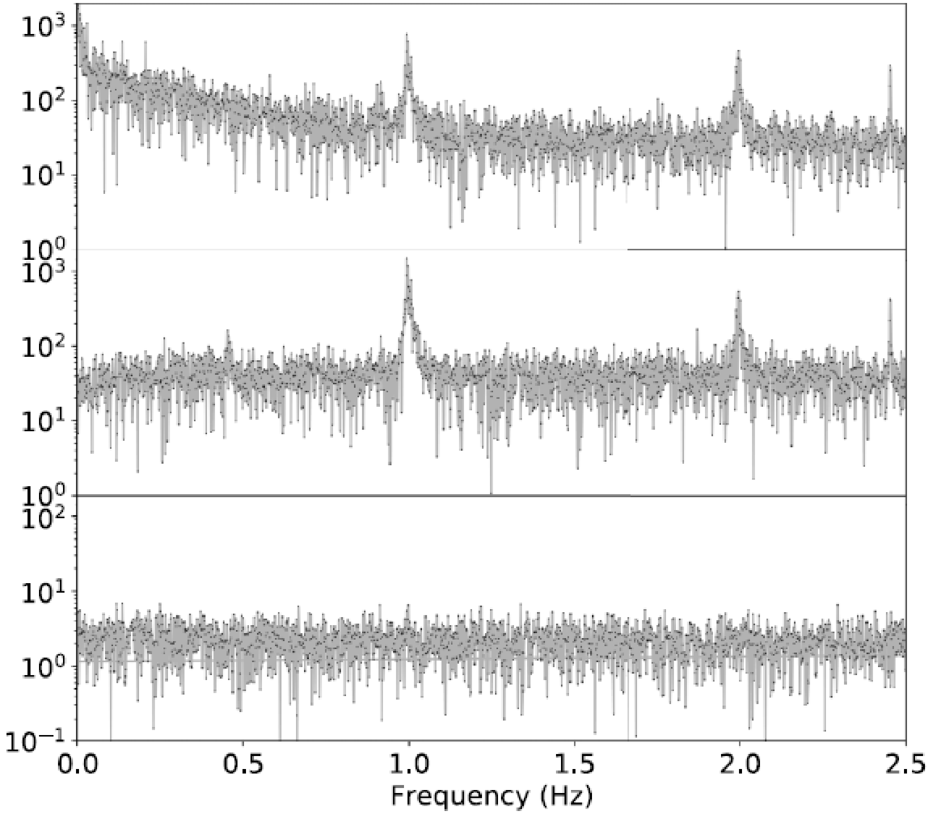
8000 laser shots
$T_{obs} \cong 15$ mn
Here Sagnac w/o focus

CCD Basler camera
- Pixel size = 5.8×5.8 μm^2
- Saturation charge ~ 10^4 e^- per pixel

σ_y = 40 nm

Corresponds to the expected shot noise





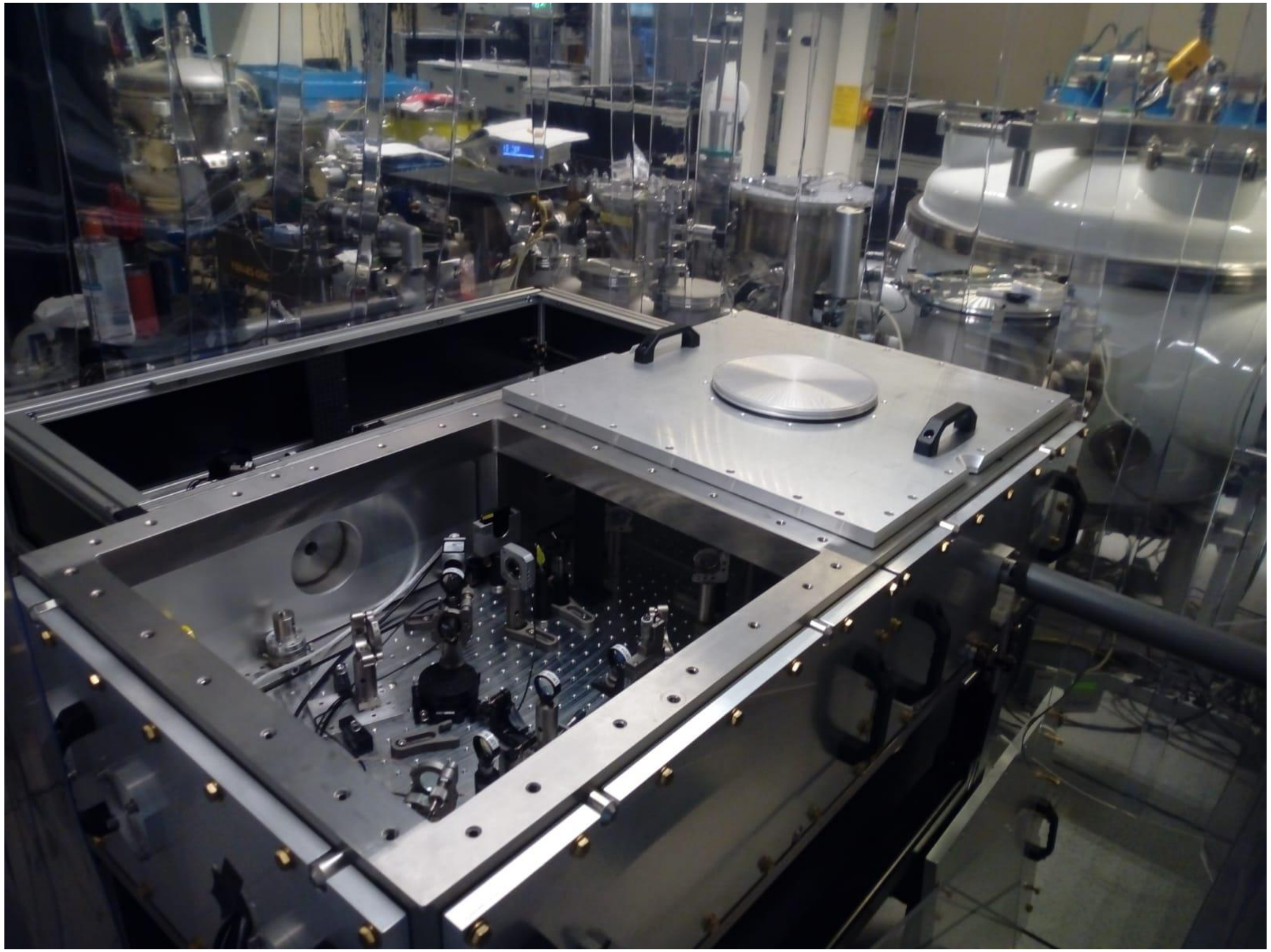
In the future

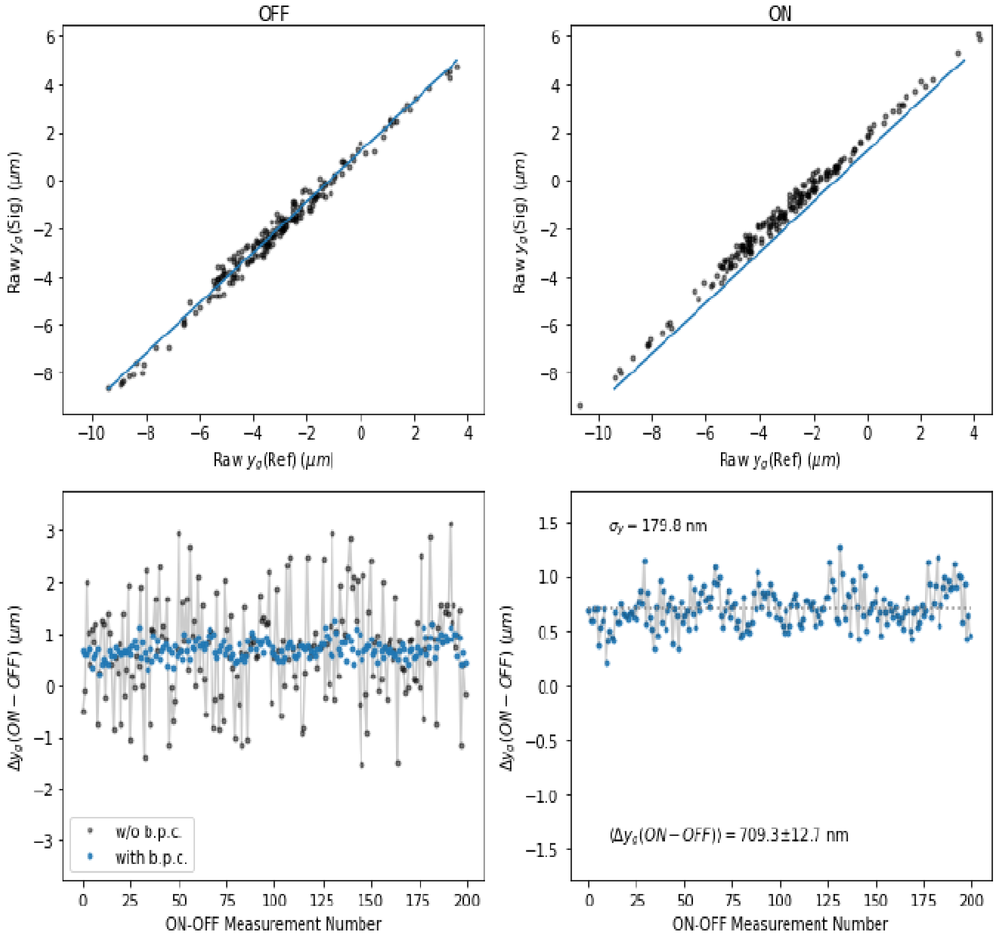
CCD Basler camera
- Pixel size = 1.8×1.8 μm^2
- Saturation charge ~ 10^4 e^- per pixel

Expected shot noise : σ_y ~ 13 nm

Current prototype

Measurement of the Kerr effect in air at low energy





Technical issue

- Sagnac interferometer with intense femtosecondes laser pulses (~ 10^{11} W/cm²)

  Large spectrum

  Nonlinear effect in the beamsplitter

  Monitoring and feedback for the Sagnac alignment

- Surface quality of lenses, mirrors and beamsplitter

  Current development with LMA Lyon

  Replace [Mirrors + Lenses] by Off Axis Parabolic Mirrors ?

- Stability of the transverse intensity profile of the femtosecond pulses at 10 Hz repetition rate

  Work in progress…

- High spatial resolution for the position of the intensity profile in the dark output

  Today we use CCD camera which gives good resolution + imaging