Laboratoire d'Optique Appliquée

Palaiseau – FRANCE http://loa.ensta.fr

ENSTA IP PARIS

UMR 7639

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Carrier-envelope phase control of a kilohertz laser-wakefield accelerator

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PhD student with Jérôme Faure

20/09/2022

iFAST

EUROPEAN NETWORK FOR NOVEL ACCELERATORS

EuroNNAc4

NPACT supported by EU via I-FAST

2022 EuroNNAc Special Topics Workshop

Outline of the presentation

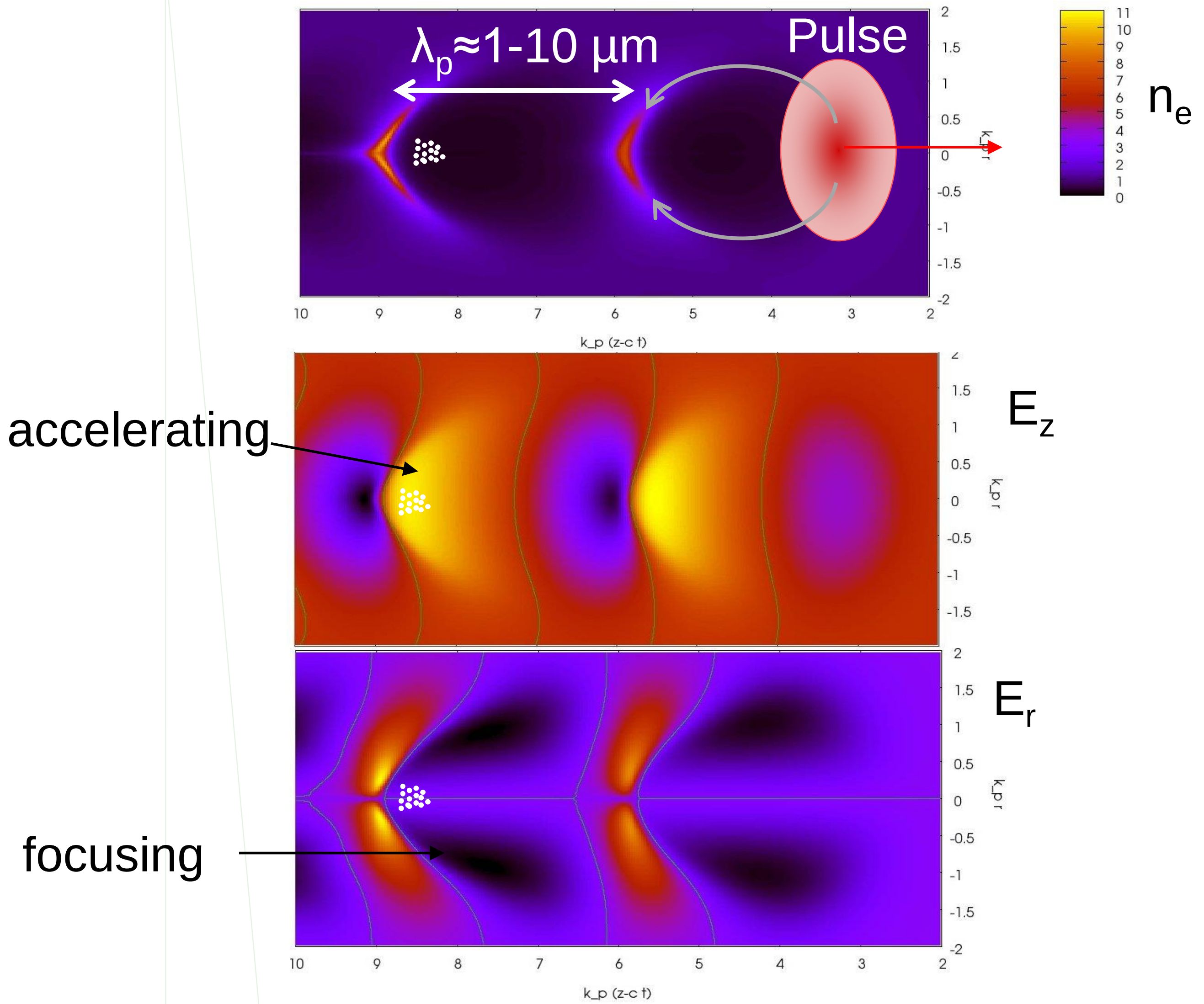
I. Introduction to LWFA with near-single cycle pulses

II. Predicted CEP effects

III. CEP-controlled injection: experiments and simulations

Accelerating electrons in wakefields

Principle : Tajima & Dawson, PRL 1979

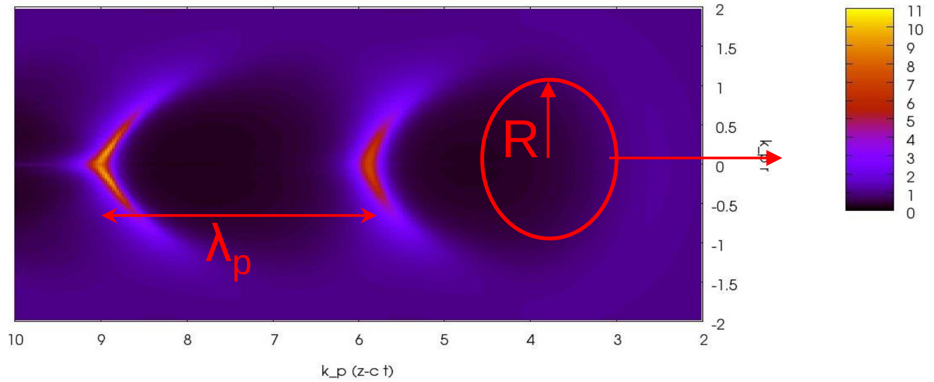


Avantages :

- Extreme fields: 1 MeV / 10 µm
  → Compact accelerator
- fs bunch
  < $\lambda_p/4$

Scaling laws : toward kHz lasers

Average laser power ≈ constant



Laser pulse has to be resonant with plasma wave: $R \approx \lambda_p/2$, $c\tau \approx \lambda_p/2$

Laser energy scaling $E_L \propto \tau^3 \propto \lambda_p^3$

Electron energy gain $\Delta E \propto \tau^2 \propto \lambda_p^2$

30 fs → 1 J → 100 MeV-1 GeV

3 fs → 1 mJ → 1-10 MeV

and high density $n_e > 10^{20}$ cm^{-3}

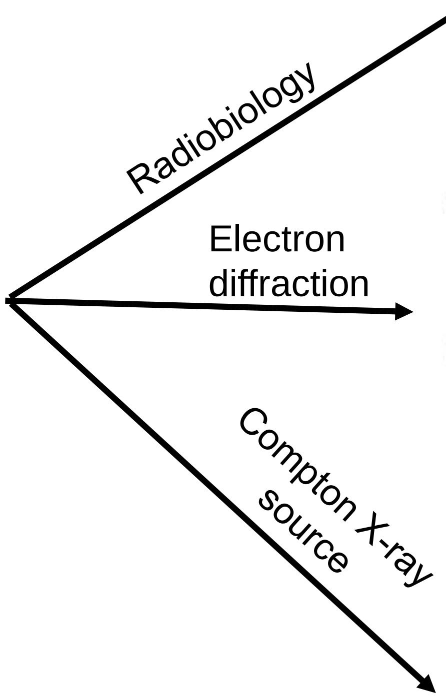
Near-single cycle pulse!

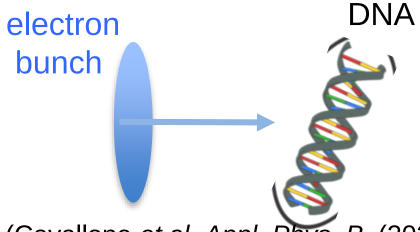
Lu *et al.*, PRSTAB **10**, 0613001 (2007)

Beaurepaire et al., NJP **16**, 023023 (2014)

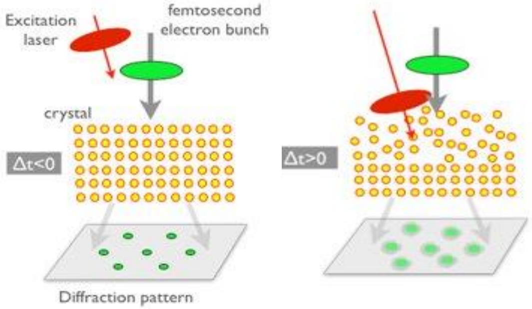
Motivations for high-repetition rate

- Statistics in experiments (source and applications)
- Active feedback loops
- Electrons at 1-20 MeV : fit several applications

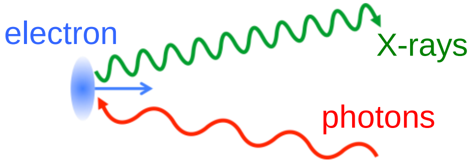




(Cavallone *et al*, *Appl. Phys. B*, (2021))



(Mourou & Williamson, APL (1982),
Z-H He et al, APL (2013))



(Ta Phuoc, Nat. Phot. 2012)

Motivations for high-repetition rate

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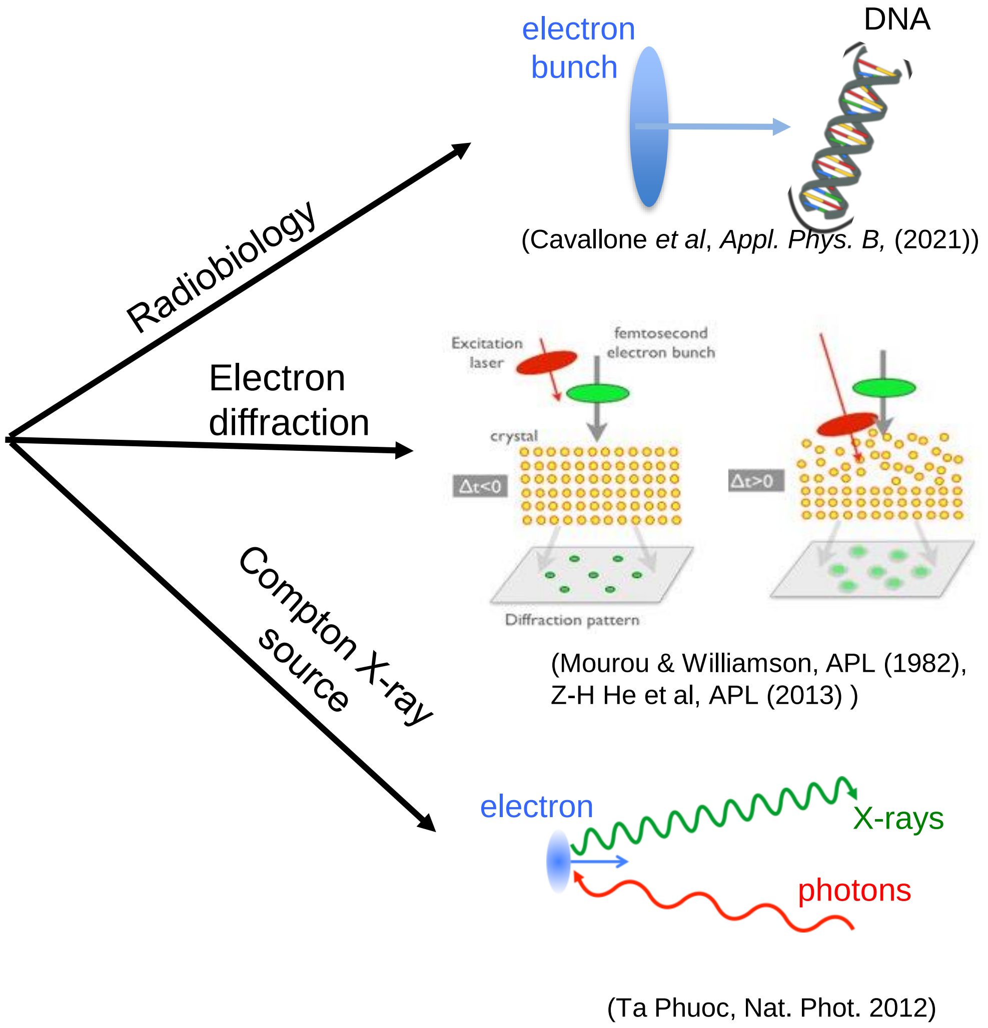
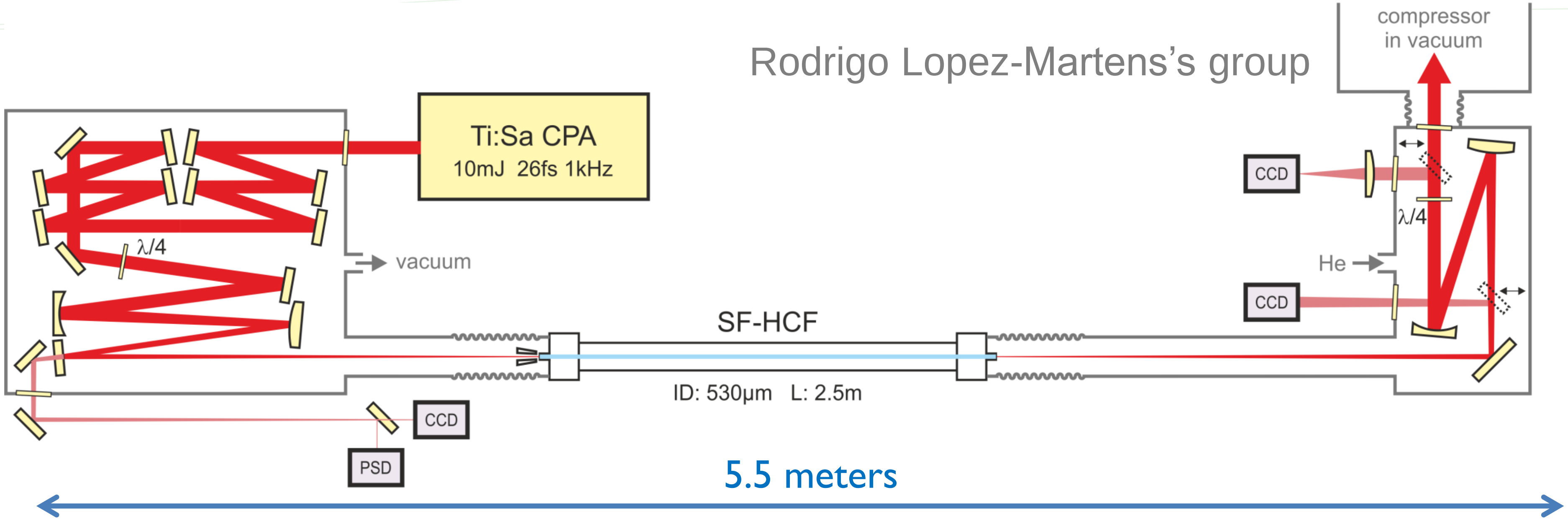


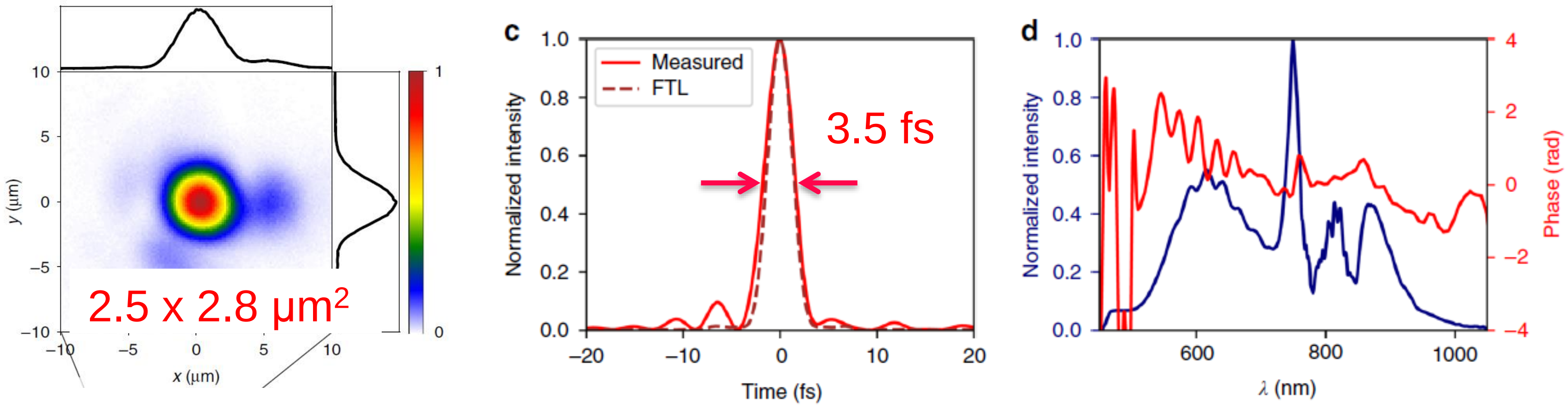
Our Goals: source for applications

- Operate at kHz (with only <10 mJ)
- Accelerate electrons to few MeV
- High beam quality
- Sub-10 fs duration

1 TeraWatt few-cycle kHz laser system

Rodrigo Lopez-Martens's group





M. Ouillé et al., Light: Science & Applications, **9**, 47 (2020)
F. Böhle et al., Laser Physics Letters, **11**, 9 (2014)

Plan

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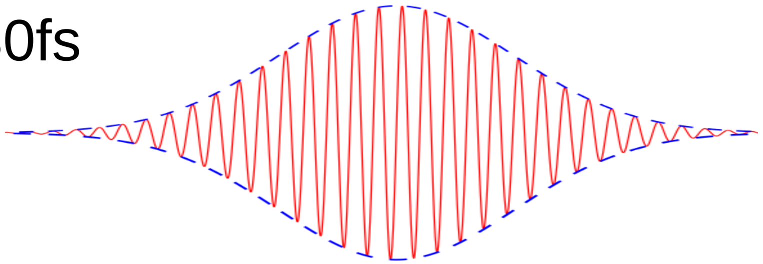
CEP and ponderomotive force

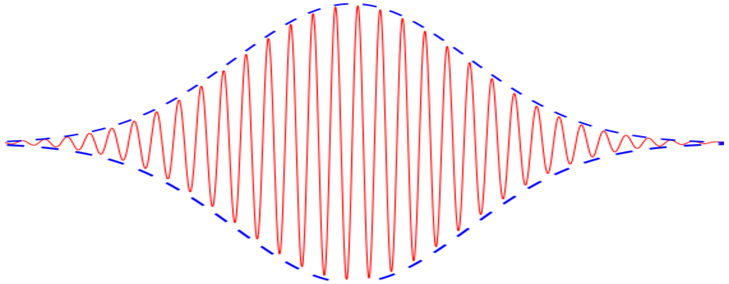
CEP = **C**arrier-**E**nveloppe **P**hase

CEP = 0

30fs



CEP = π/2



Quasi-identical

Many cycles = ponderomotive force

- Only the envelope plays a role
- Polarization independent
- Axial symmetry

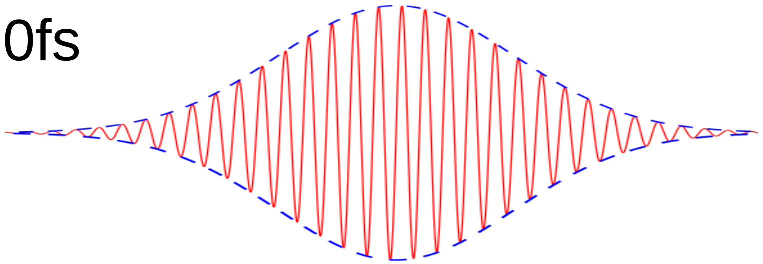
CEP and ponderomotive force

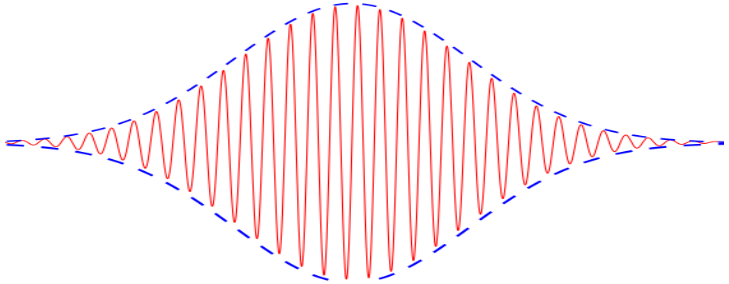
CEP = **C**arrier-**E**nveloppe **P**hase

CEP = 0

CEP = π/2

30fs



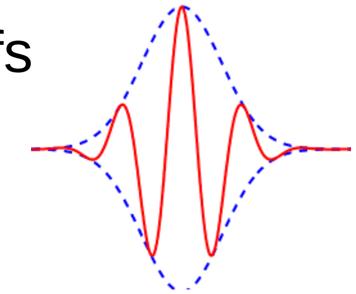


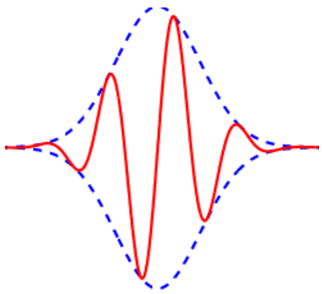
Quasi-identical

Many cycles = ponderomotive force

- Only the envelope plays a role
- Polarization independent
- Axial symmetry

3fs



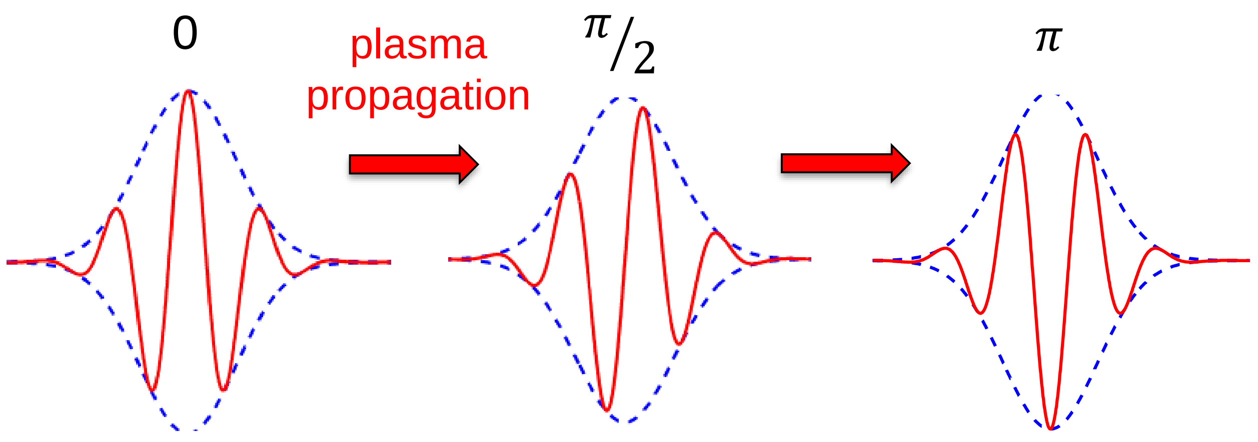


Different

Single cycle = cannot average on the optical cycle !

- Necessary to consider the waveform of the electric field
- Broken symmetry

CEP slippage



In the plasma :

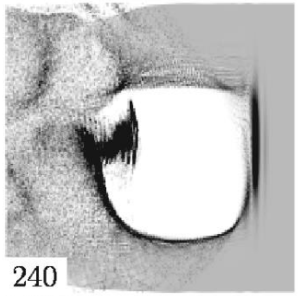
$$v_\varphi > v_g$$

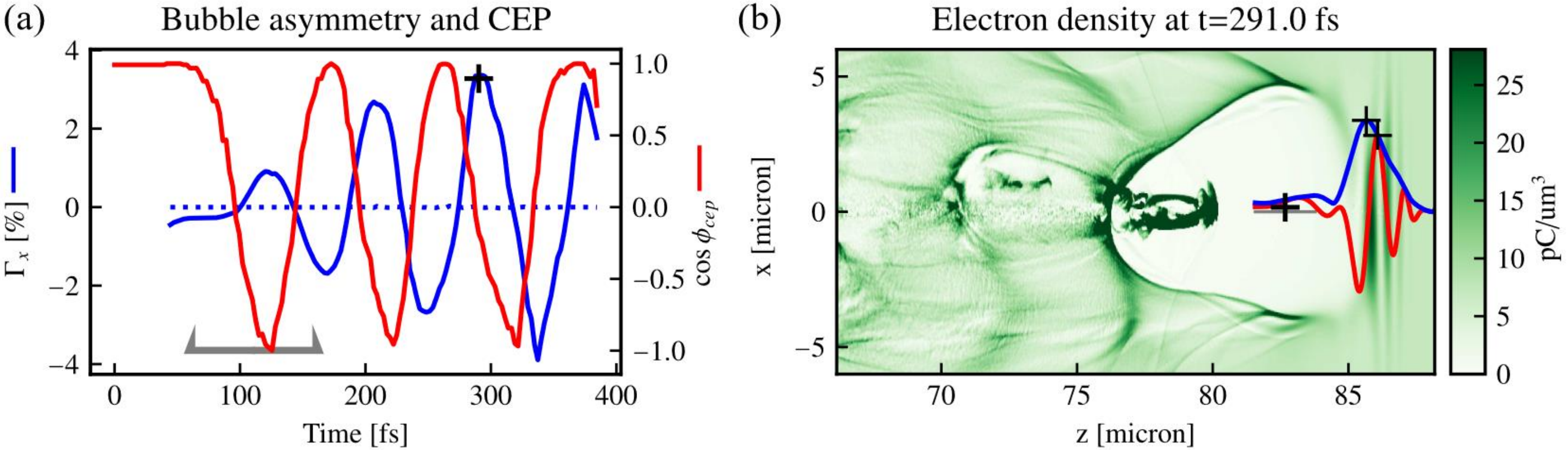
The CEP slips by 2π after propagation of :

$$L_{2\pi} = \lambda_0 \frac{c}{v_\varphi - v_g} \simeq \lambda_0 \frac{n_c}{n_e}$$

CEP and bubble asymmetry

Nerush et Kostyukov, PRL (2009) : CEP-dependent asymmetry in the plasma response





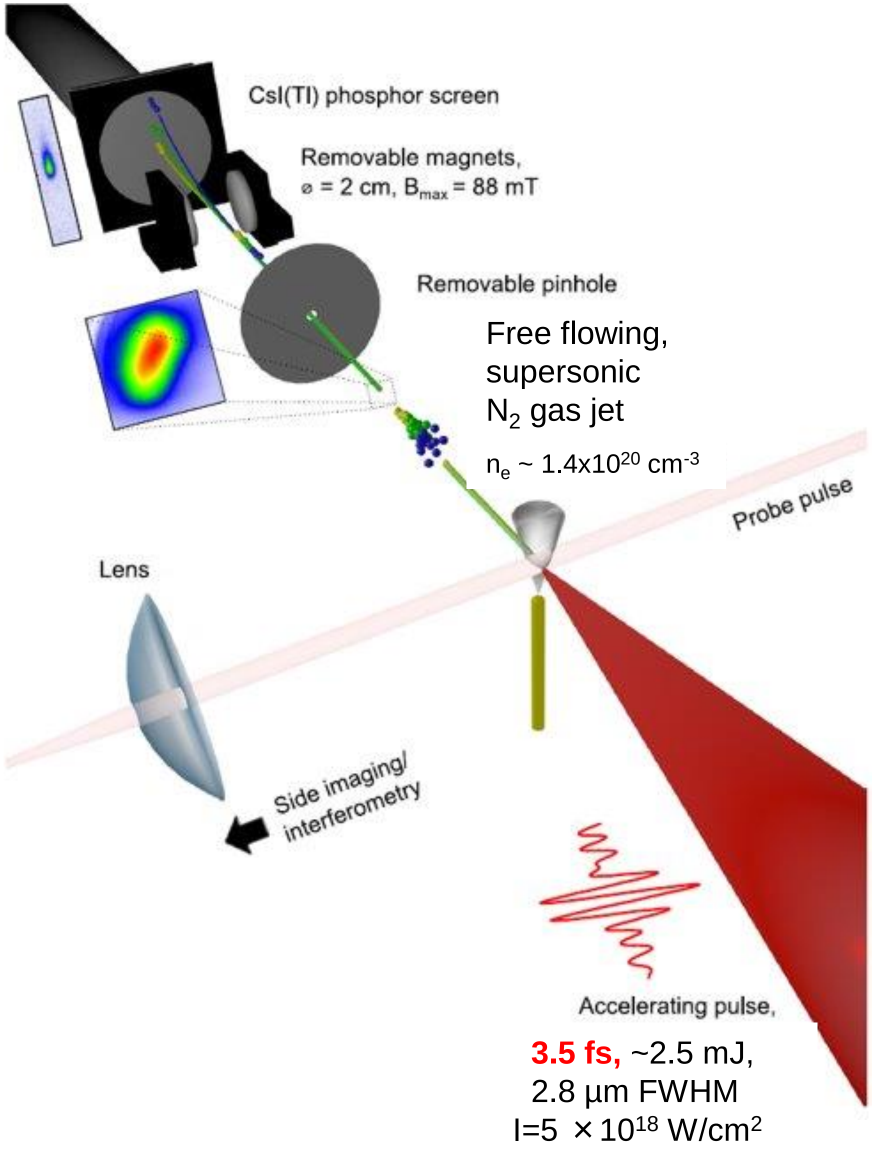
J. Huijts *et al*. Phys. of Plasma (2021)

The wakefield oscillates with the shifting CEP

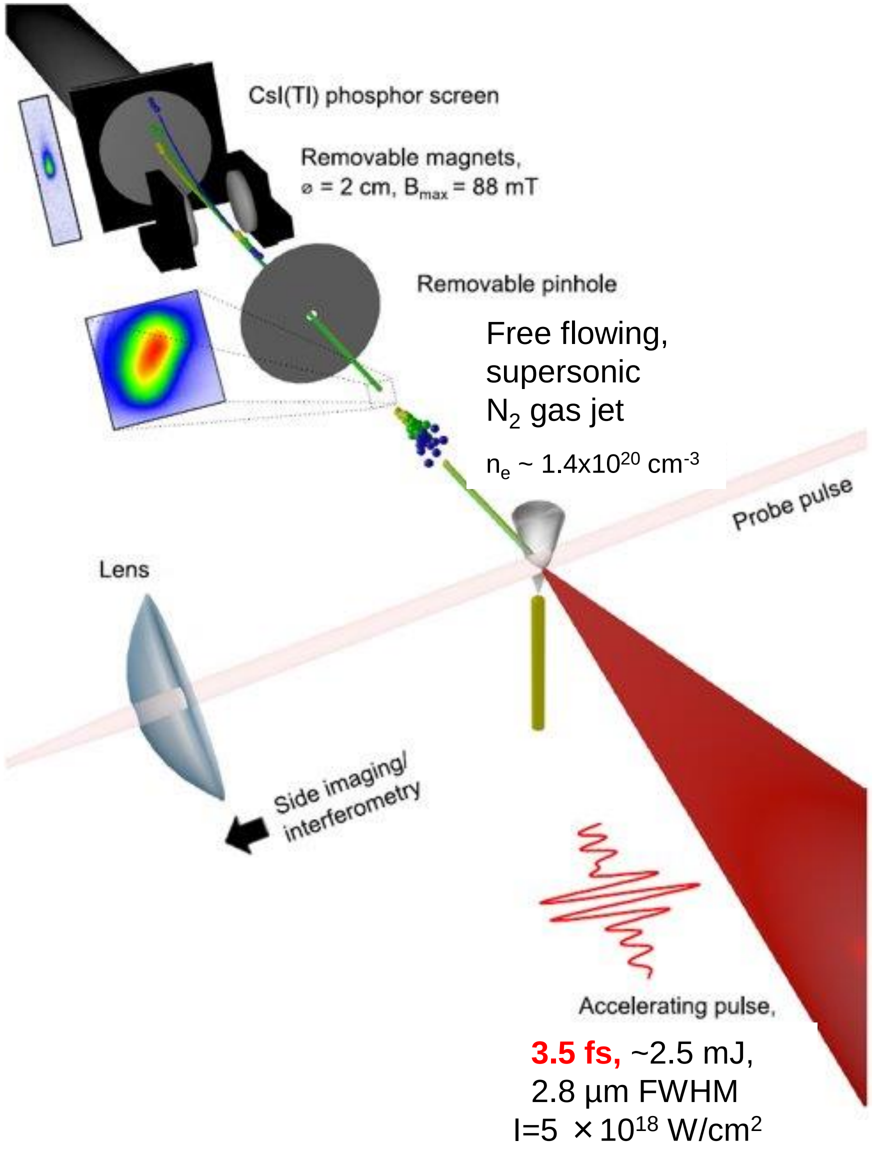
Other recent work on CEP (circular polarization) :
F. Salehi *et al*, PRX, (2021)

Plan

Experimental set-up

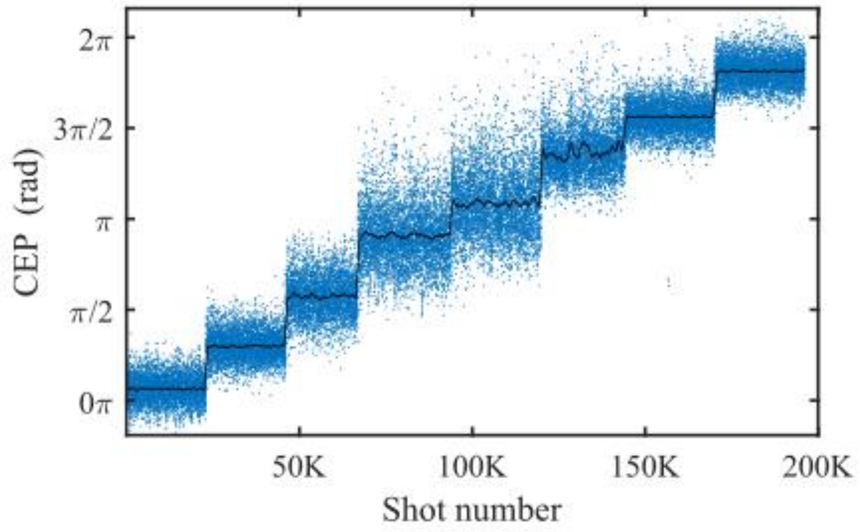


Experimental set-up



- Laser CEP-controlled
- 300 mrad RMS stability

(30 mrad on 200 averaged shots)



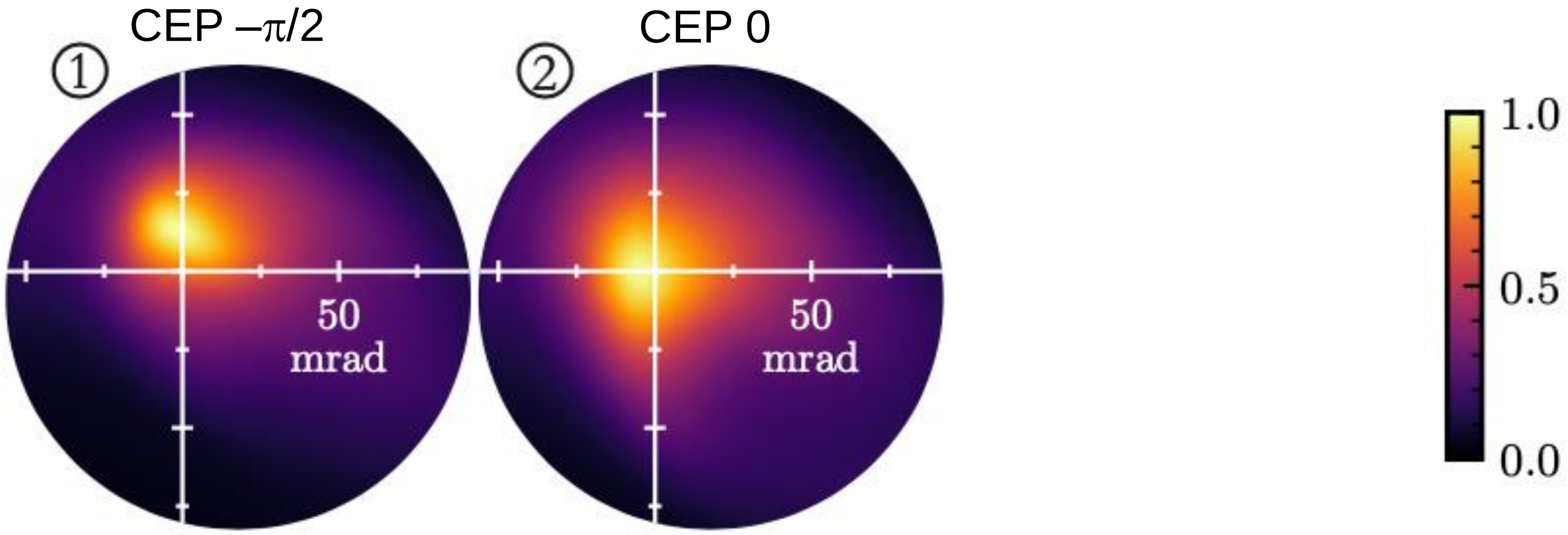
Experiment : CEP and electron beam pointing

CEP –π/2

1 exp. point = 20 x 200 = **4000 shots**

J. Huijts, L. Rovige *et al.* Physical Review X (2022)

Experiment : CEP and electron beam pointing



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J. Huijts, L. Rovige *et al.* Physical Review X (2022)

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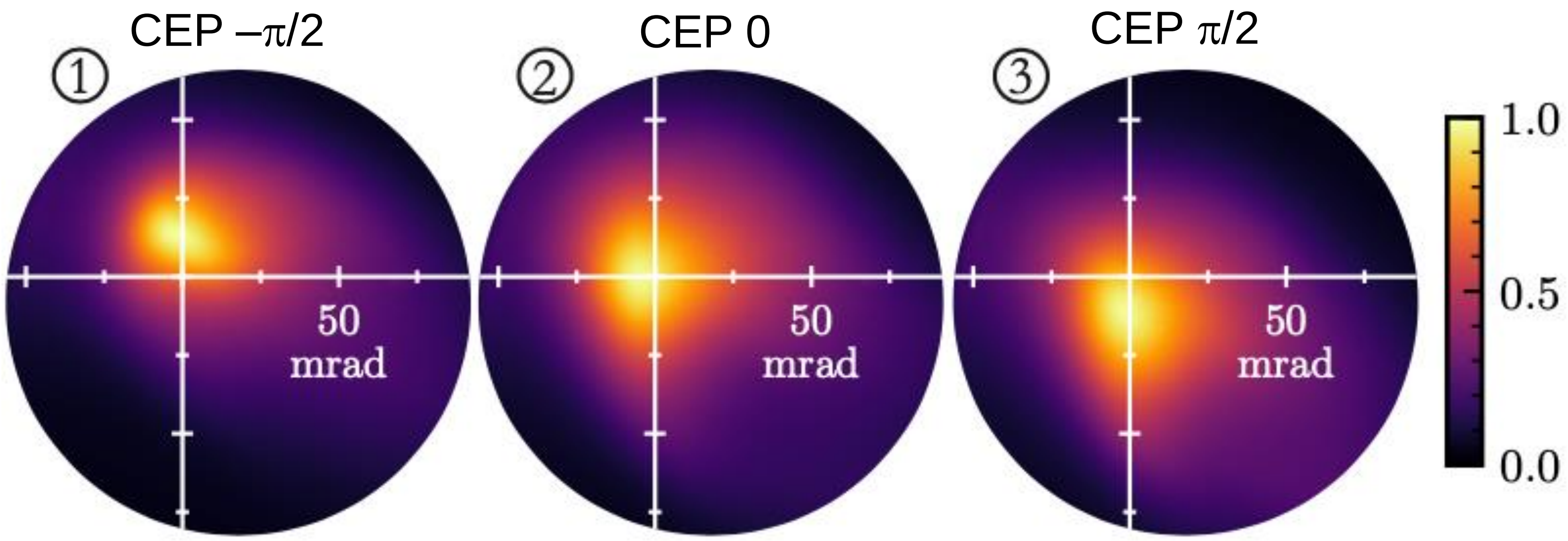

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J. Huijts, L. Rovige *et al.* Physical Review X (2022)

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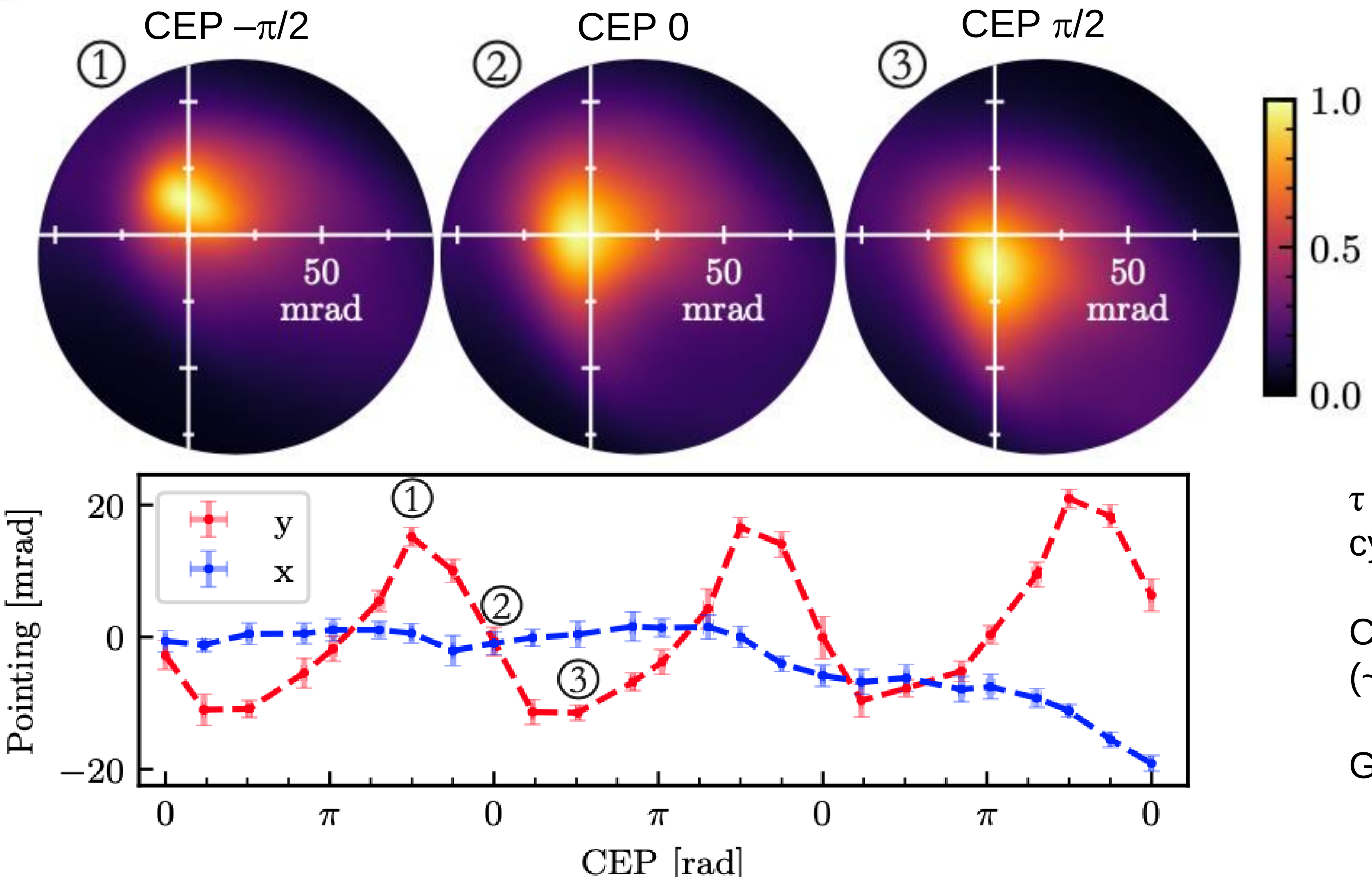


First observation of CEP effects in LWFA !

τ = 4.0fs (=1.5 optical cycle at 800nm)

Controlled CEP (~300mrad RMS)

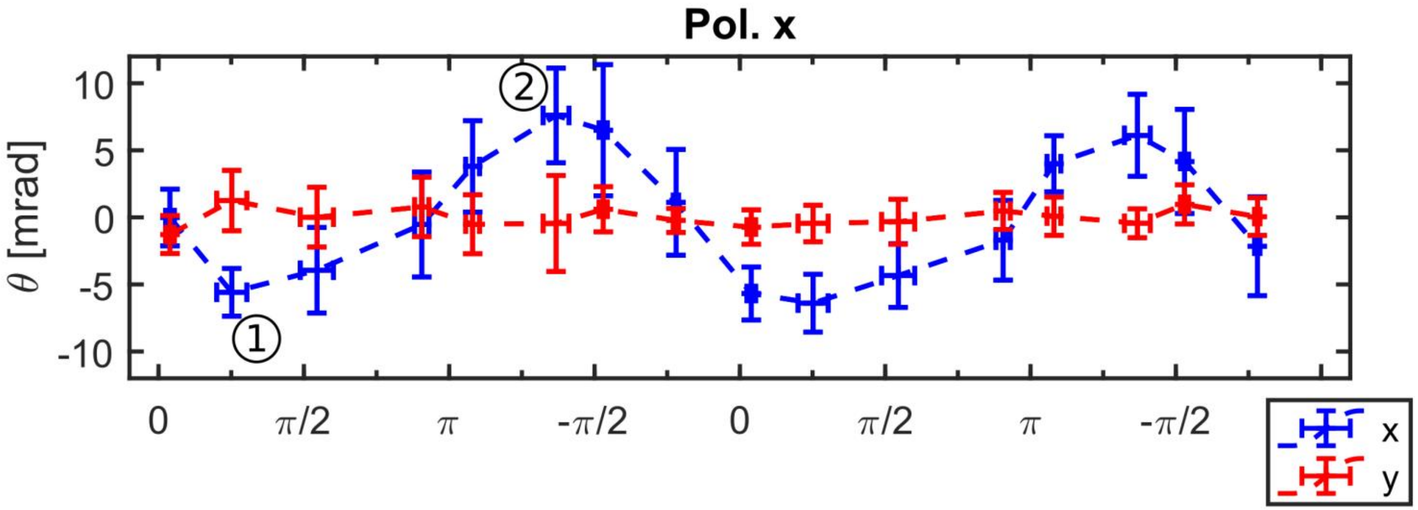
Gas : N_2

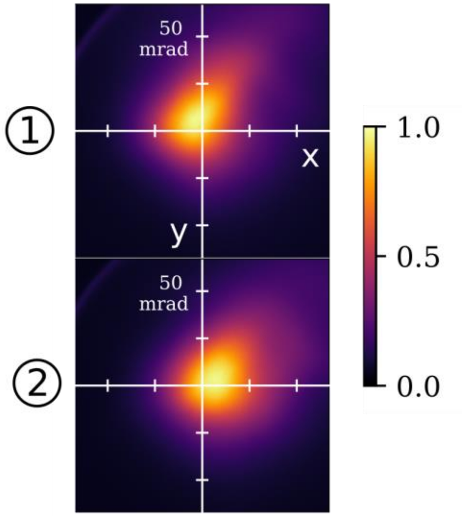
1 exp. point = 20 x 200 = **4000 shots**

J. Huijts, L. Rovige *et al.* Physical Review X (2022)

Experiment : CEP and polarization control

- Polarization control by adding a λ/2-waveplate





Rovige *et al.* arXiv:2205.08374 (2022)

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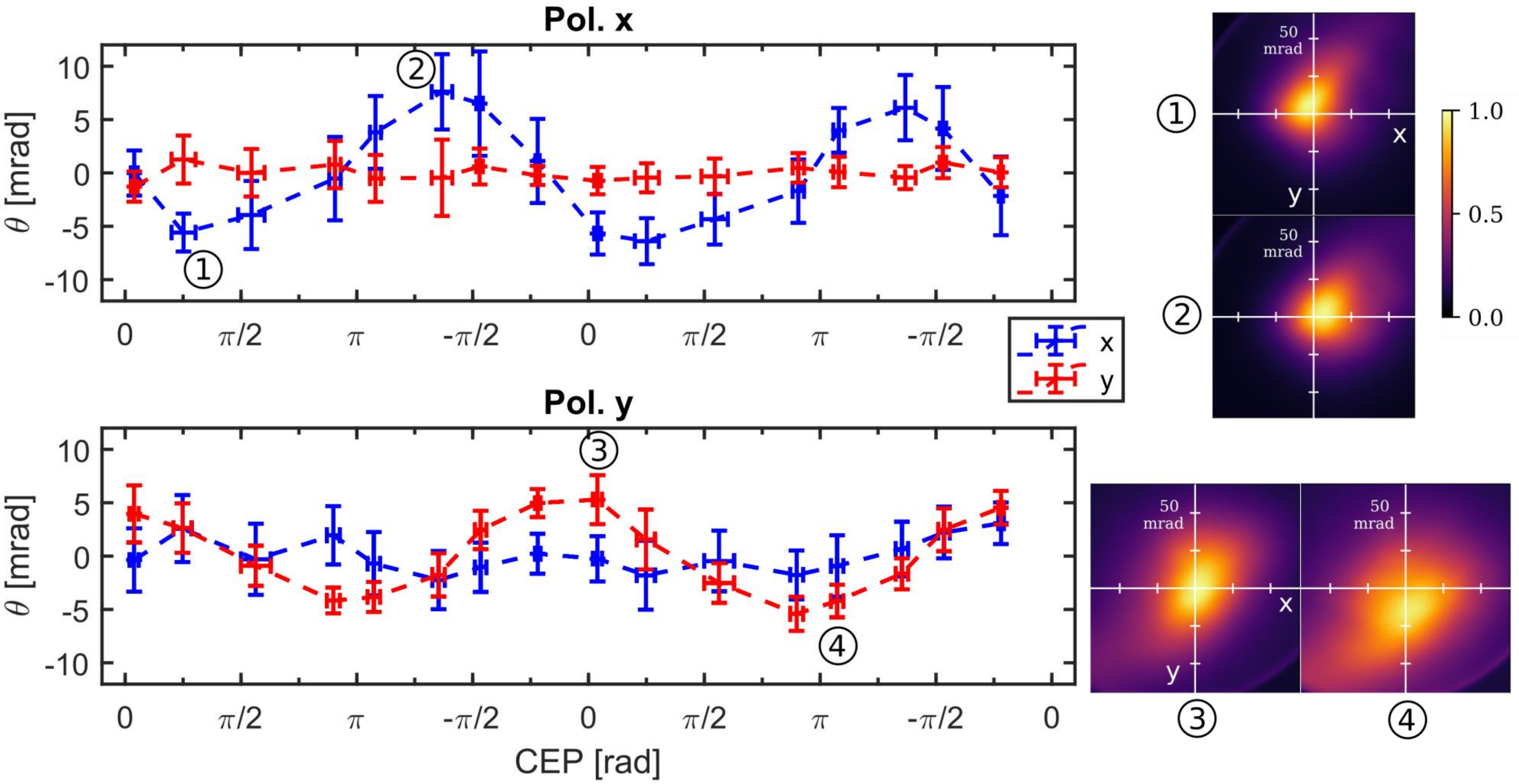
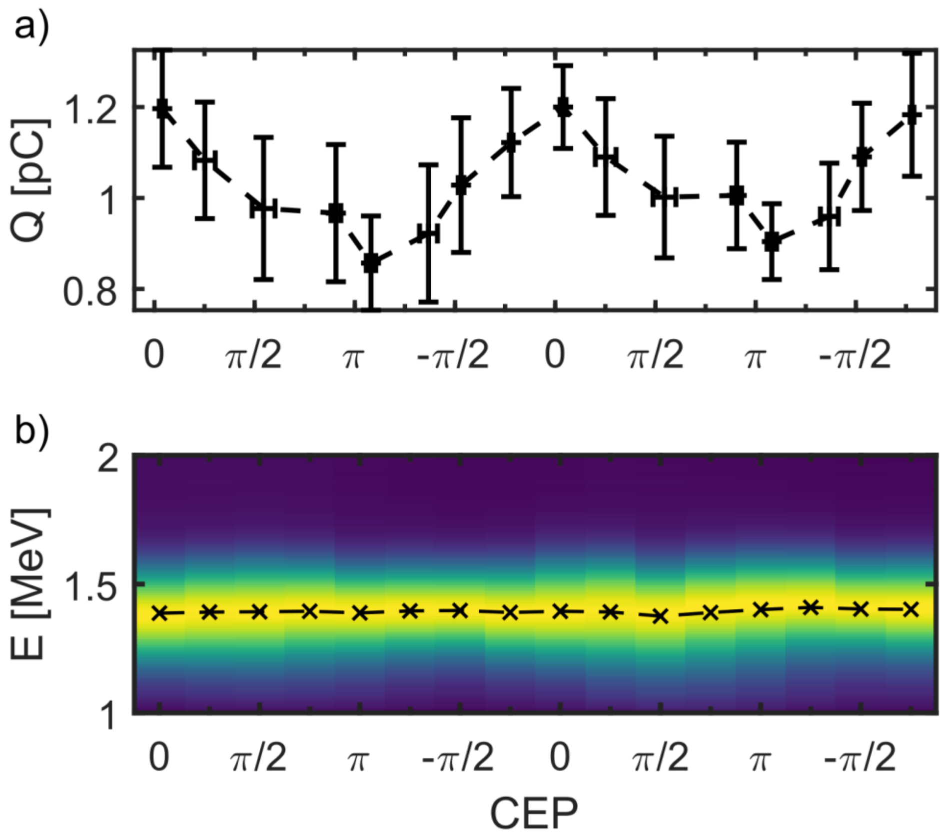


Rovige *et al.* arXiv:2205.08374 (2022)

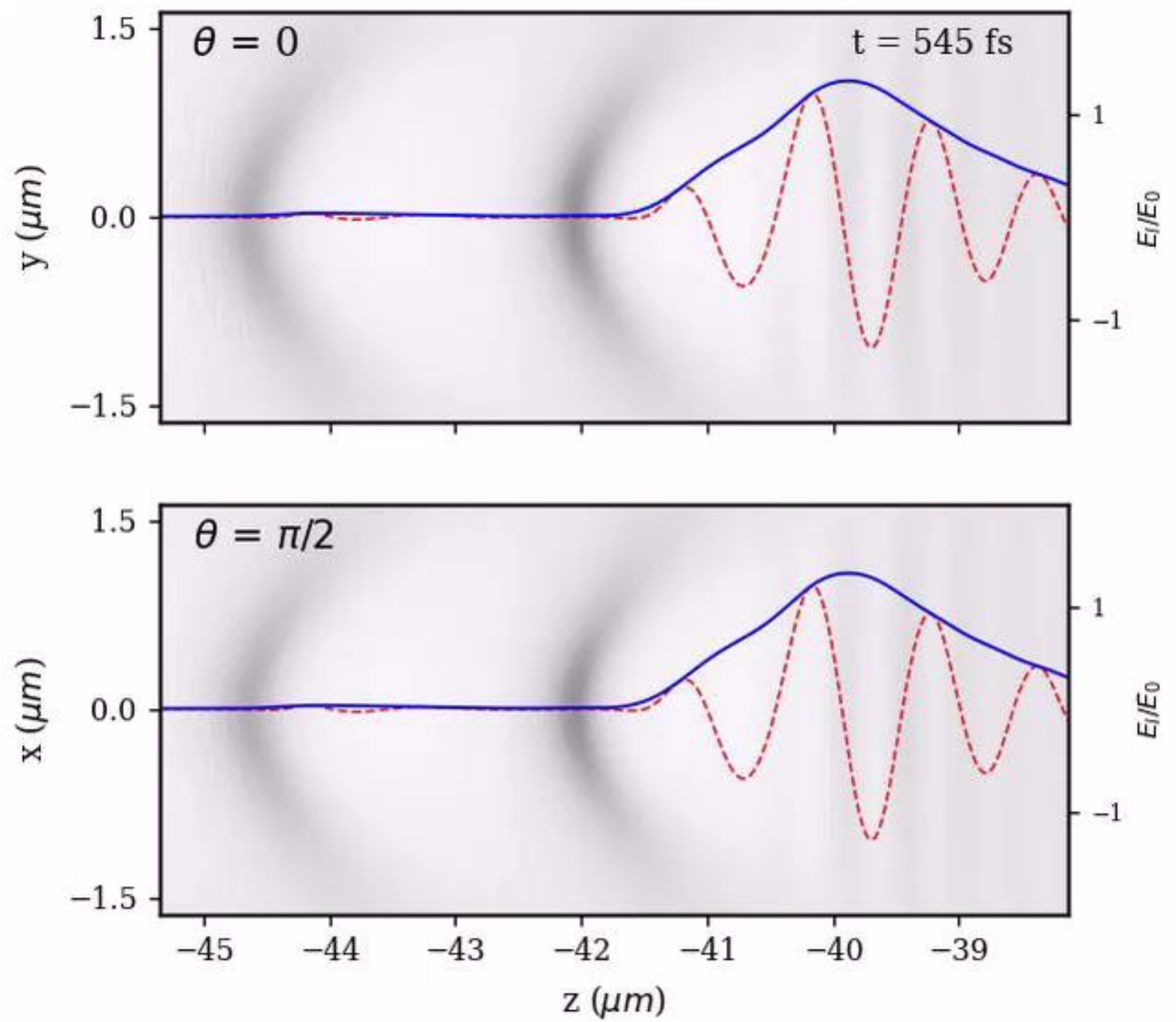
Charge and energy dependence on CEP

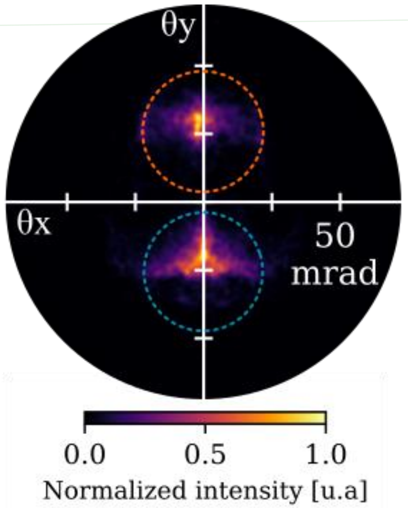


- 30% charge variation with CEP
- No clear effect on the energy spectrum

Rovige *et al.* arXiv:2205.08374 (2022)

PIC simulation : wake oscillation with CEP





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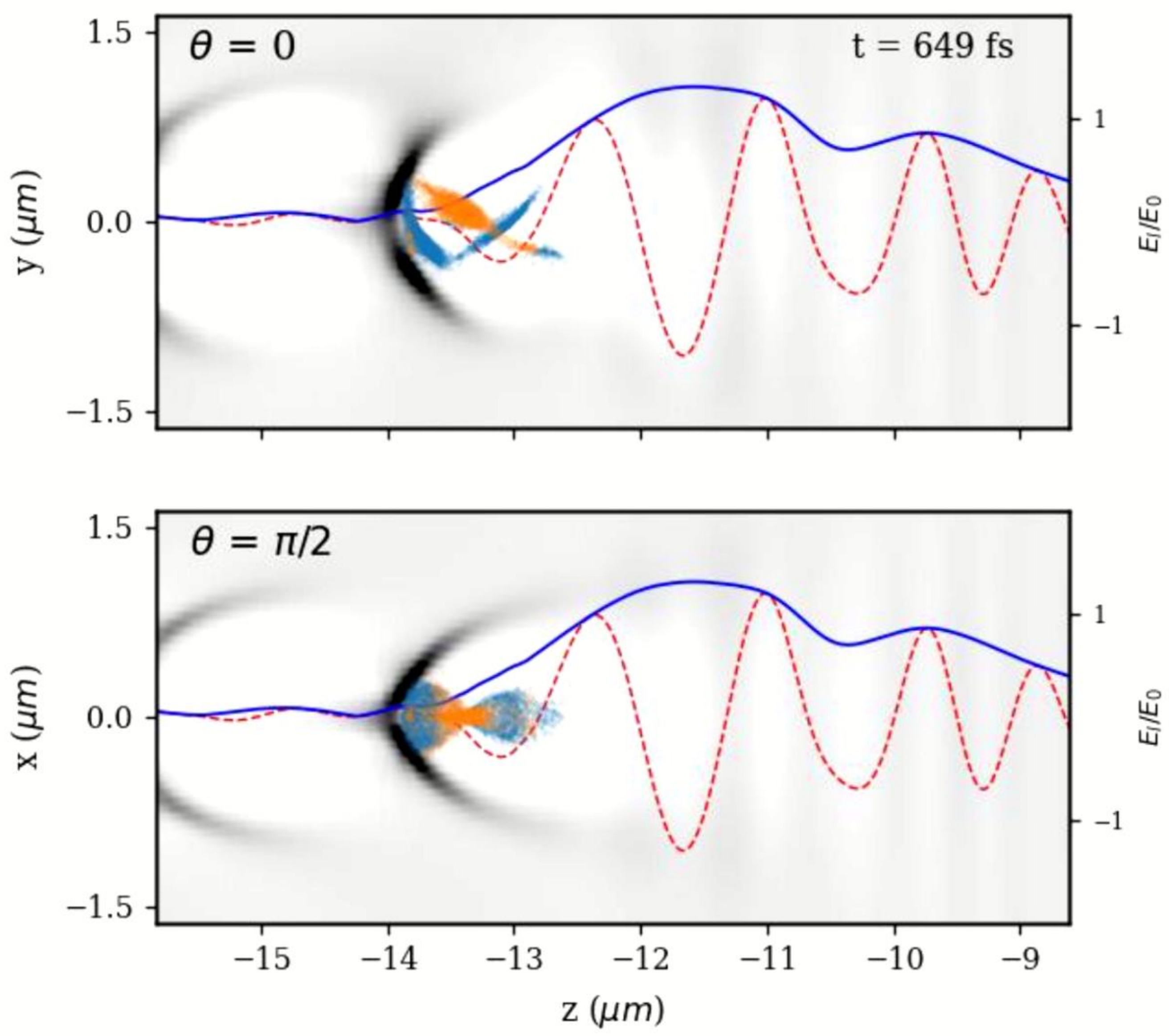
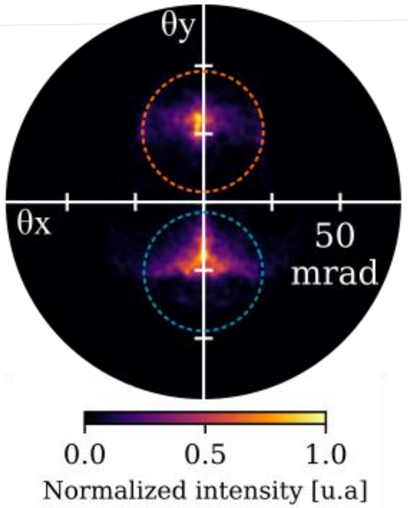
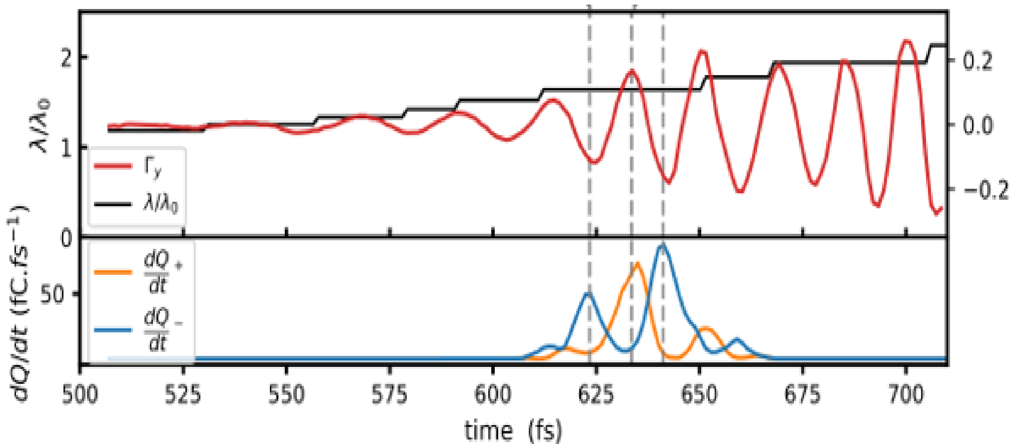
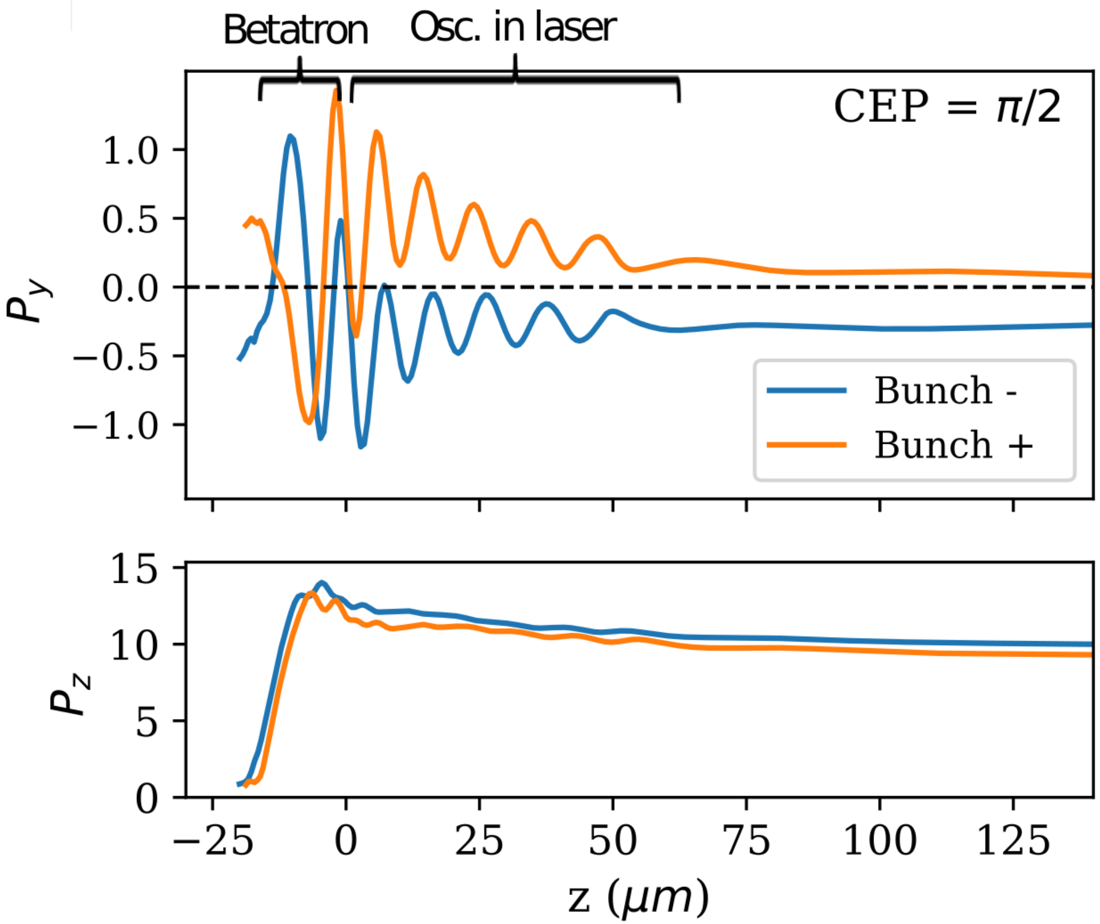






The wake oscillates with CEP : triggers off-axis injection

PIC simulations : tracking of the sub-bunches



- Bunches perform a Betatron oscillation and then oscillate in the laser field
- Final transverse momentum associated to initial transverse momentum

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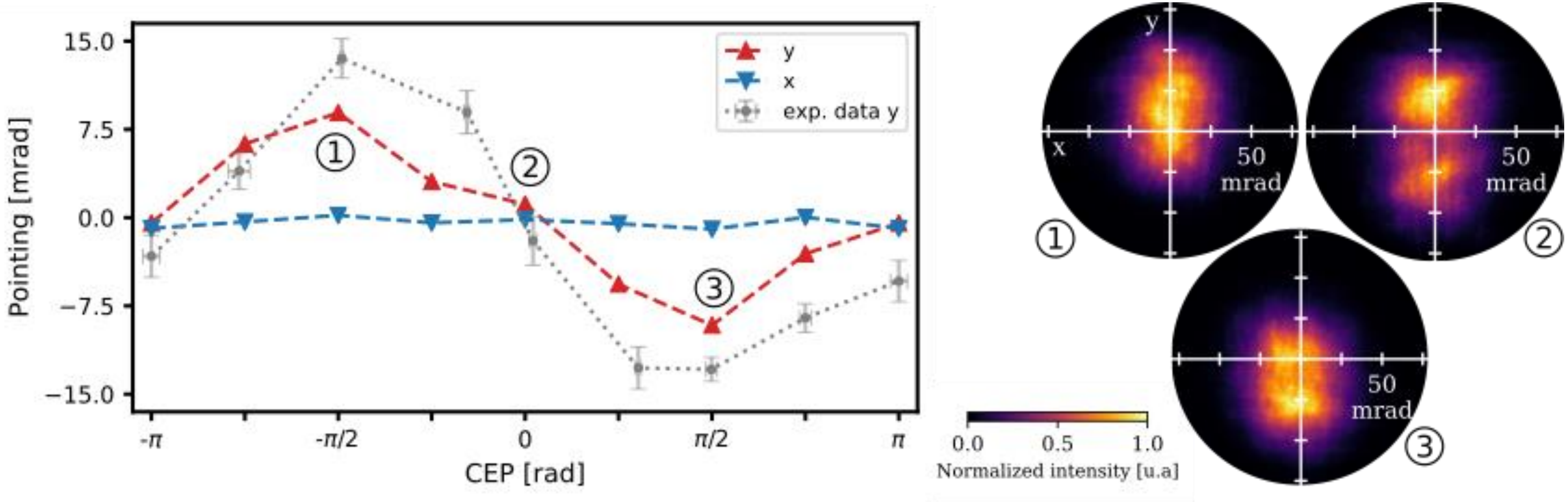
PIC simulations : pointing variations with CEP



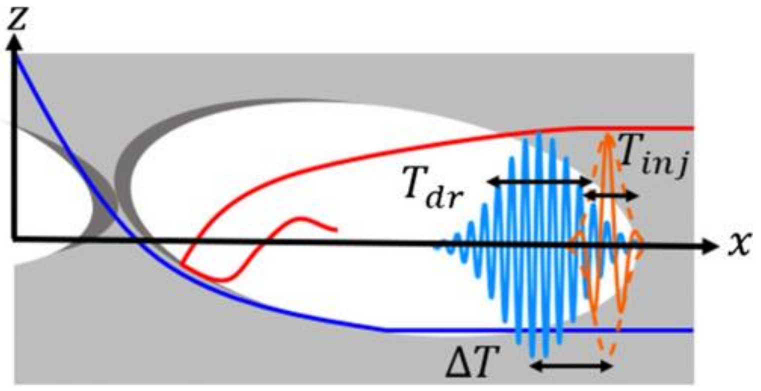
Experimental behavior well reproduced by the simulations

Conclusion and perspectives on CEP

- First experimental observation of CEP effect in LWFA
- Control on the injection through CEP

- The micro-bunches have really interesting properties:
    - sub-fs duration
    - emittance of a bunch ~ 50 nm ! (in sims)
    - collective betatron oscillation

- Recently proposed idea in: [Kim et al, Phys. Rev. Lett. 127, 164801 – 2021]:
    - Use single-cycle as injector
    - Combined with longer driver pulse



From : [Kim et al, Phys. Rev. Lett. 127, 164801 –2021]

The team

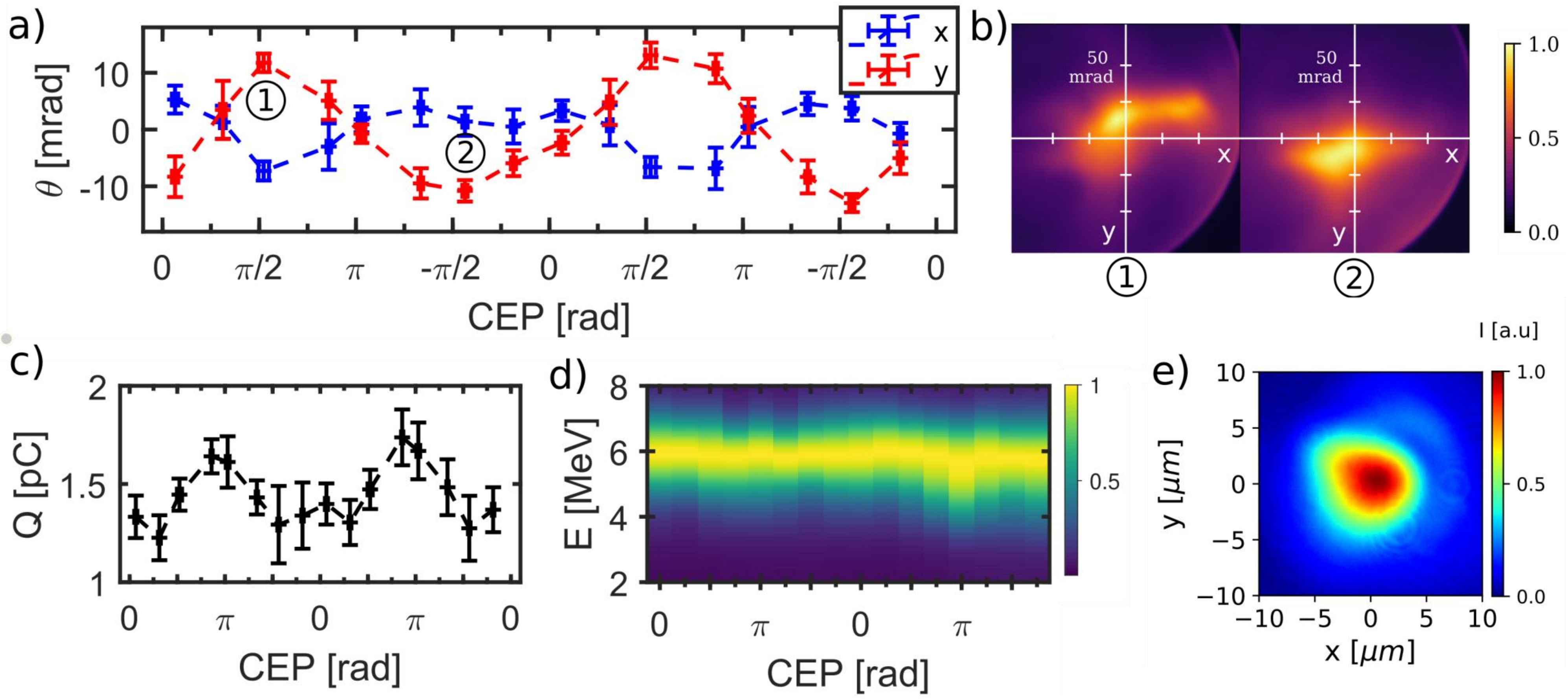
kHz laser-plasma source
J. Huijts, J. Monzac, A. Vernier, I. Andriyash, J. Faure

Salle Noire Laser system:
M. Ouillé, J. Kaur, Z. Cheng, R. Lopez-Martens

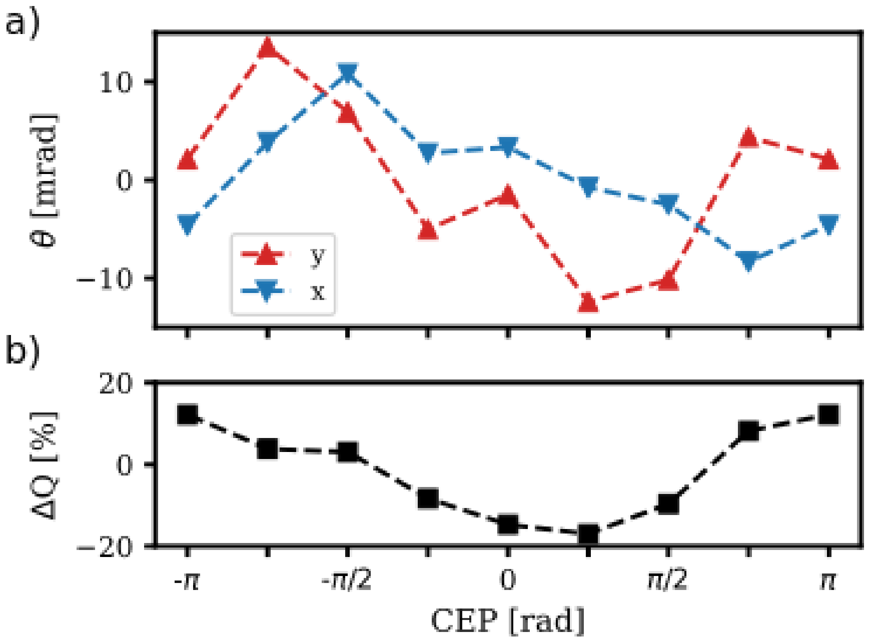
Gas jet fabrication:
V. Tomkus, V. Girdauskas, G. Raciukaitis, J. Dudutis ,
V. Stankevic , P. Gecys

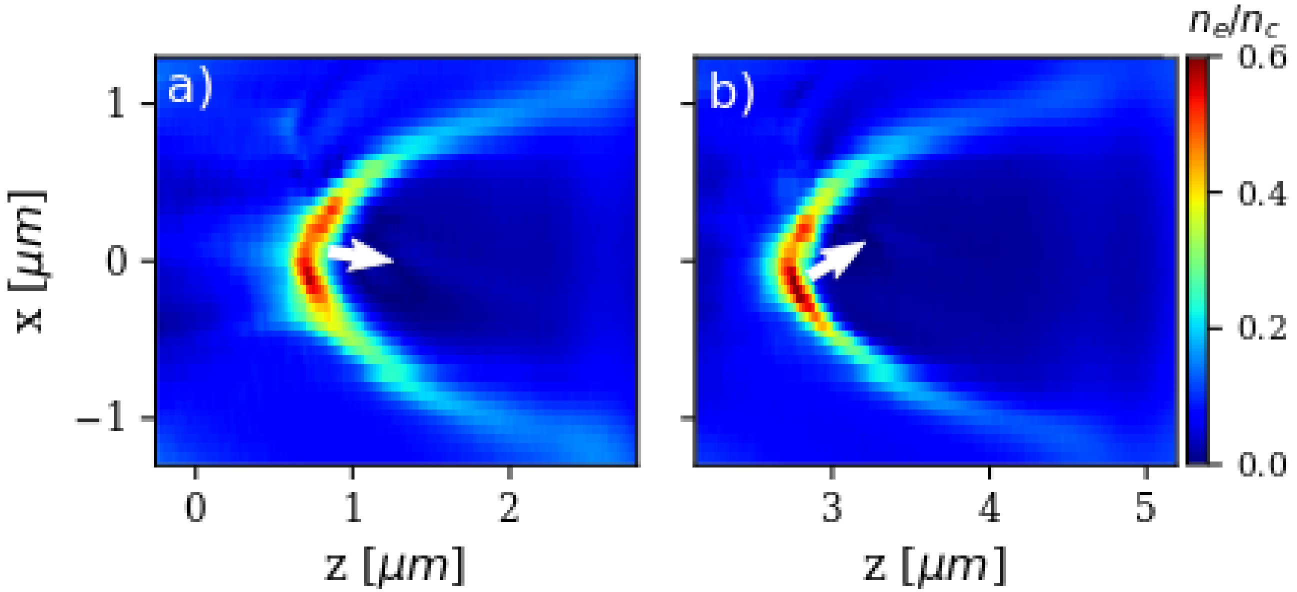
Supplementary

CEP effects in Helium

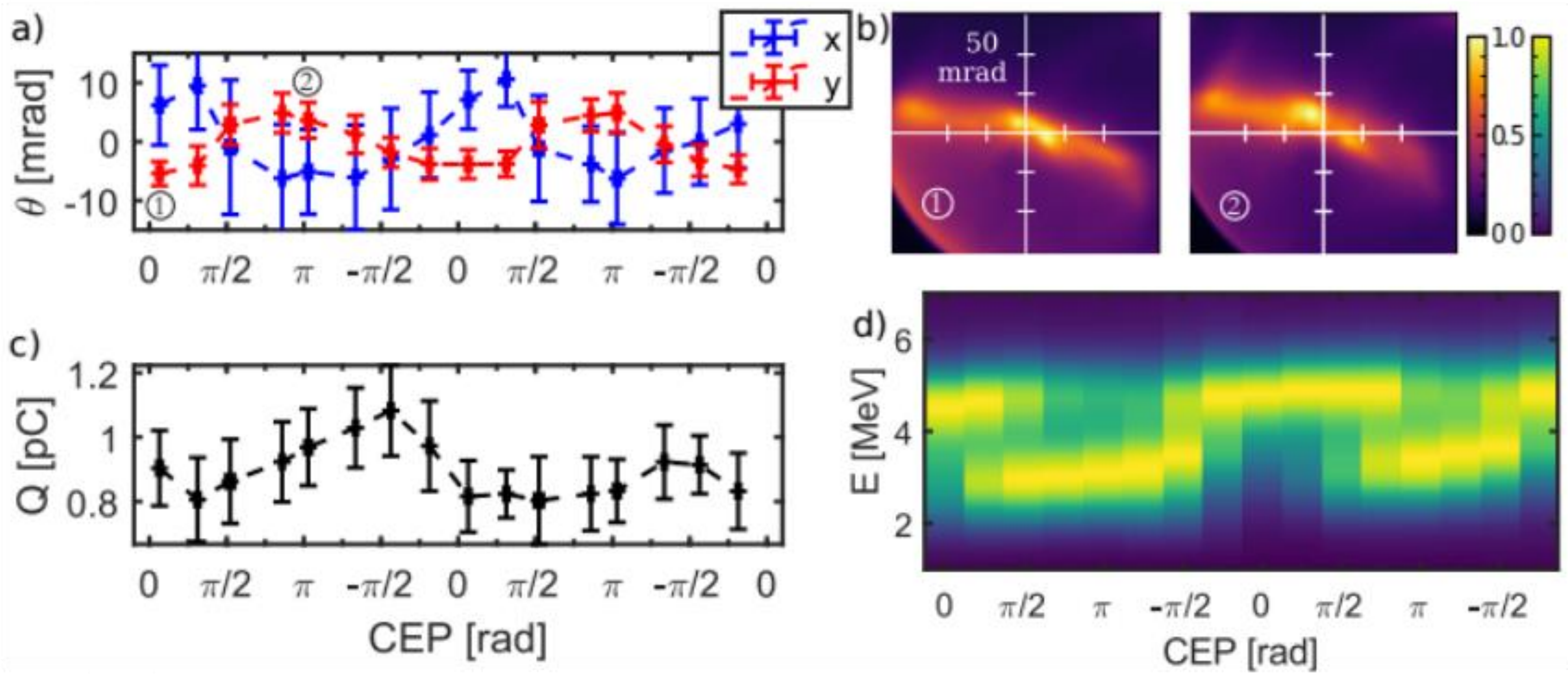


CEP and asymmetric laser spot

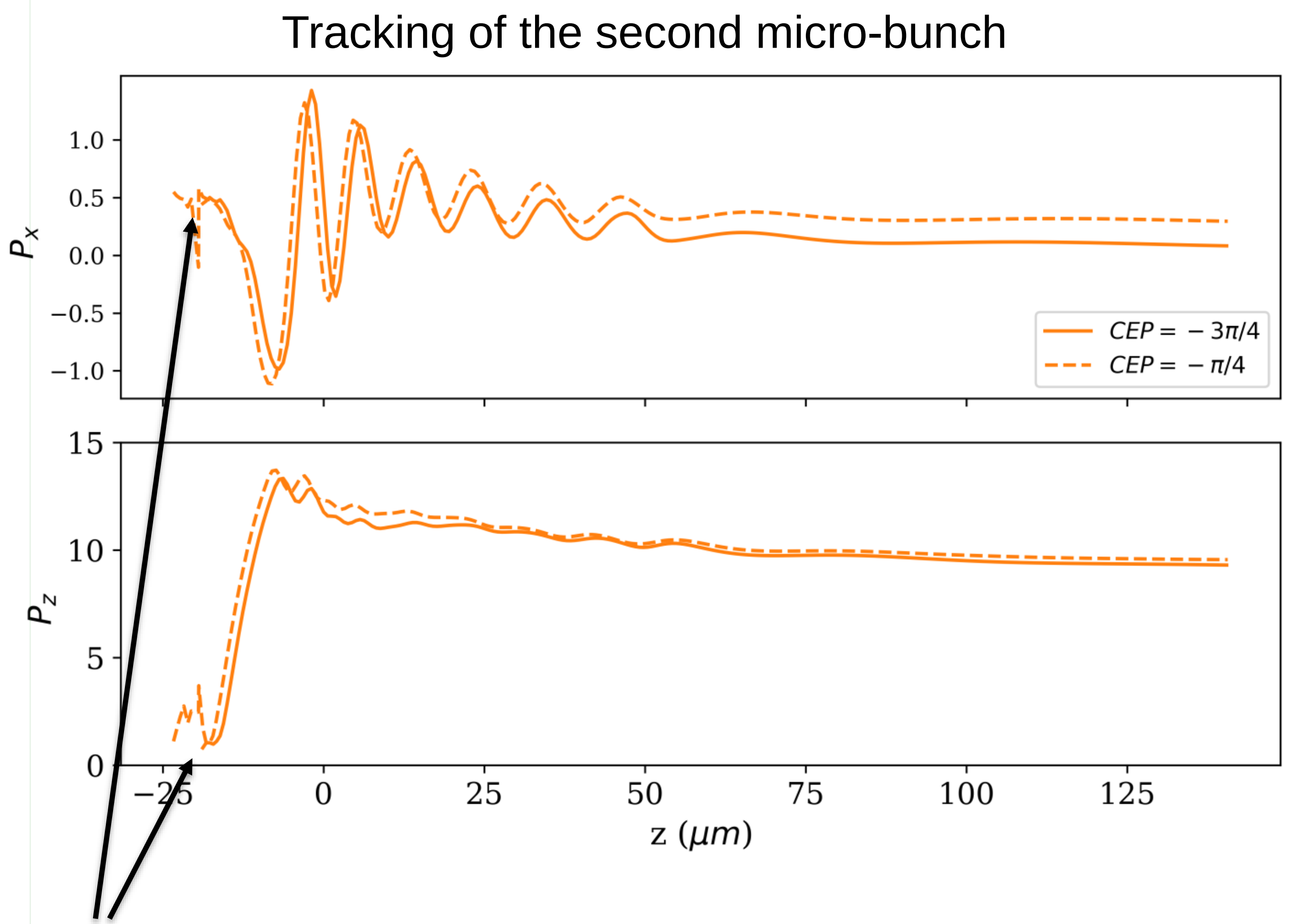




CEP and ionization injection in argon



Tracking of a micro-bunch

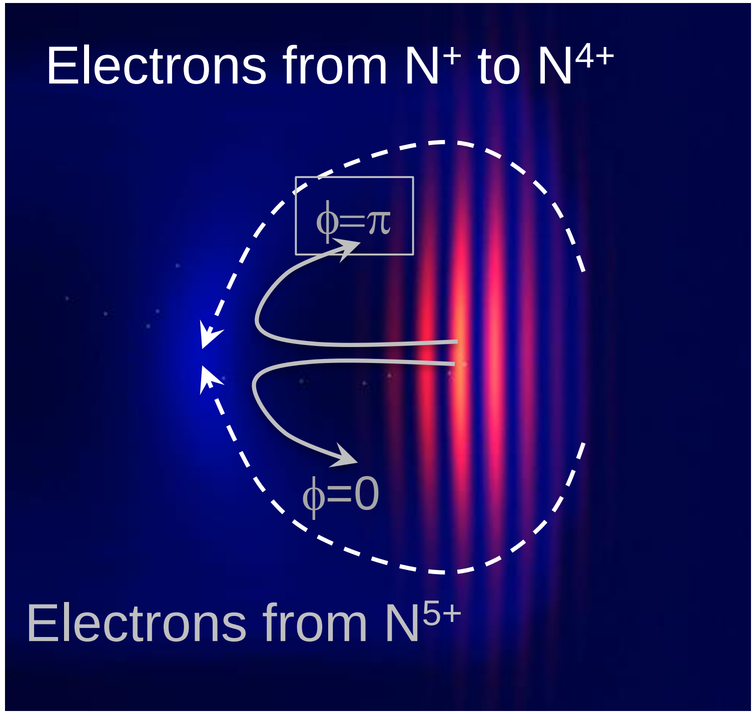


Micro-bunch injection

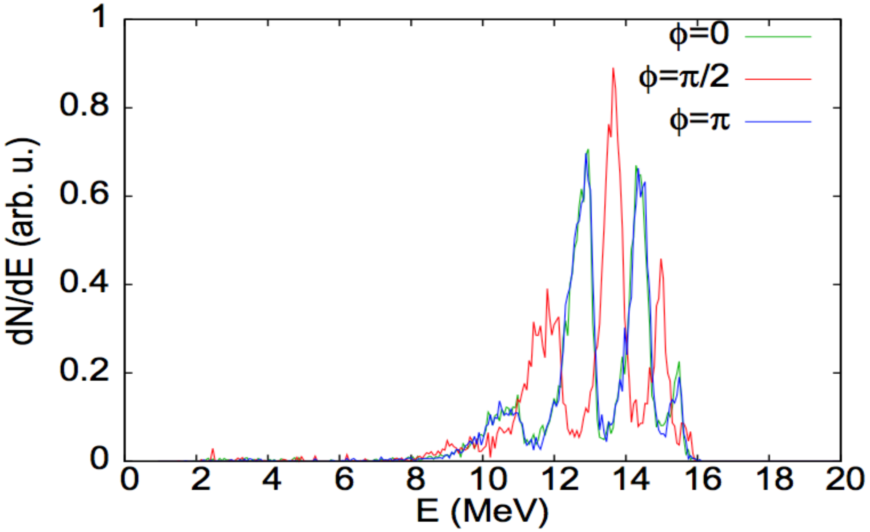
- Different CEP = shifted injection time for the micro-bunch
- Different initial conditions → different transverse momenta
- Similar longitudinal momenta

CEP effects : what is expected

Ionization-injection case



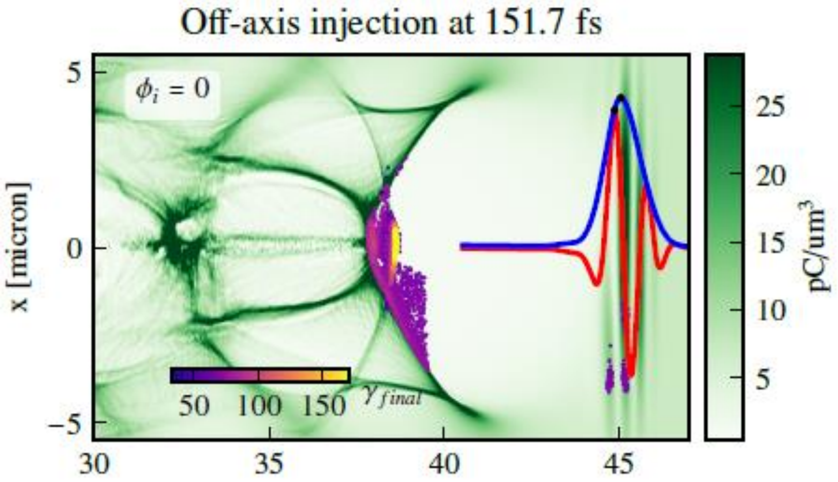
electron spectra (3D PIC)

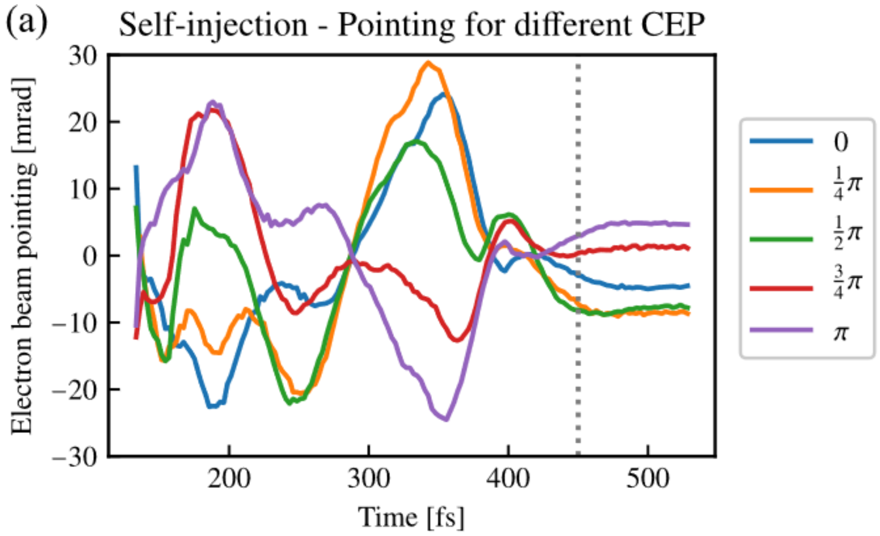


Lifschitz & Malka, NJP 14 053045 (2012)

CEP effects : what is expected

Self-injection case



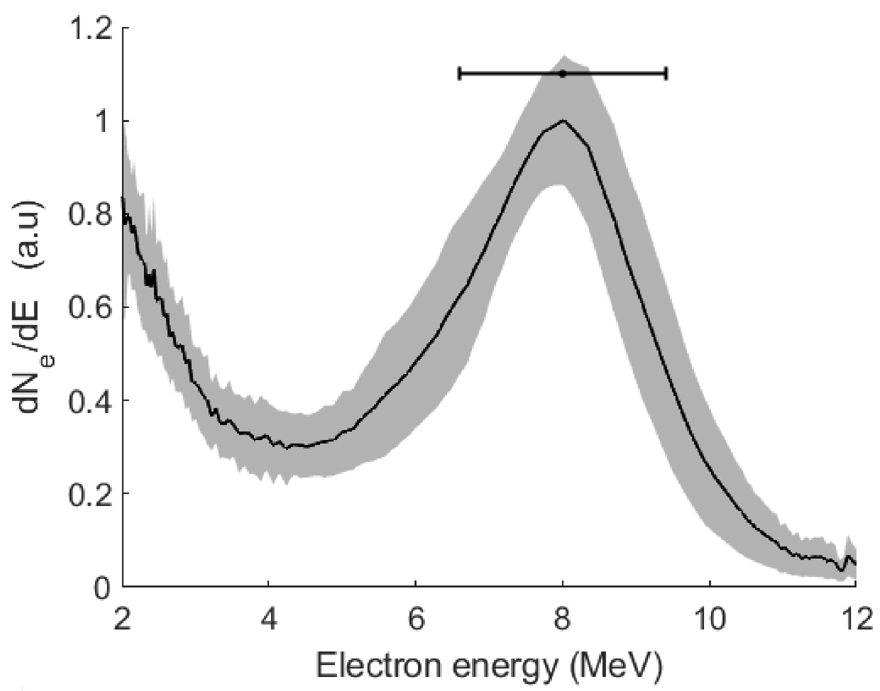


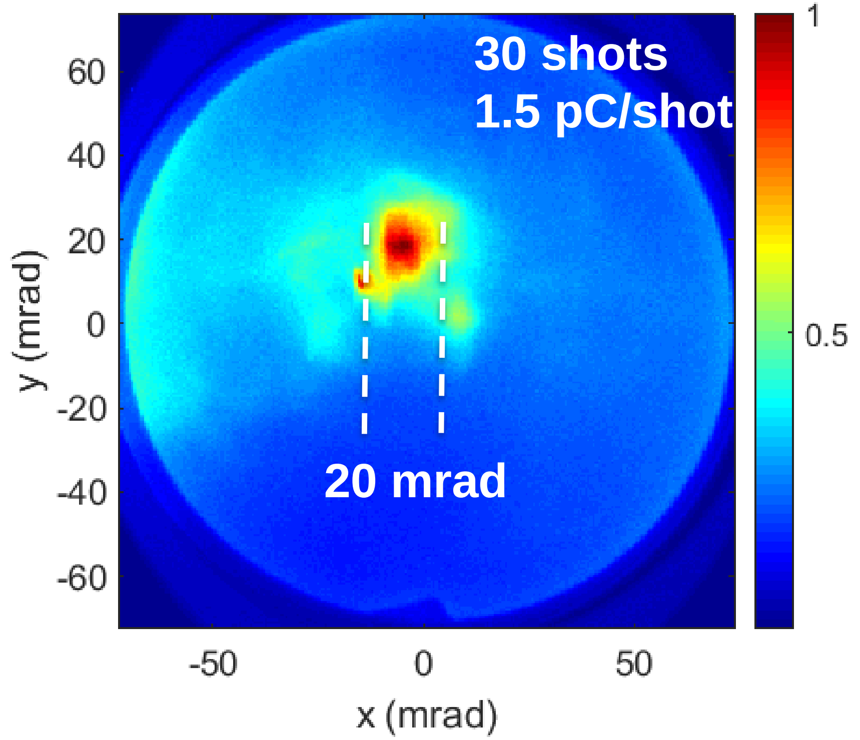
J. Huijts et al. arXiv:2006.10566 (2020)

Asymetry in self-injection leads to CEP-dependent pointing

Perspectives : 8-10 MeV at kHz!

Differential pumping: shot in hélium at kHz !





Soon in H_2 = 15 MeV possible ?

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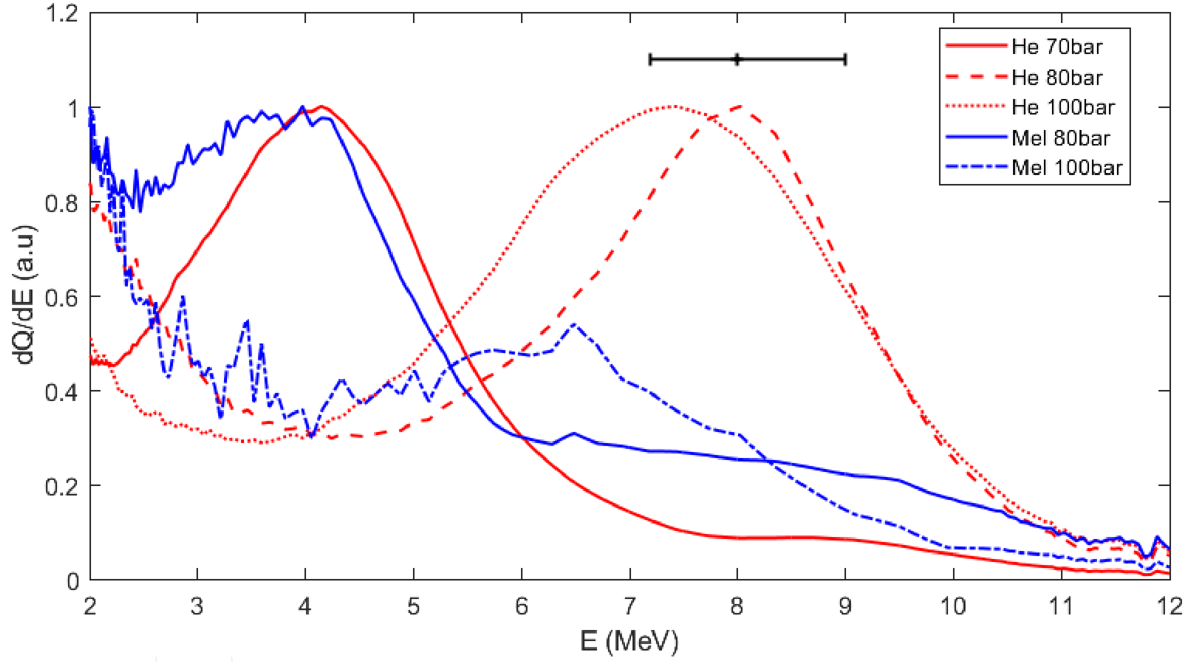
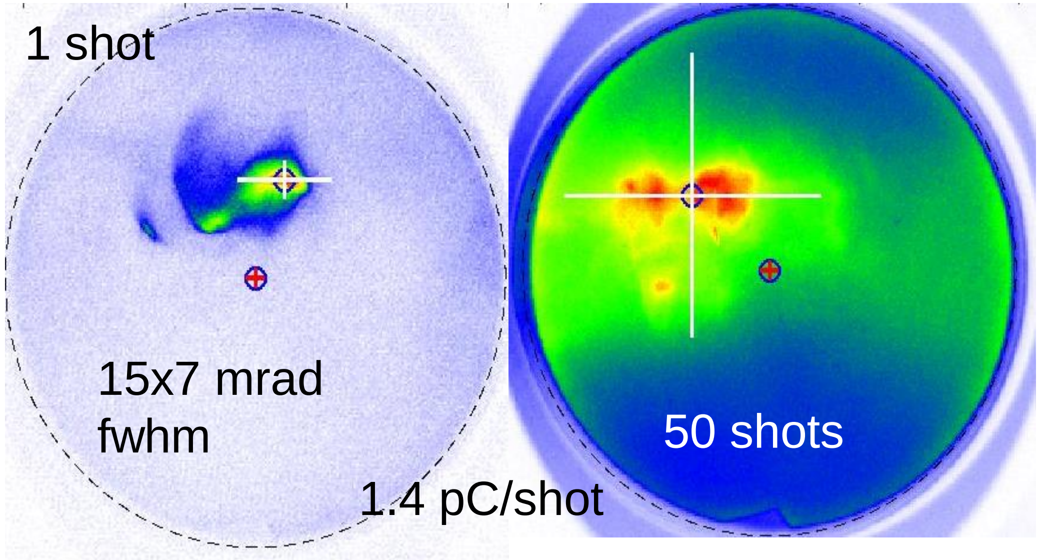
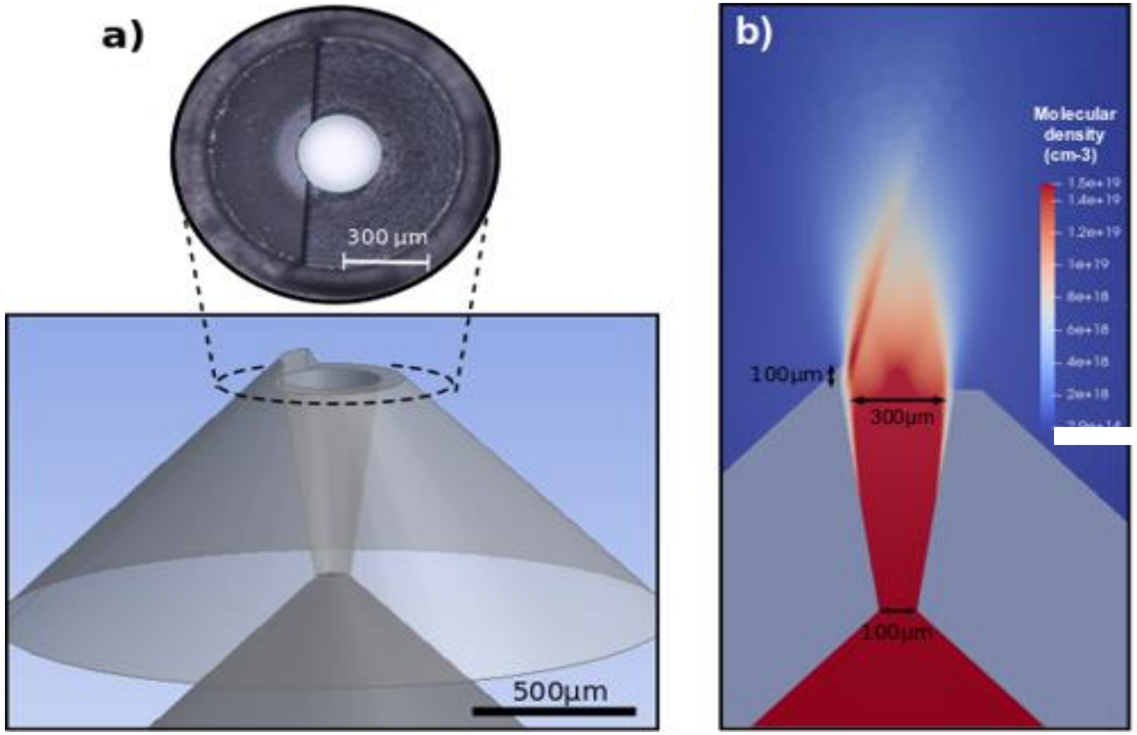
8-10 MeV

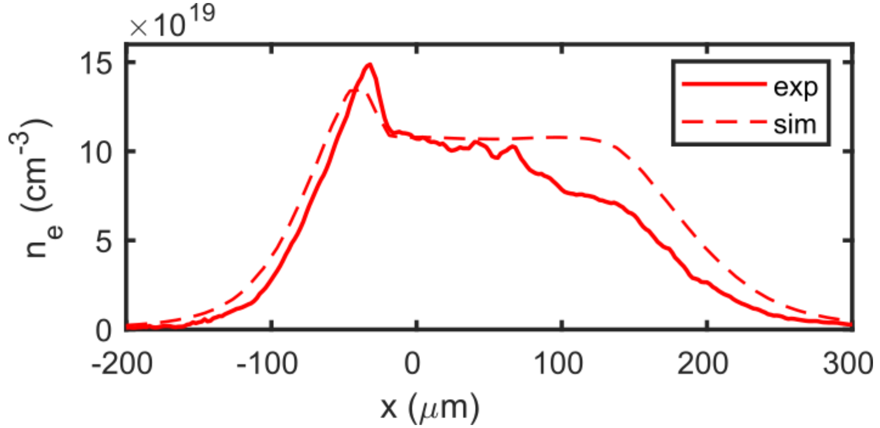


P100 He



New design : shocked micro-jet





Why use a shock ?

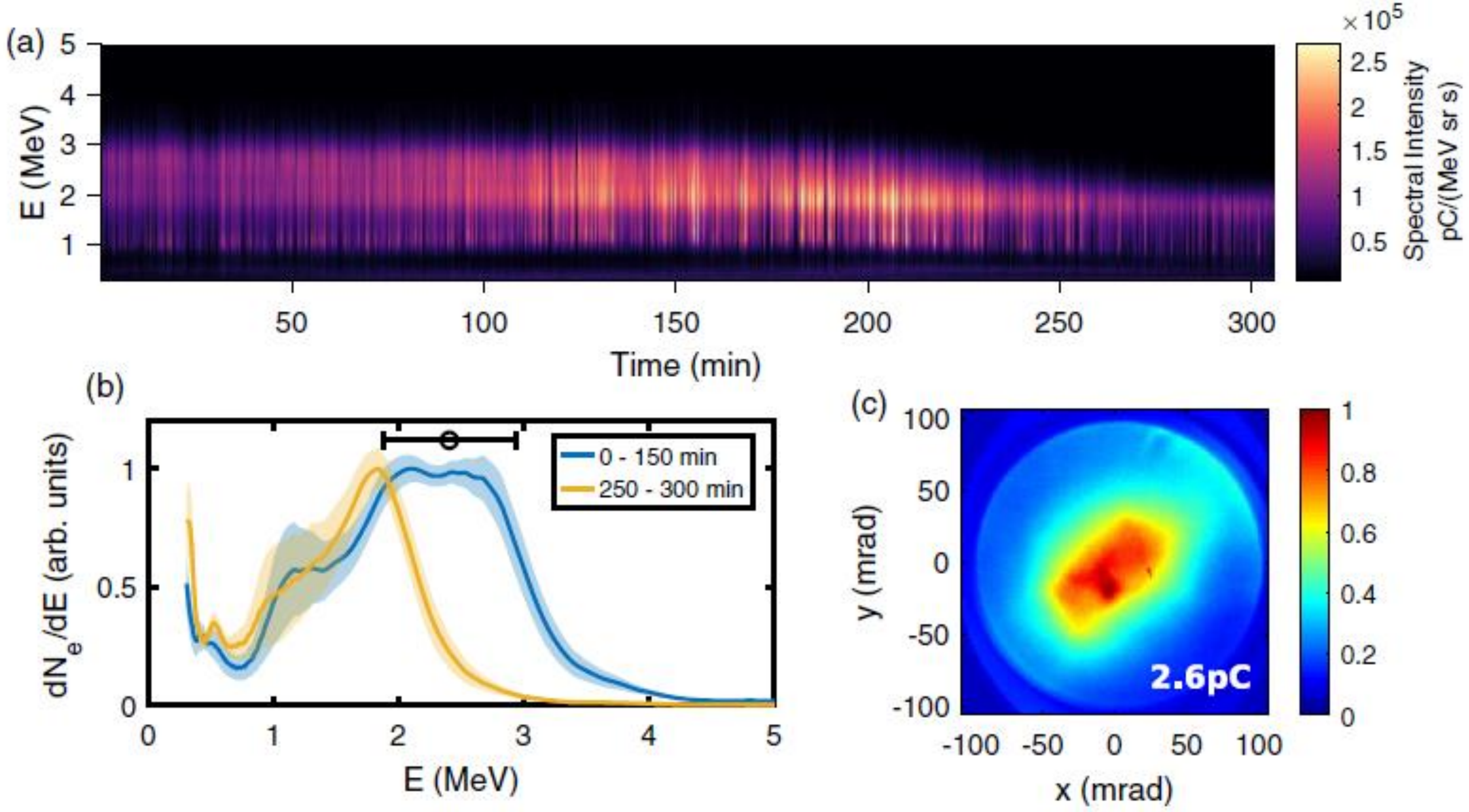
- High density region, possibly well above the tip of the nozzle
  → avoid damage

- Creates a density gradient: useful for triggering injection
  → stabilize the beam

OSS = **O**ne-**S**ided **S**hock

L. Rovige *et al,* RSI 92, 083302 (2021)

5h hands-off continuous operation



18 x 10^6 shots !

<u>Param. exp.:</u>
El = 3.8 mJ ; τ = 4.1fs
I= 2×10^{18} W/cm²
Spot size : 6.2x5.5 µm FWHM
One-sided shock jet (densité pic: ≈1×10^{20}cm^{-3})

L. Rovige et al., PRAB **23**, 093401 (2020)