How are CEP effects affected by the injection mechanism in a Laser Wakefield Accelerator driven by near single-cycle laser pulses?

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Collaborators

High repetition rate laser-plasma source
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Laser system:
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Gas jet fabrication:
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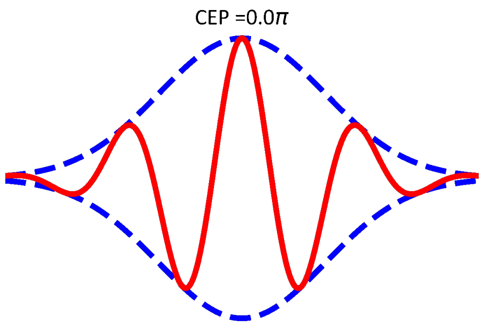
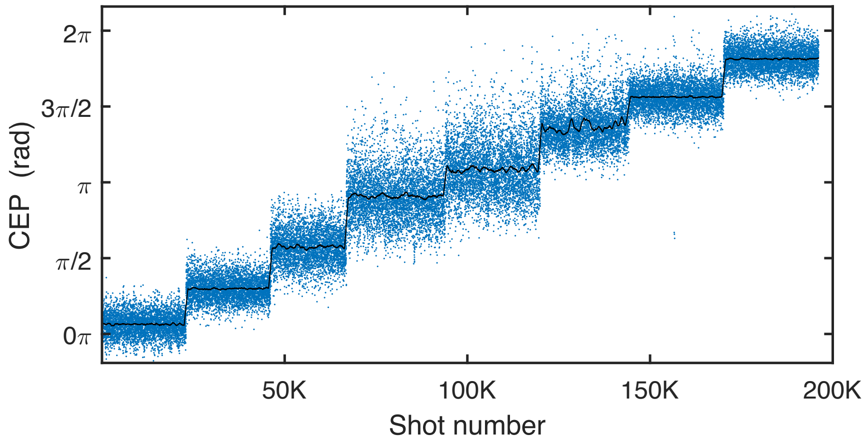
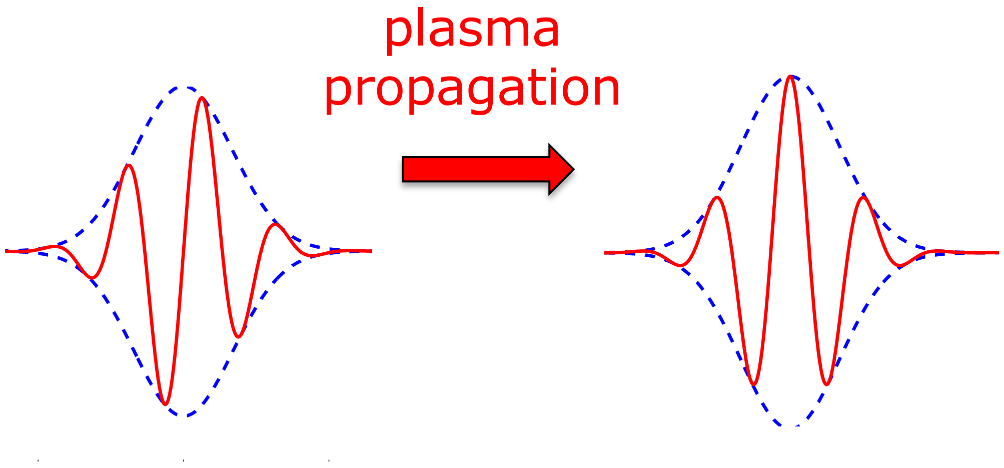
What is the Carrier Envelope Phase (CEP) ?





At LOA:
Controlled & stable CEP
stab 200-300 mrad rms
20 mrad when averaging



In a plasma, the CEP slips because

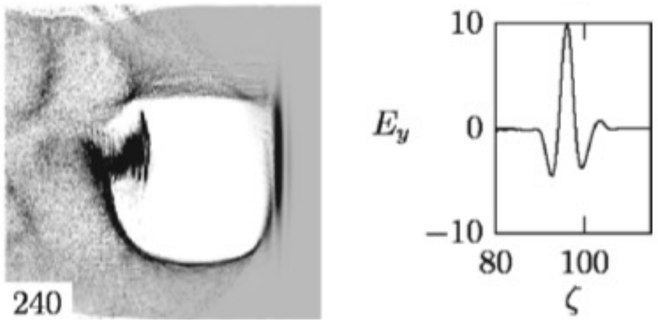
$$v_\varphi > v_g$$

Slippage length

$$L_{2\pi} \simeq \lambda_0 \frac{n_c}{n_e} \sim 10\,\mu\text{m}$$

Motivation for studying CEP effects

- Curiosity driven: fundamentals of laser-plasma interaction



For few-cycle pulses
Asymmetric plasma response in polarization plane
Depends on CEP
→ **Oscillating bubble**

Nerush & Kostyukov, PRL **103**, 0035001 (2009)

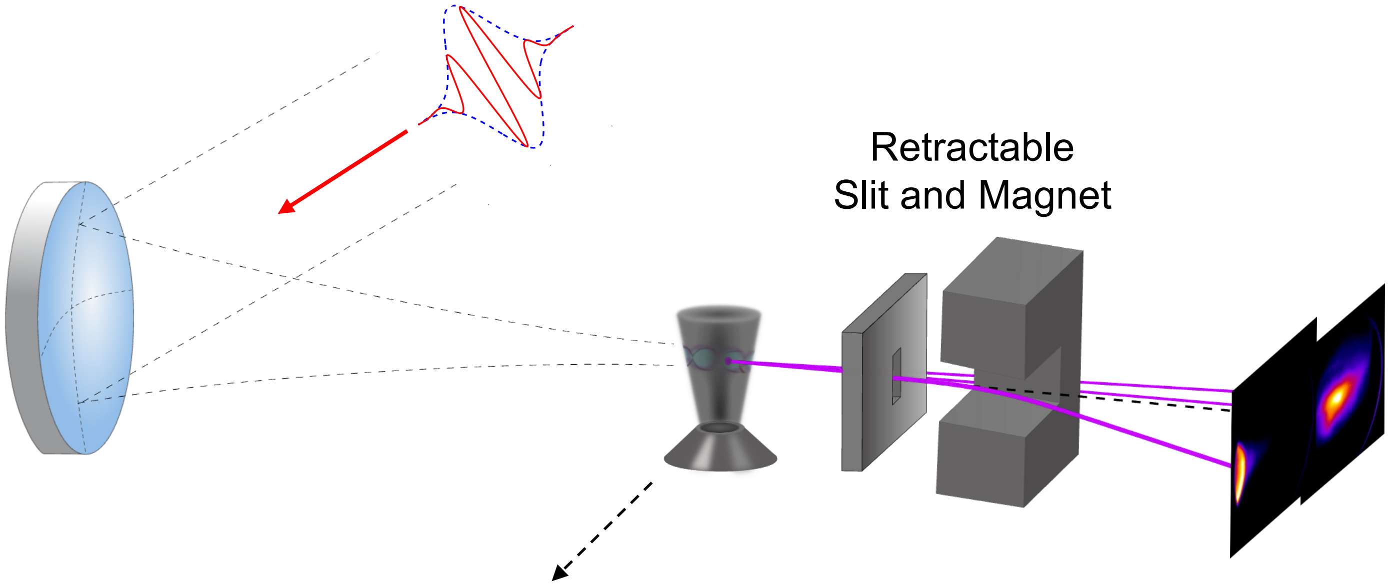
- Technology driven : current kHz LWFA use few cycle pulses
  - Post-compressed Ti:saph pulses → 3-4 fs, 3 mJ, kHz

    Guénot et al., Nat. Phot. **11**, 293 (2017); Salehi et al., PRX **11**, 021055 (2021)
  - OPCPA laser systems → 8-10 fs
    - SYLOS laser at ELI-ALPS: 8 fs, 100 mJ, 1 kHz — Budriunas et al., Opt. Exp. **25**, 5797 (2017)
    - L1 laser at ELI-Beamlines: 15 fs, 30 mJ, 1 kHz — Lazzarini et al., PoP 31 030703 (2024)

Experimental set-up

Laser

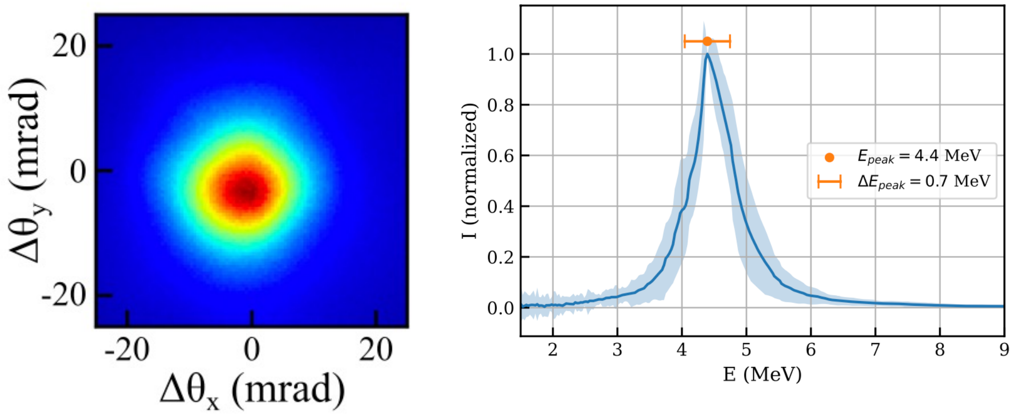
- τ = **3.5-4.0 fs**, E = **2.5 mJ**, Spot **: 5 µm** FWHM
- I = **$2x10^{18}$** $W.cm^{-2}$



Plasma target

- Micrometer gas jet (150 µm)
- Differential pumping for continuous operation
- H_2 experiments

Stable kHz beams in H_2

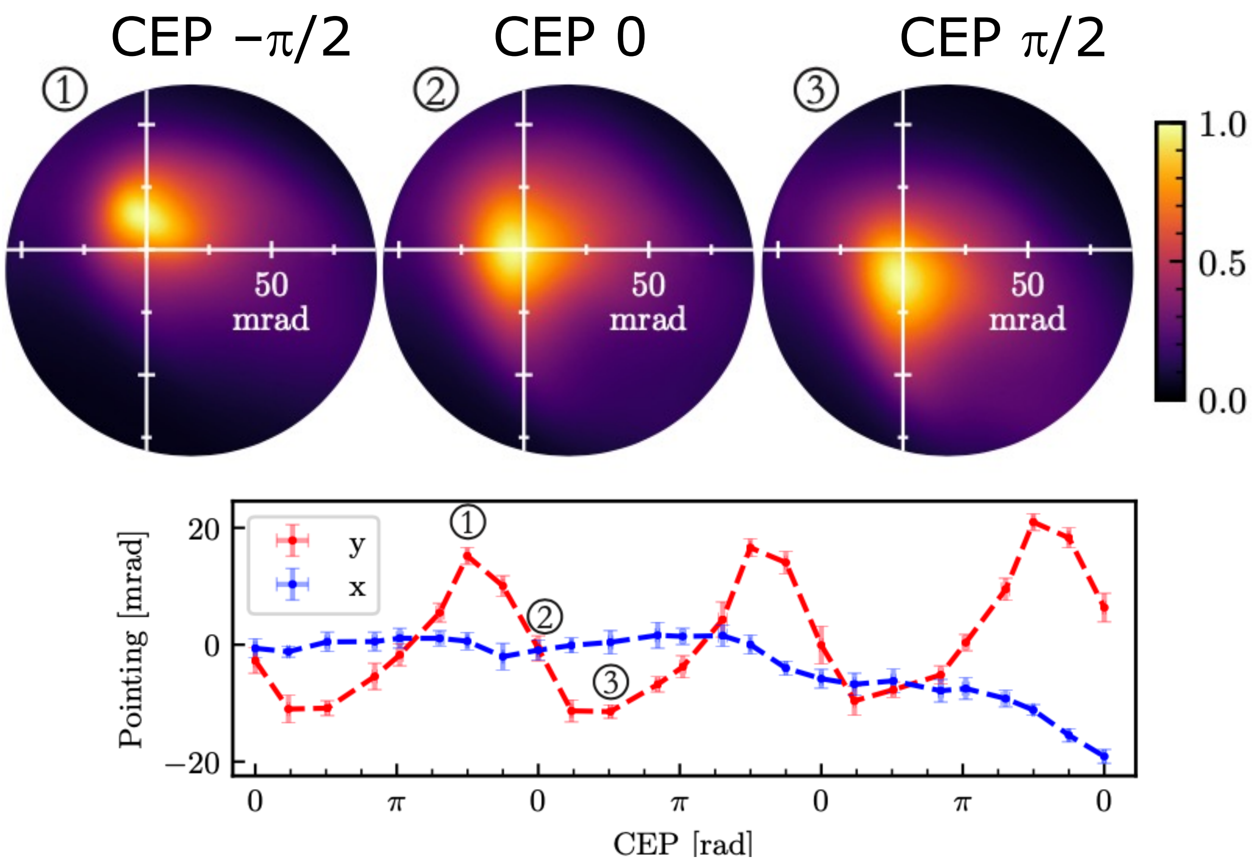


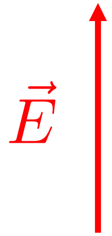
We vary the CEP and monitor:

- Beam profile
- Charge
- Energy spectrum

Previous results: CEP dependent beam pointing (in N_2 and He)

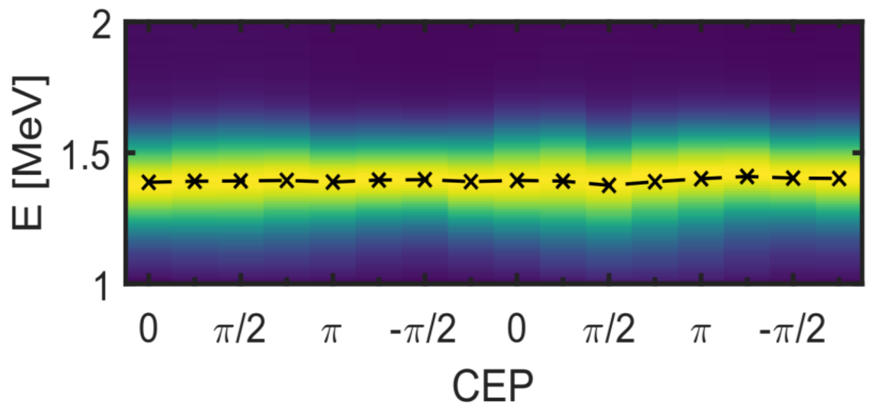
Self-injection





CEP dependent beam pointing
+/- 15 mrad

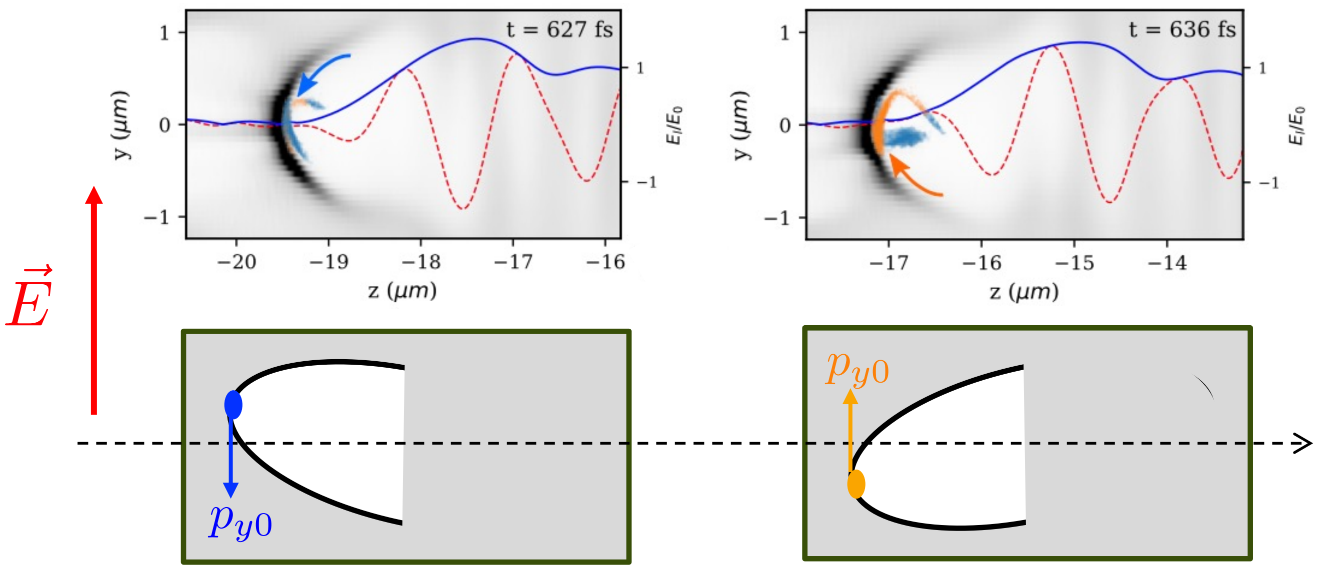
No significant energy variation



Similar behavior in N_2 and He excluding ionization injection

Huijts & Rovige *et al.*, Phys. Rev. X **12** 011036 (2022) → In N_2
Rovige et al. Eur. Phys. J. Spec. Top. (2023) → In He

Interpretation (FBPIC): off-axis self-injection



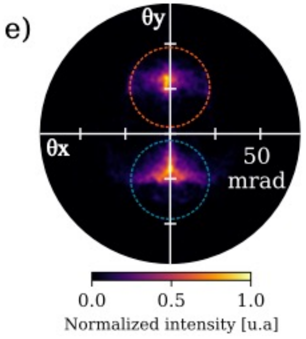
Wake asymmetries driven by CEP

Off-axis self-injection

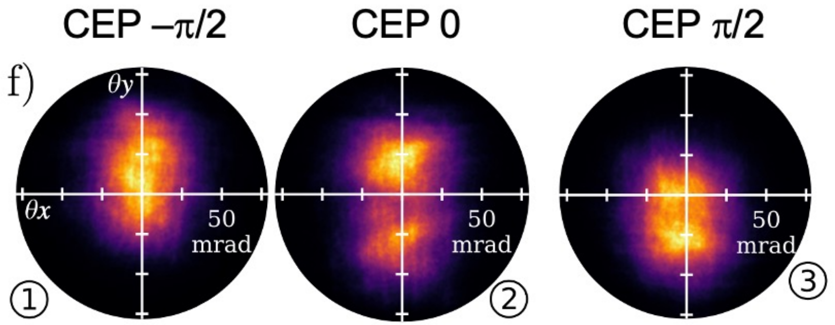
Initial transverse momentum

→ CEP dependent beam pointing

2 sub-beams from
2 injection events



Including space charge and pointing fluct.

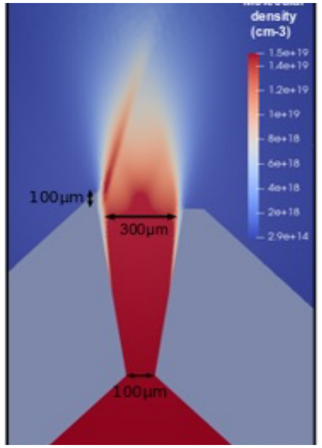


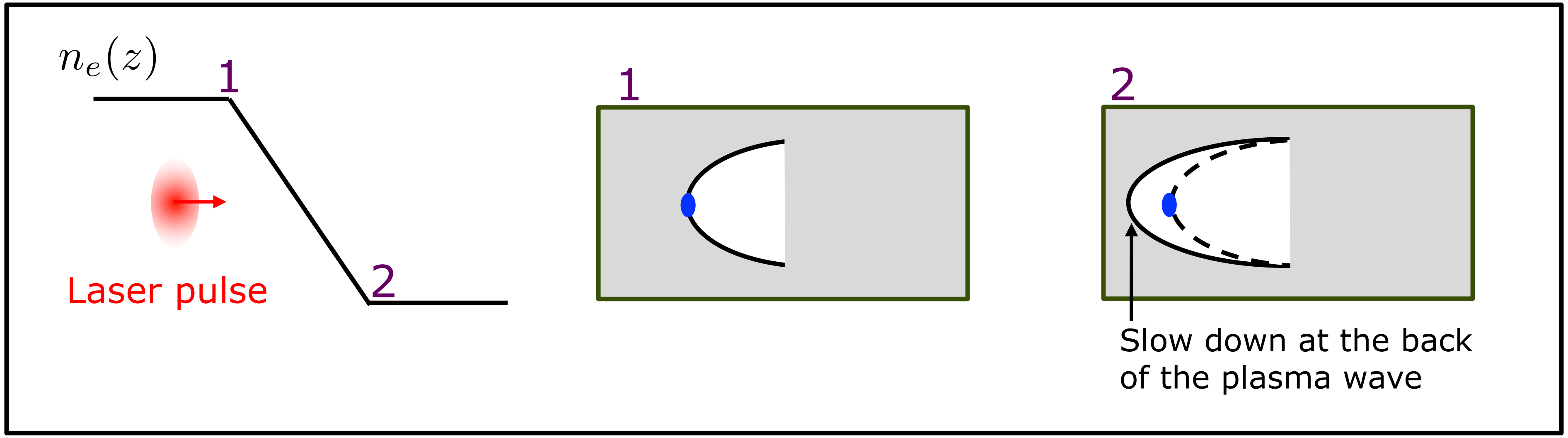
Huijts & Rovige *et al.*, Phys. Rev. X **12** 011036 (2022); Rovige et al. Eur. Phys. J. Spec. Top. (2022)

What about other injection mechanisms ? Gradient injection

- **Gradient injection in shocked micro-nozzles**

Rovige et al., RSI **92**, 083302 (2021); L. Rovige et al., PRAB **23**, 093401 (2020)



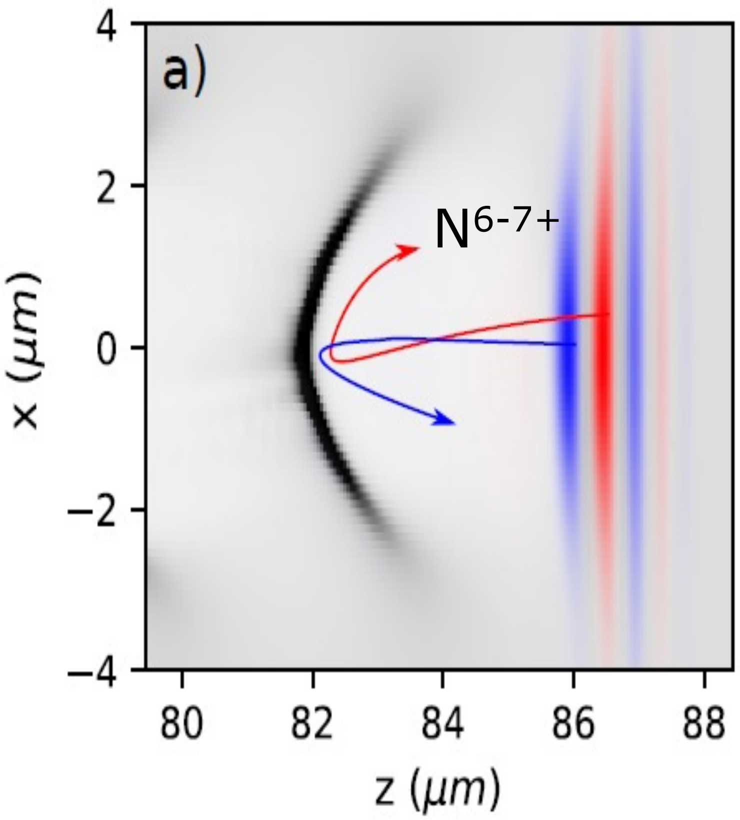


Here injection is triggered by ***longitudinal*** dynamics of plasma wake

Mitigation of CEP effect is expected: factor of 2-3 decrease of beam oscillation was observed in PIC simulations in Huijts *et al.*, Phys. Plasmas **28**, 043101 (2021)

What about other ionization injection ?

- **Ionization injection**



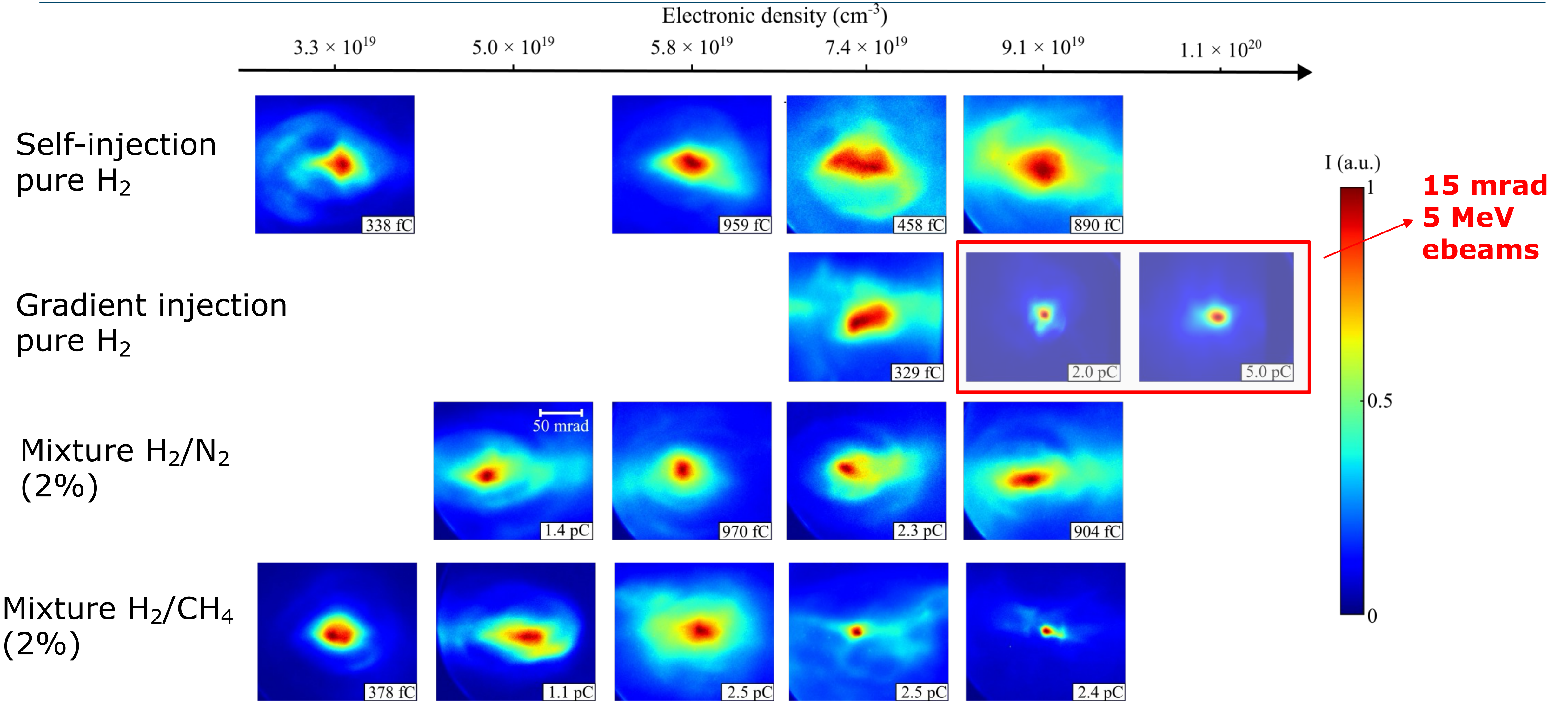
- Minor modifications of electron energy
- Transverse momentum depends on sign of E-field
- **CEP dependent beam pointing?**

In our experiment, we tried:

- H_2/N_2 (2%) → $I_{N^{6+}} = 10^{19}\ \mathrm{W.cm^{-2}}$
- H_2/CH_4 (2%) → $I_{C^{5+}} = 3.8 \times 10^{18}\ \mathrm{W.cm^{-2}}$

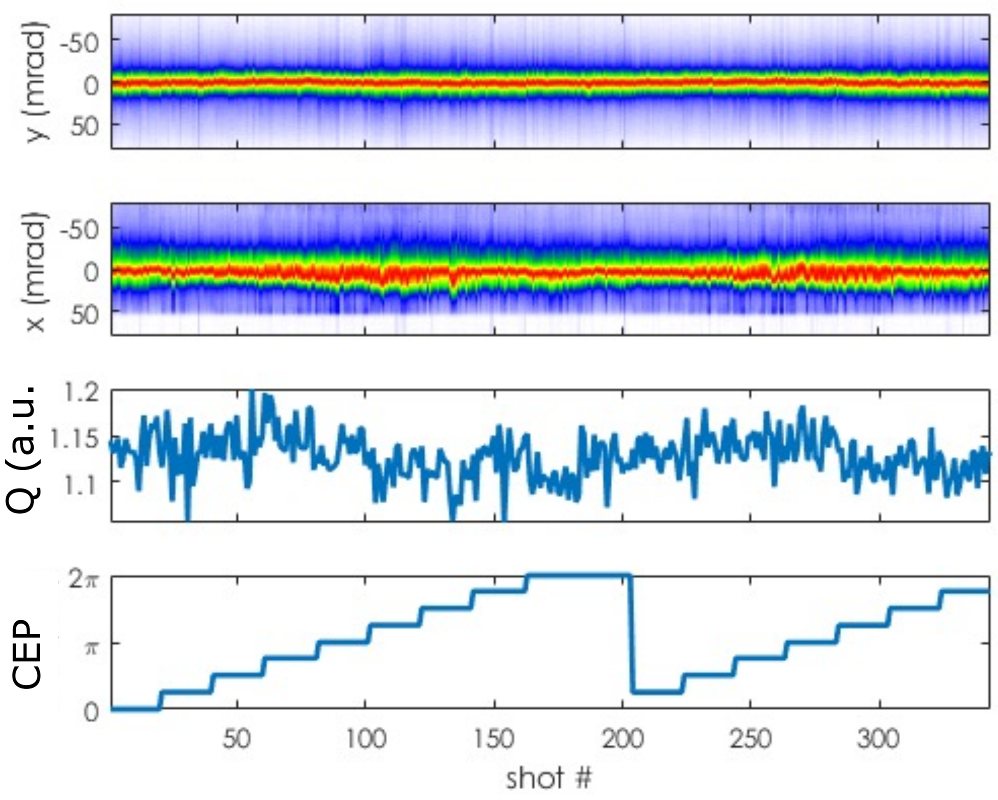
Lifschitz & Malka, **NJP** 14 053045 (2012)

Overall behavior of e-beams in different injection schemes



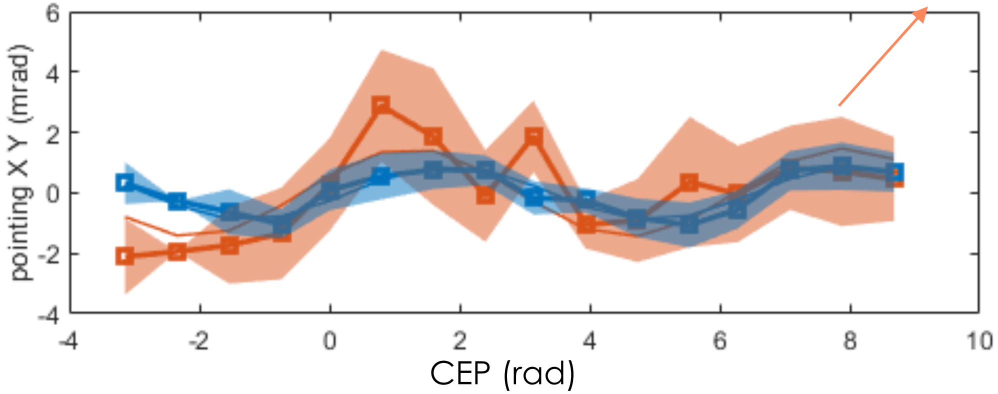
Mitigated CEP effects with gradient injected beams

Gradient injection: 140 bars (1.1×10^{20} cm^{-3})



Beam centroid

polarization along x

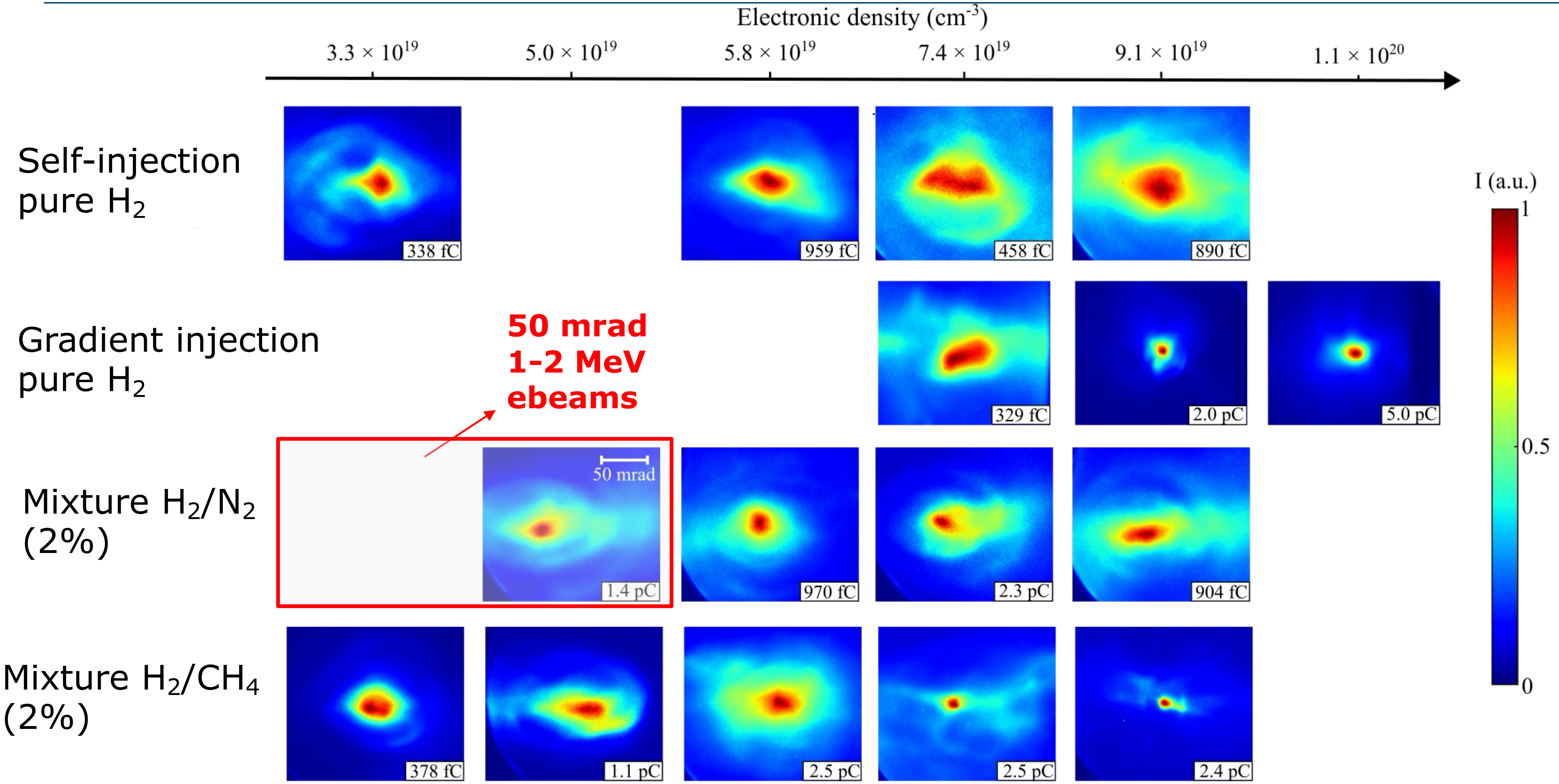


- Bad correlation in polarization direction (x)
  Amplitude (<2 mrad): 10 x less than previous

- No significant energy changes

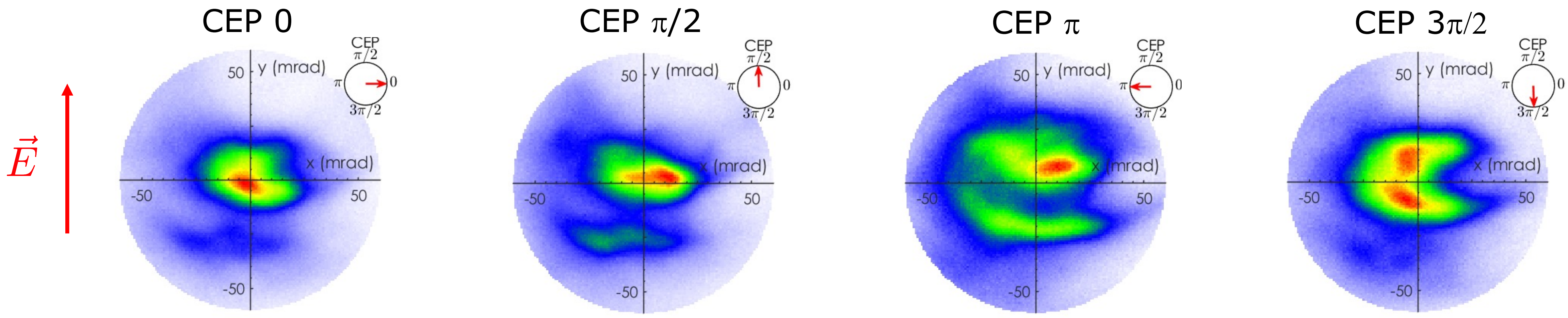
→ Similar to off-axis self-injection results but with reduced amplitude

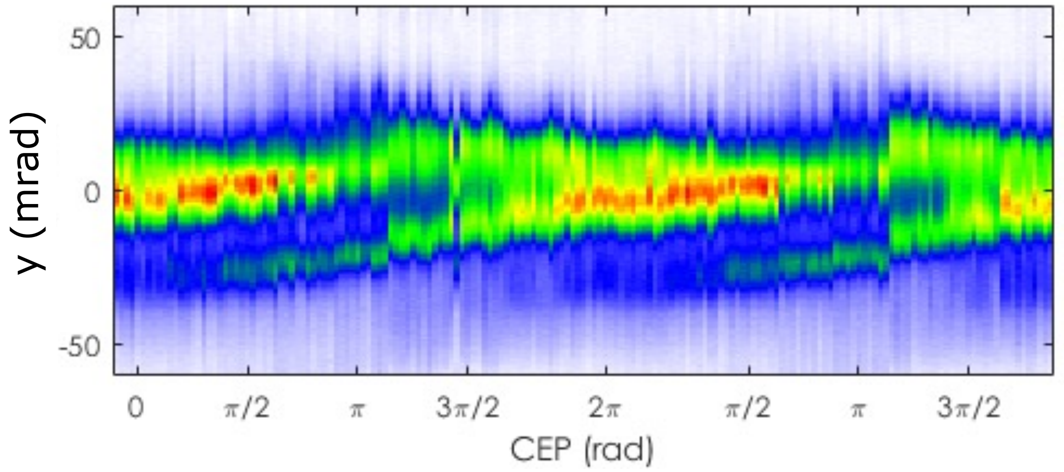
Overall behavior of e-beams in different injection schemes



CEP effect in H_2/N_2 (2%) mixture

30 bars (2×10^{19} cm^{-3}), polarization along y



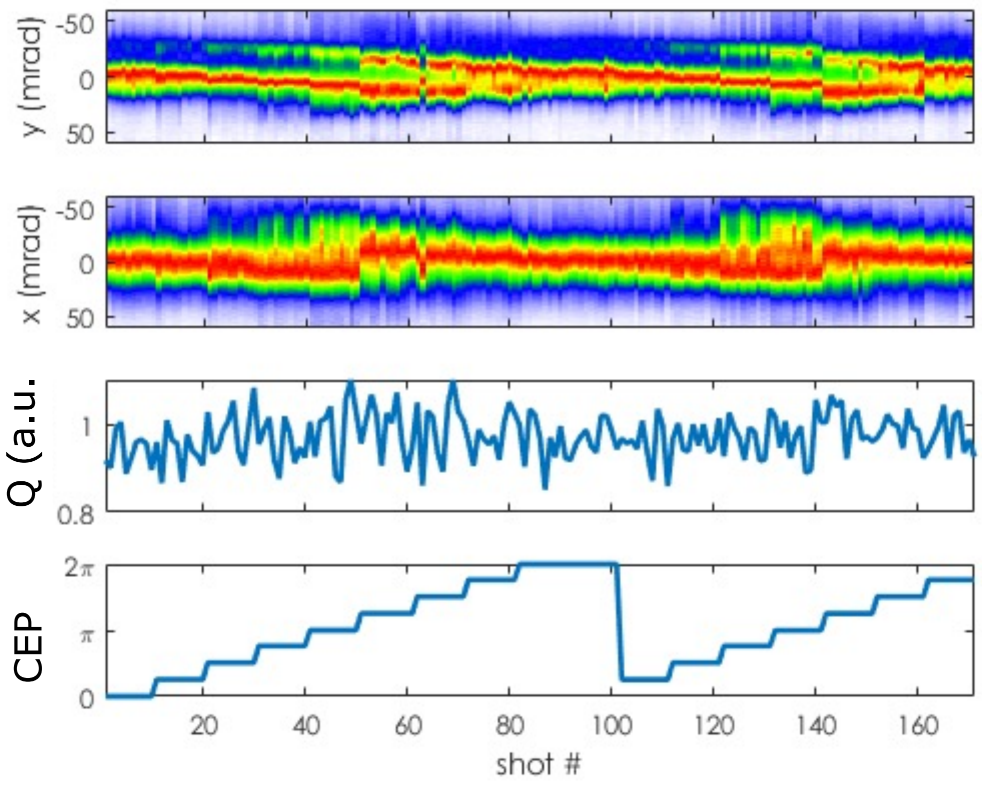


We observe an **angular splitting of the beam (30 mrad)** in the polarization direction.

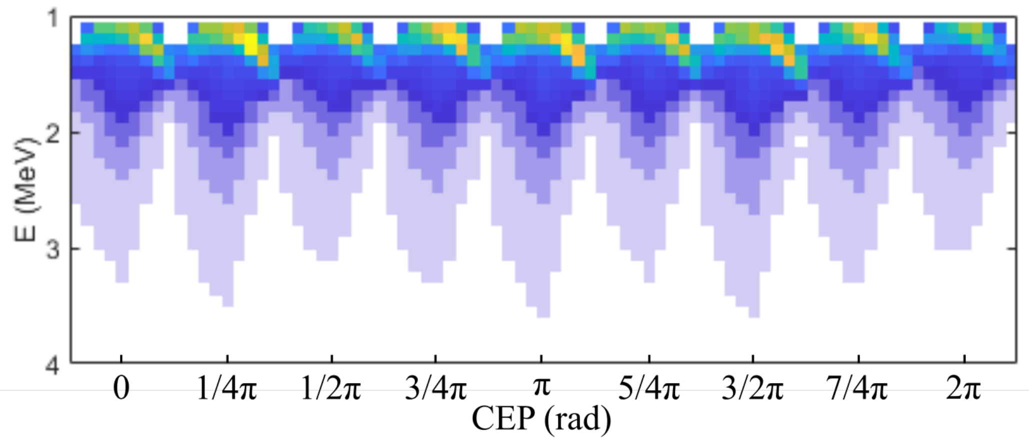
Excellent correlation with the CEP

CEP effect in H_2/N_2 (2%) mixture

Polarization along y



Energy spectra



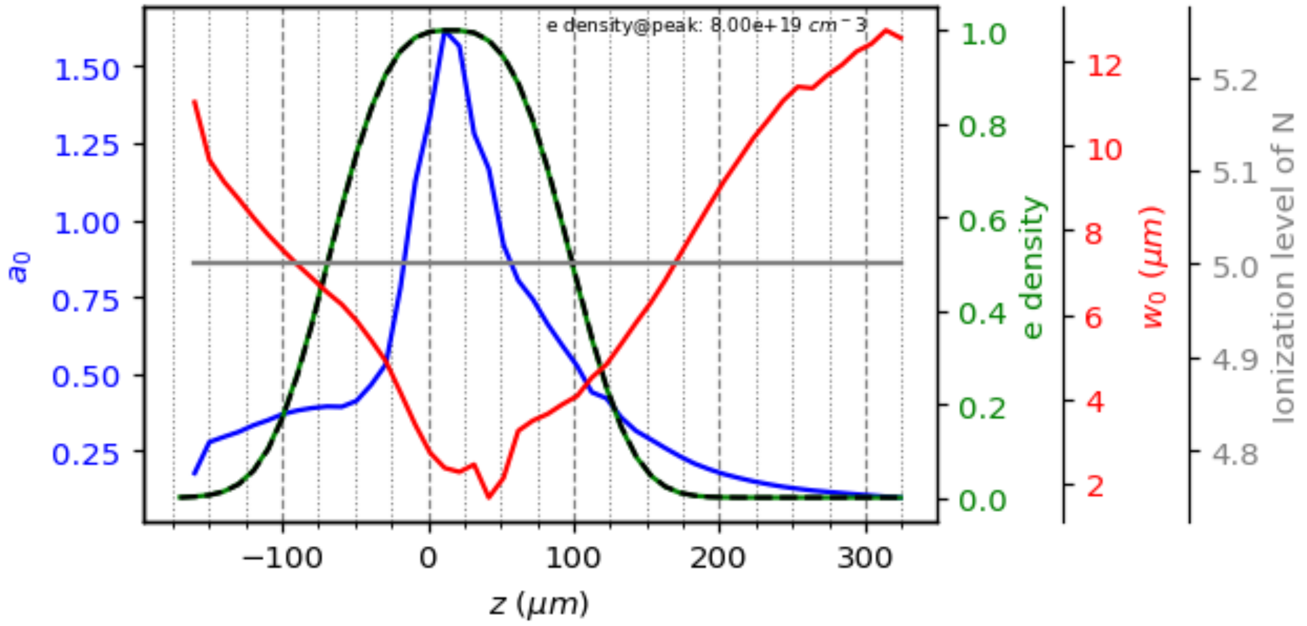
- No significant charge variation
- No significant energy variation

→ Is this a signature of ionization injection ?

FBPIC indicates very small amount of ionization injection

Exp. focal spot, and pulse shape, $n_e = 8\text{x}10^{19}$ cm^{-3}

H_2/N_2 (2%)



- **Self-injection = 0.8 pC**
- **Negligible ionization injection = 80 fC**

- Max intensity too small for significant ionization of N^{5+} :

$$I_{max} = 5 \times 10^{18}\ \mathrm{W.cm}^{-2}$$
$$I_{N^{6+}} = 10^{19}\ \mathrm{W.cm}^{-2}$$

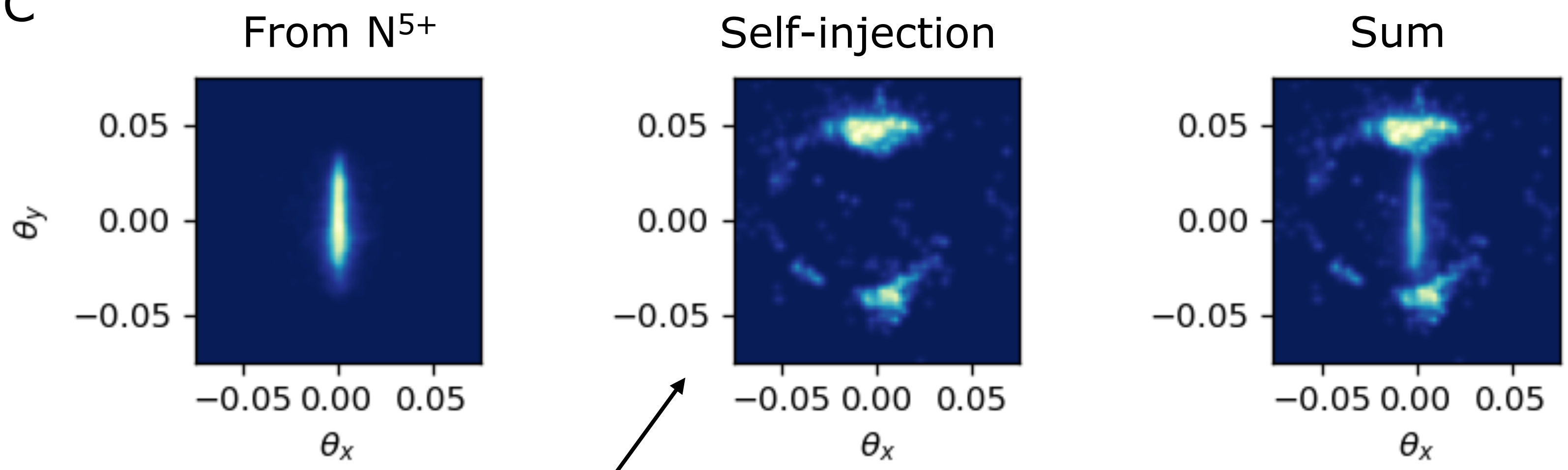
→ Probably no significant ionization injection in experiment…

Ionization injection should lead to a different beam topology

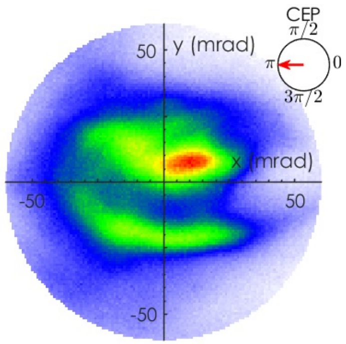
We boost the doping to H_2/N_2 (20%)

- **Self-injection = 1.5 pC**
- **Significant ionization injection = 0.5 pC**

FBPIC



Experiment

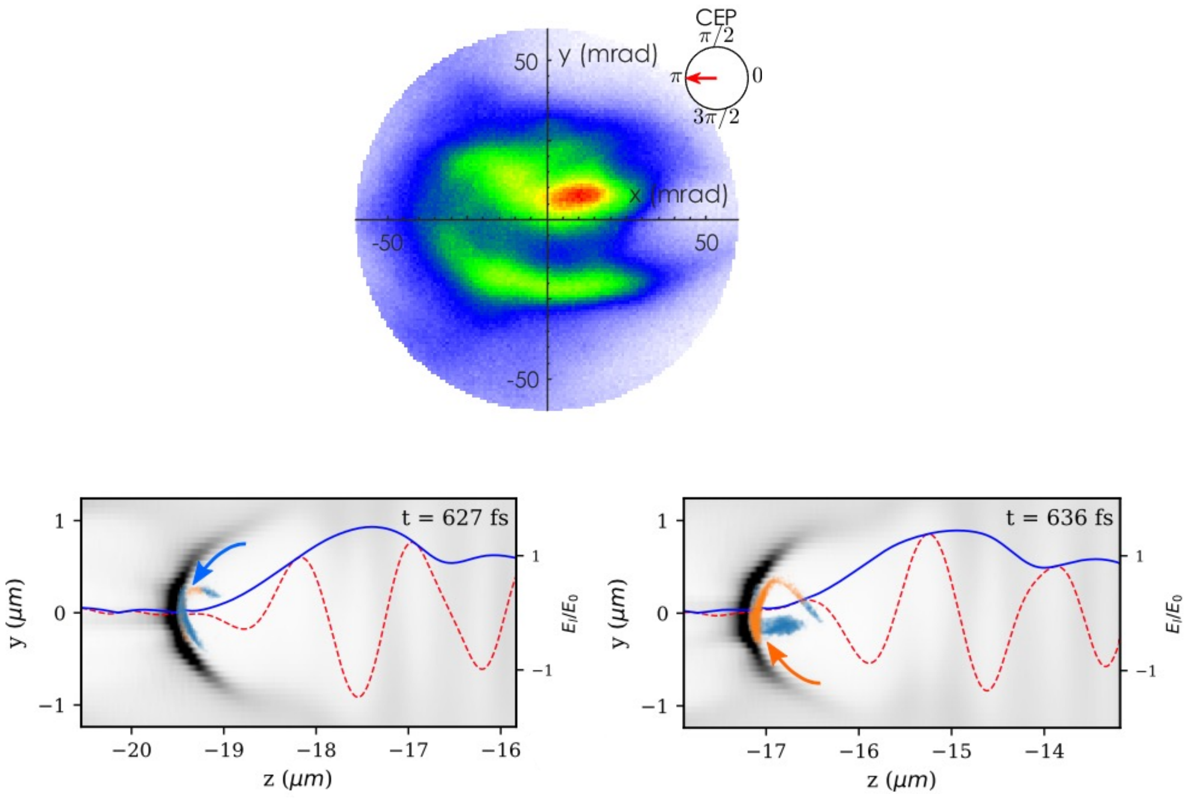


Beam topology is:

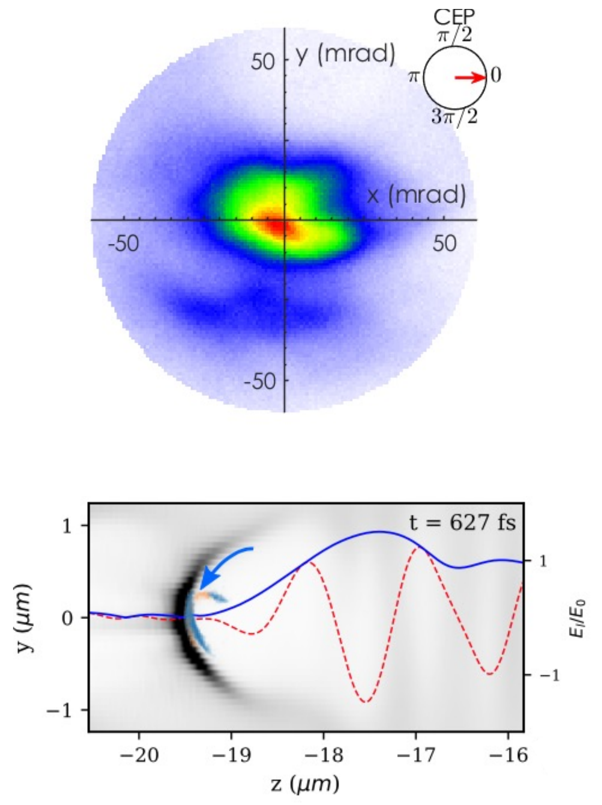
- Consistent with *off-axis self-injection*
- Inconsistent with *ionization injection*

→ Evidence that we are now seeing the 2 beamlets from 2 injection events

Let us speculate !



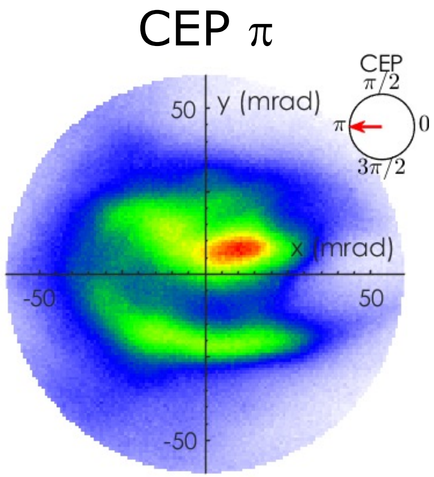
2 beamlets from 2 injection events



Is this 1 beamlet from a single sub-cycle injection event ?

Conclusions / perspectives

In the few cycle regime, CEP effects can play a role



- The wakefield becomes an asymmetric oscillating structure
- Off-axis self-injection leads to CEP dependent beam pointing oscillations
- Gradient injection mitigates the amplitude of the oscillation
- The observation of 2 beamlets might be another signature of off-axis self-injection

Future explorations few cycle / CEP effects with ionization injection:

- Self-injection in H_2/N_2 requires higher intensity
- Alternatively, H_2/Ar mixture could also be tried

} Upcoming beamtime on Sylos 3 at ELI-ALPS

We are hiring at LOA

1 postdoc position open on high rep. Rate LWFA

2 PhD position: Marie Sklodowka-Curie fellowship
https://www.epace.eu

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European compact accelerators,
their applications,
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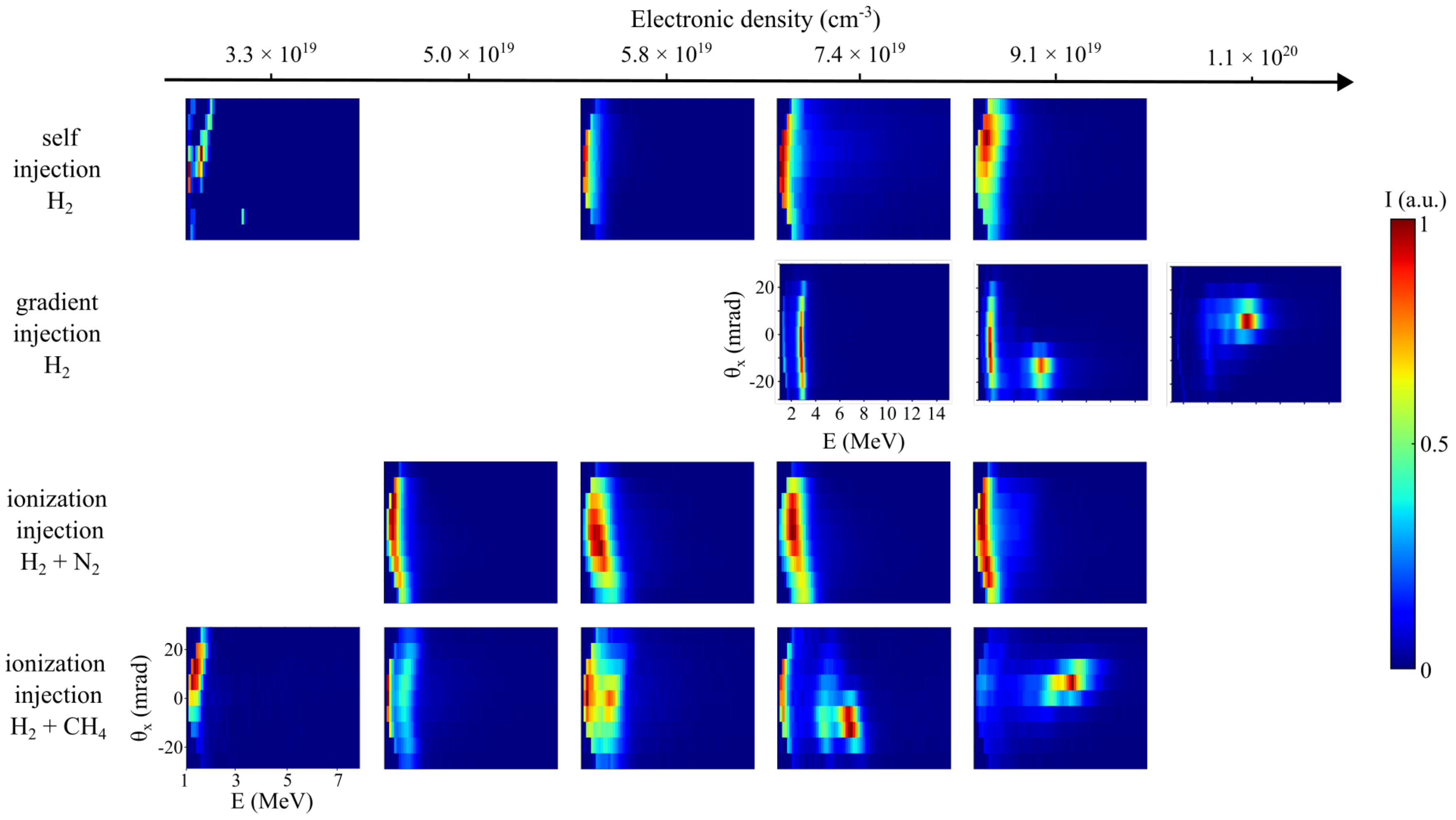
EXTRAS

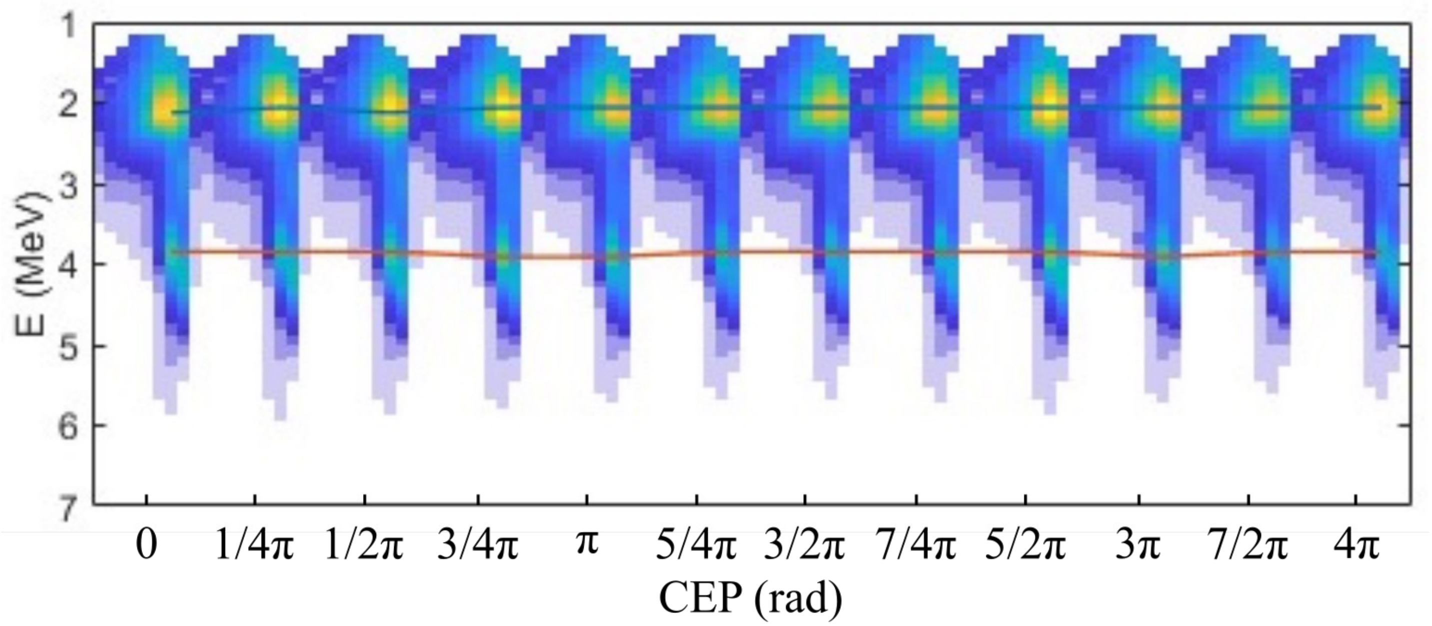
Spectra for different regimes



Gradient injection: no CEP effect visible on spectrum

24 May 2023
Shocked nozzle
H_2
140 bar
$n_e = 1.1 \cdot 10^{20} cm^{-3}$
Laser polariz. – **x axis**
(crossed periscope is in)

Spectra vs CEP



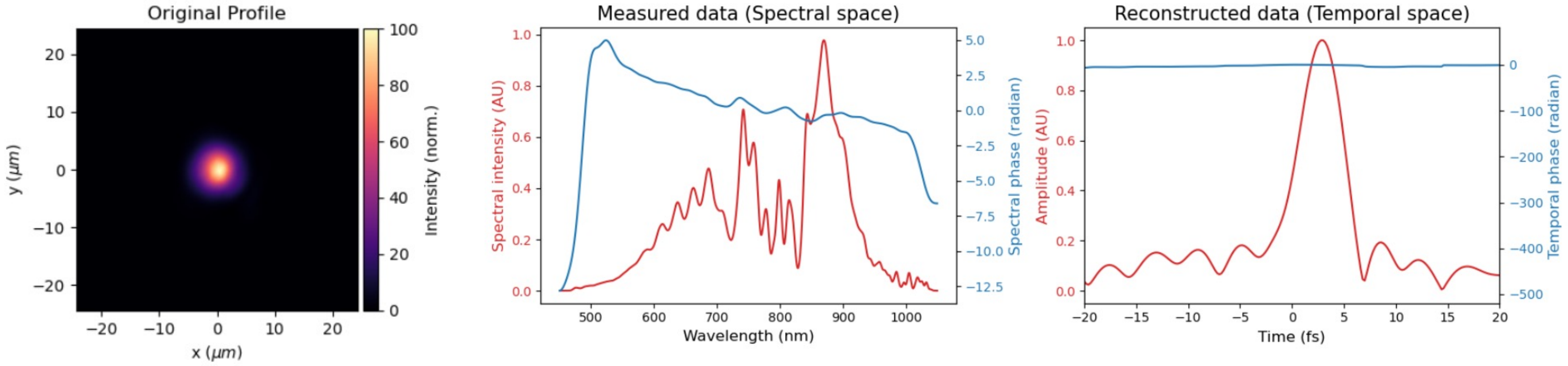
FBPIC important parameters of the simulation

PIC parameters:
4 azimuthal modes
p_nz = 4 # Number of particles per cell along z
p_nr = 4 # Number of particles per cell along r
p_nt = 16 # Number of particles per cell along theta

Preionized plasma:
Hydrogen: Z0_H = 1
Nitrogen: Z0_N = 5
Ne = 6×10^{18} cm^{-3}

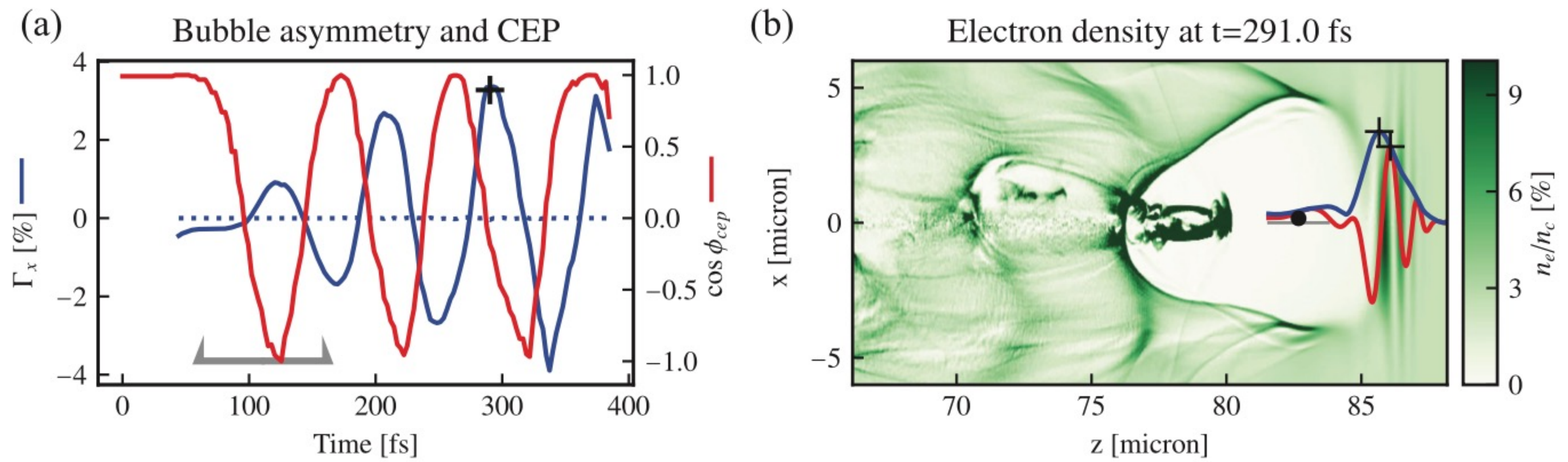
Laser constructed with
LASY library using
Measured spatial and
spectral phase data.

energy = 3.3 mJ
gdd = 17 fs^2



Predicted CEP-effects from asymmetric wakes

$a_0 = 4$ (vacuum), $\tau = 3$ fs



From PIC simulations:

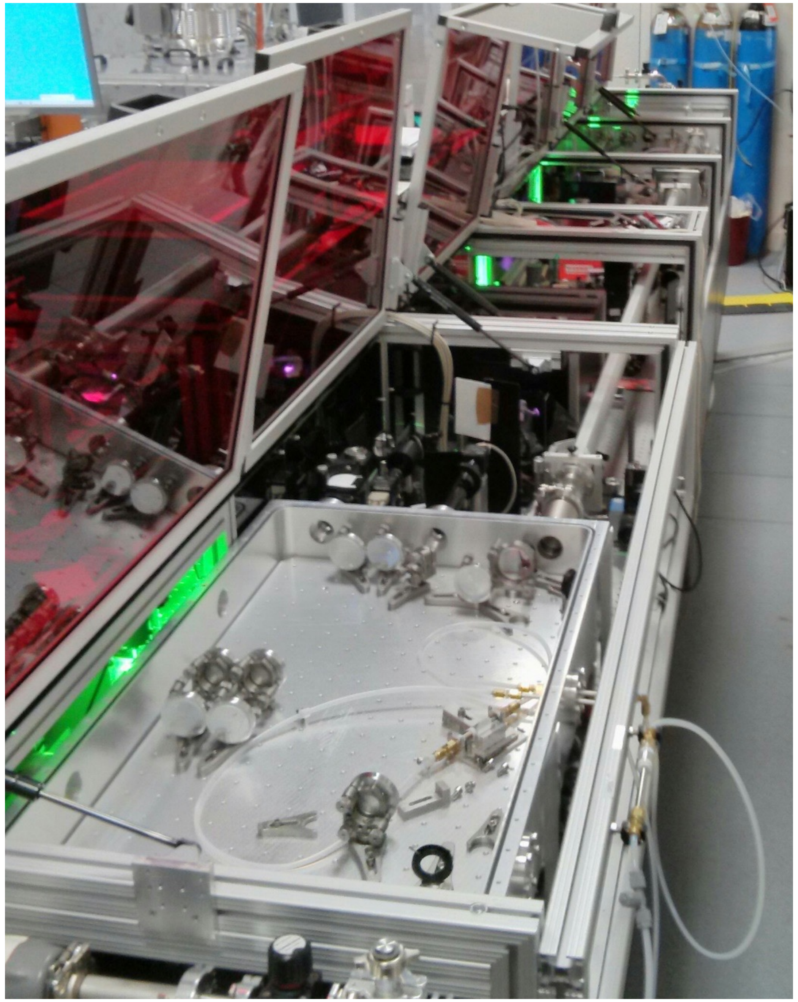
- Bubble oscillations in polarization plane
- Causes off-axis injection with non zero transverse momentum

Experimental observables:

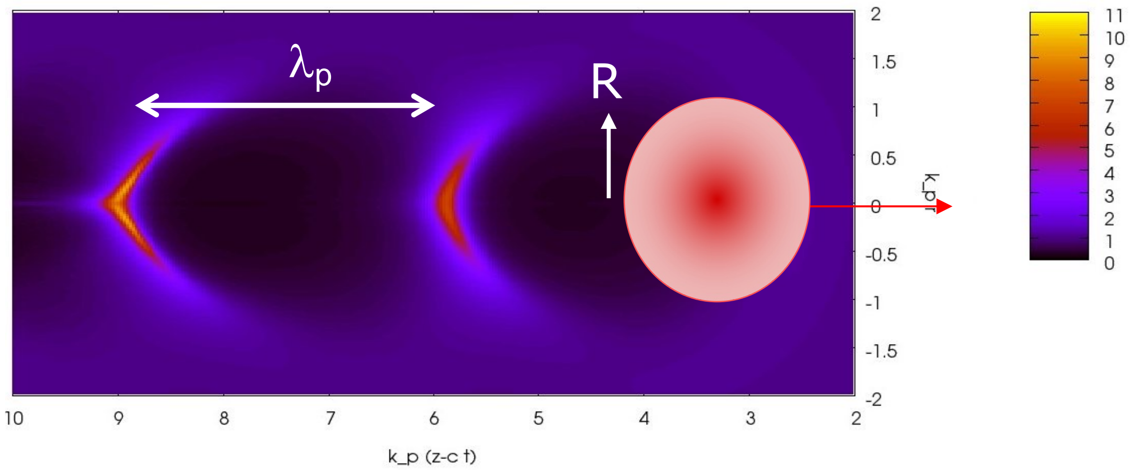
- Minor modifications of electron energy distribution
- **CEP dependent beam pointing**

Huijts *et al.*, Phys. Plasmas **28**, 043101 (2021)

Experimental set-up: laser and accelerator



Scaling laws for a kHz laser wakefield acceleration



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

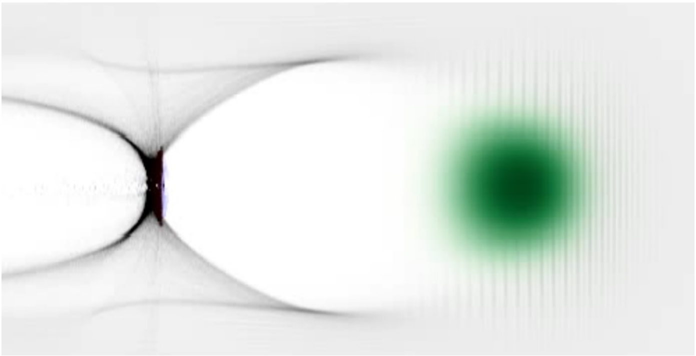
Laser energy scaling $E_L \propto \tau^3 \propto \lambda_p^3$ Electron energy gain $\Delta E \propto \tau^2 \propto \lambda_p^2$

65 fs	→ 30 J	→ 5-10 GeV		PW like
30 fs	→ 1 J	→	100 MeV - 1 GeV	100 TW like
3 fs	→ mJ	→	1-10 MeV	1 TW @ 1 kHz possible !

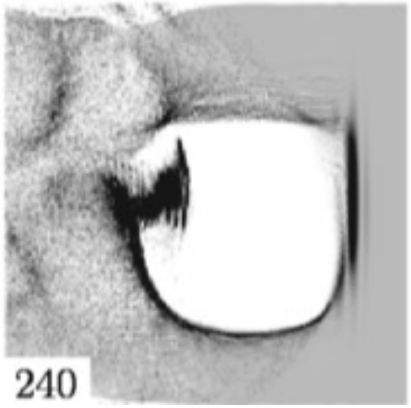
+ single cycle pulses !

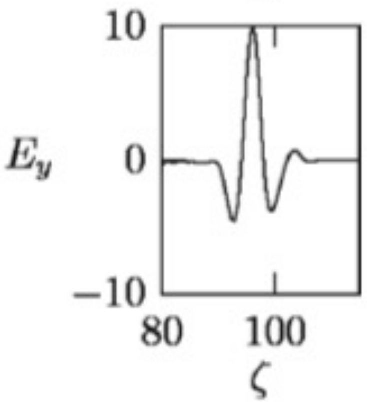
Lu *et al.*, PRSTAB **10**, 0613001 (2007) Beaurepaire et al., NJP **16**, 023023 (2014)

Asymmetric plasma response to single-cycle pulses



For "long" pulses (30 fs):
ponderomotive force is symmetric
→ Symmetric plasma wake





Single cycle pulses (3 fs):
Symmetry is broken in polarization plane
→ Asymmetric plasma response

Nerush & Kostyukov, PRL **103**, 0035001 (2009)

Huijts *et al.*, Phys. Plasmas **28**, 043101 (2021)

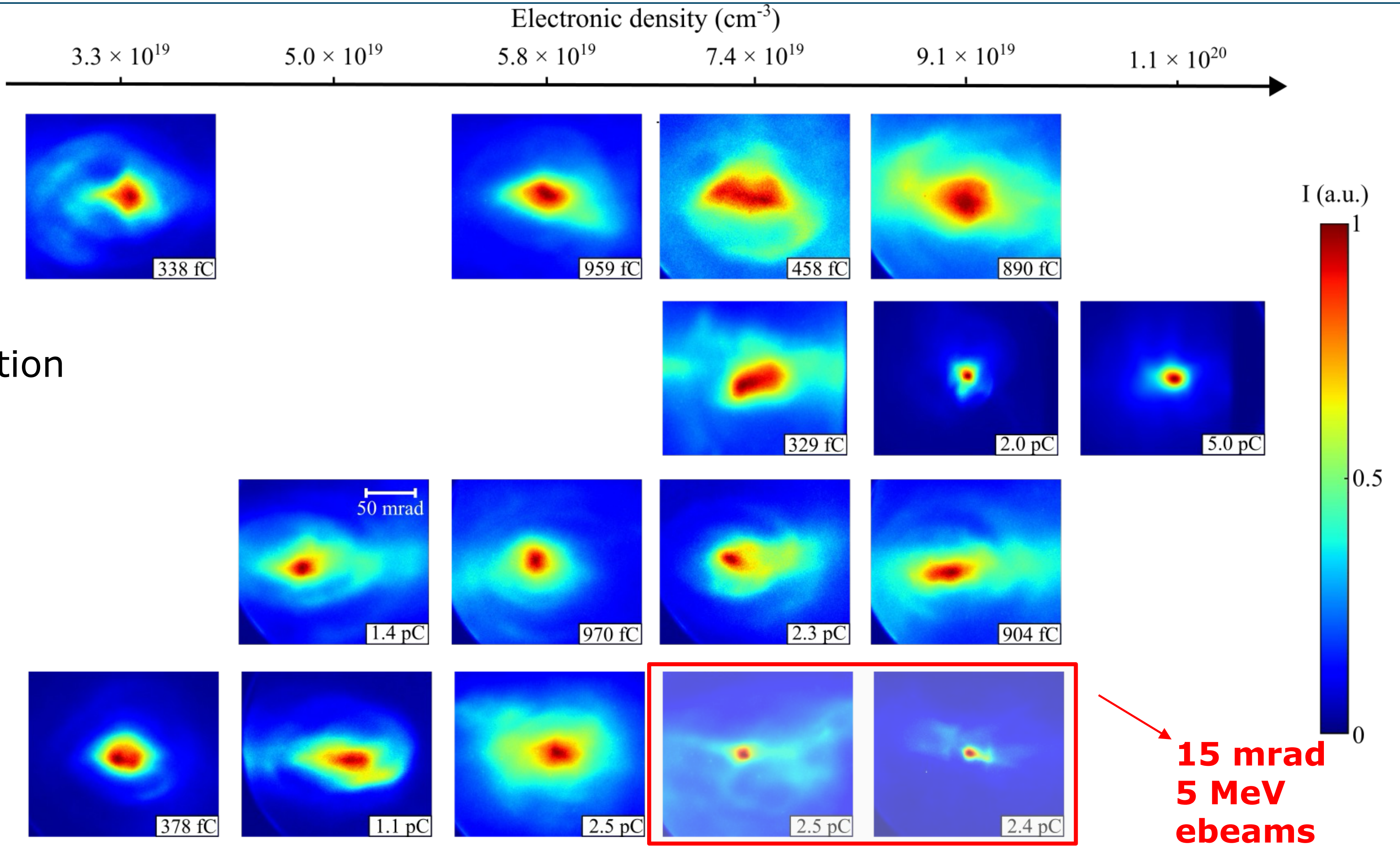
Overall behavior of e-beams in different injection schemes

Self-injection pure H_2

Gradient injection pure H_2

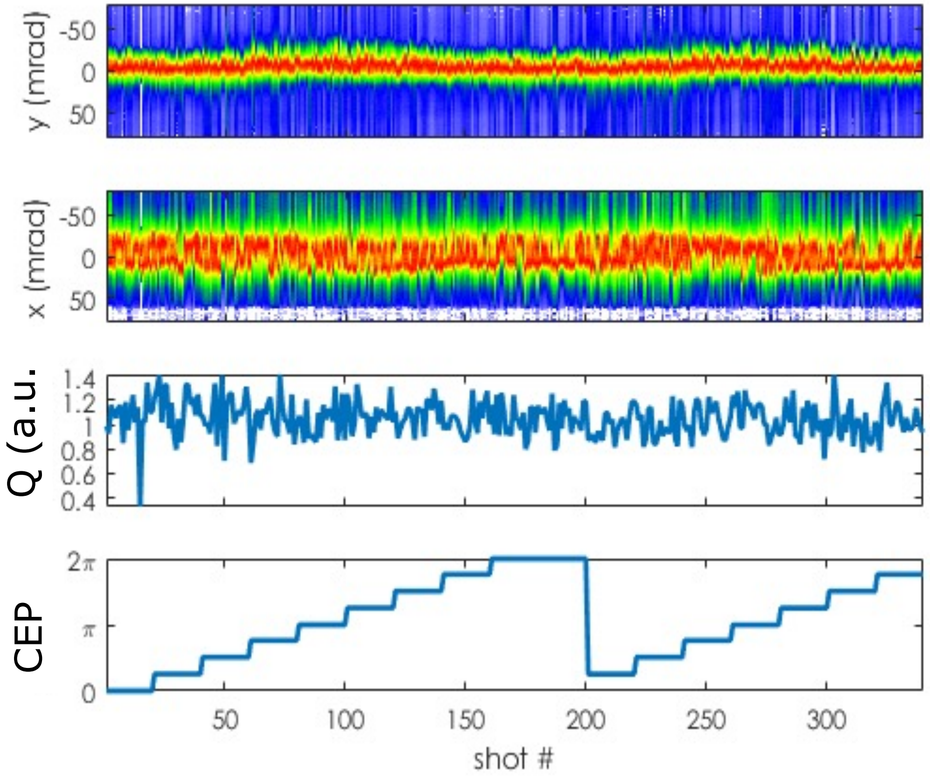
Mixture H_2/N_2 (2%)

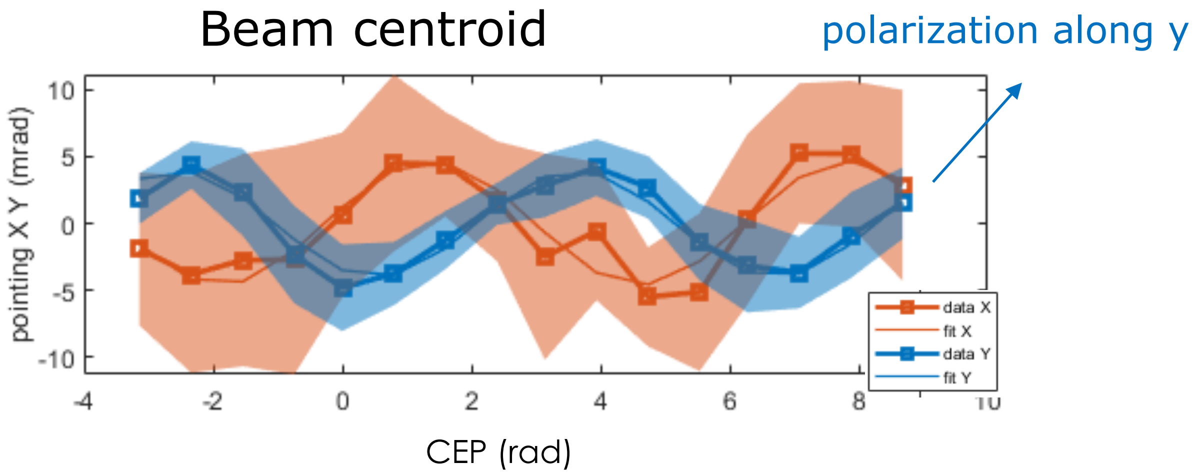
Mixture H_2/CH_4 (2%)



Beam pointing oscillations similar to previous study

CH_4 mixture: 100 bars (7.8×10^{19} cm^{-3})





- Good correlation in polarization direction (y) **Amplitude +/- 5mrad**
- No significant energy changes

→ Comparable to previous off-axis self-injection results