Task 6.3: MILPAT
Multi-scale targets for laser-plasma accelerators

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http://loa.ensta.fr/

The team

kHz laser-plasma accelerator
L. Rovige, J. Monzac, J. Huijts, A. Vernier, I. Andriyash,
J. Faure

Guiding and GeV electron beams
K. Oubrerie, R. Lahaye, S. Smartsev, L. Martelli, A. Leblanc,
J. Gautier, K. Ta Phuoc, O. Kinonenko, I. Andriyash, C. Thaury

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Laser system:
M. Ouillé, J. Kaur, A. Cavana R. Lopez-Martens (1 kHz, 1 TW)
A. Tafzi, J.-P. Goddet (1 Hz, 100 TW)

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

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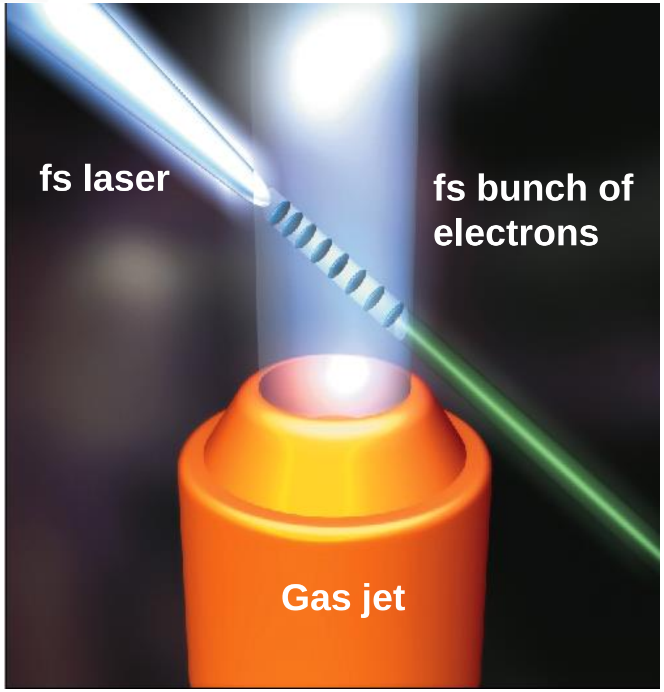
High gradient laser-plasma accelerators



Compact accelerator
100 GV/m

Electron bunch
few fs duration
no jitter with laser

In progress: quality & stability

High-repetition rate frontier

Achieve kHz operation for
Imaging & Medical application

High energy frontier

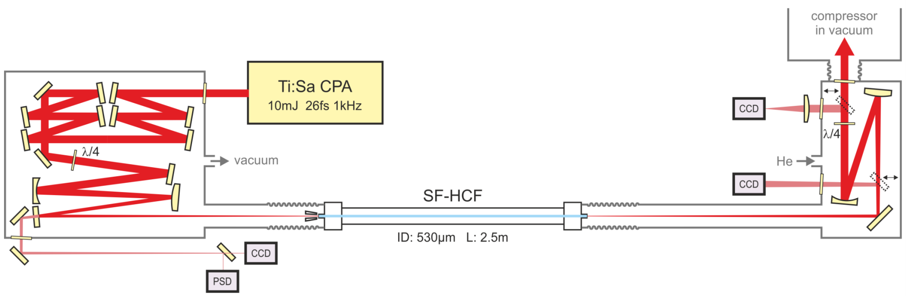
Guiding for multi-GeV beams
FEL light source, HEP

→ Ultimate goal: toward GeV beams at kHz, EUPRAXIA

Multi-scale gas jet targets for LWFA

High-repetition rate frontier

kHz, 3.5 fs, 3 mJ, 1 TW laser



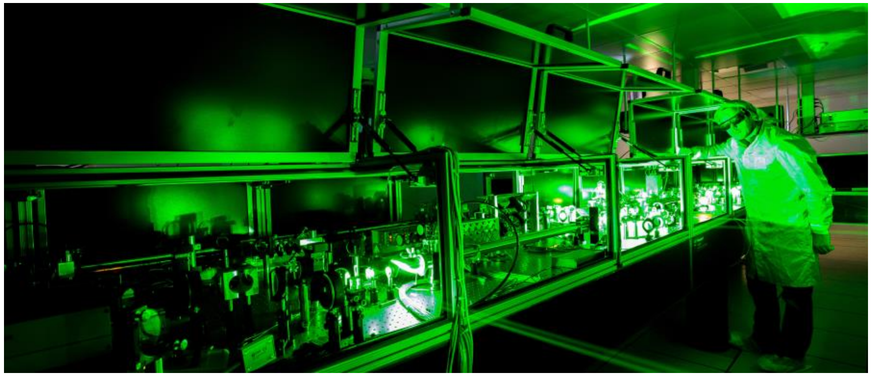
1-10 MeV e-beams @ kHz

Gas jet requirement:

- 100 micron scale
- Structured density for injection
- Resistance to high rep rate operation

High energy frontier

1 Hz, 30 fs, 3 J, 100 TW laser

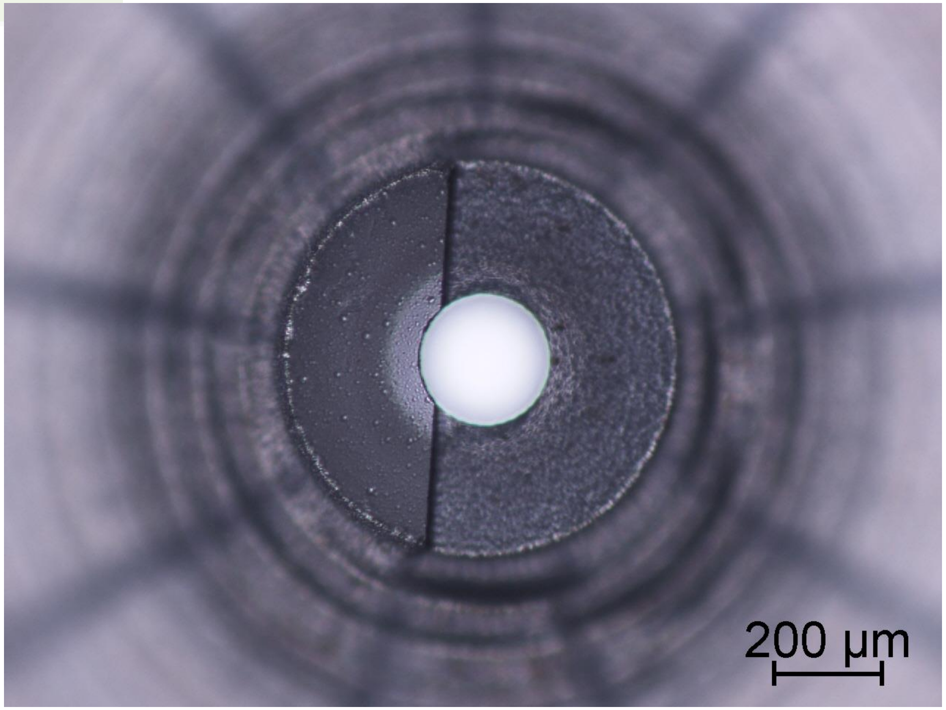


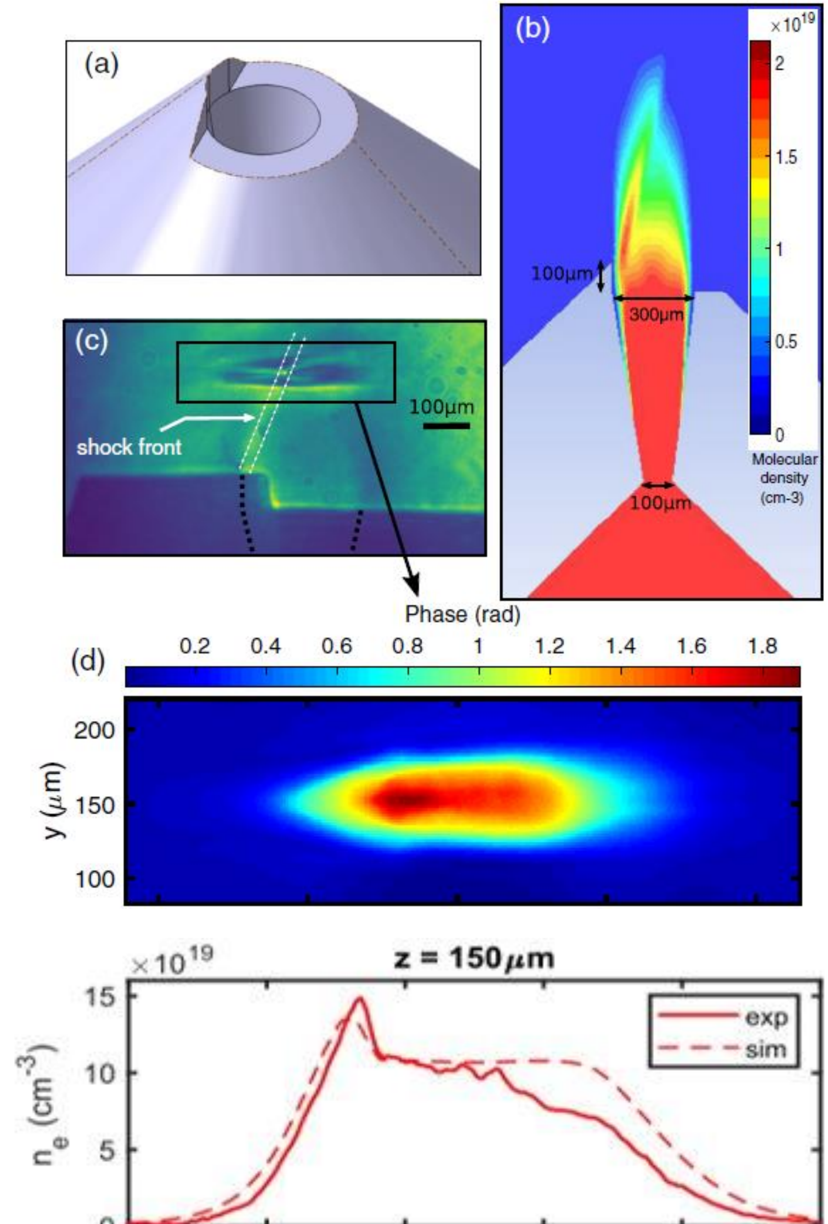
100 MeV- GeV e-beams @ 0.1 Hz

Gas jet requirement:

- Centimeter scale
- Structured density for injection
- Resistance to high energy operation

One-sided shocked micro-nozzle for kHz operation



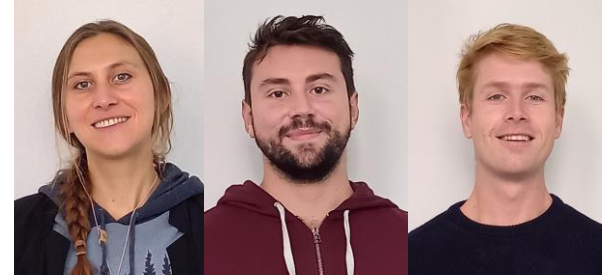


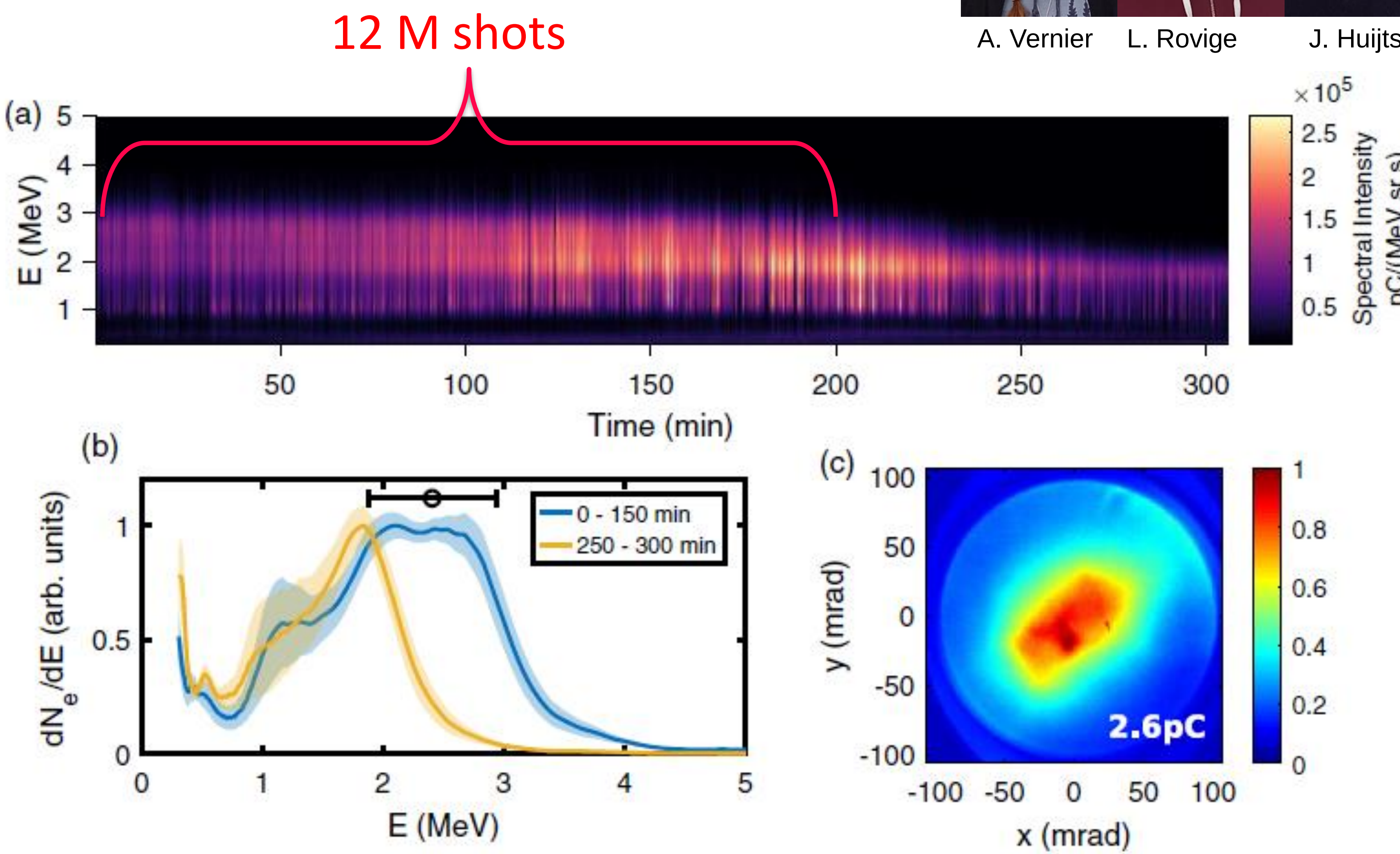
Glass nozzles have higher damage threshold compared to metal one

The shock stabilizes injection

FLSE technique: V. Tomkus et al. Opt. Express **26,** 27965 (2018)
L. Rovige et al., RSI **92**, 083302 (2021)

5-Hour Hands-Off Operation





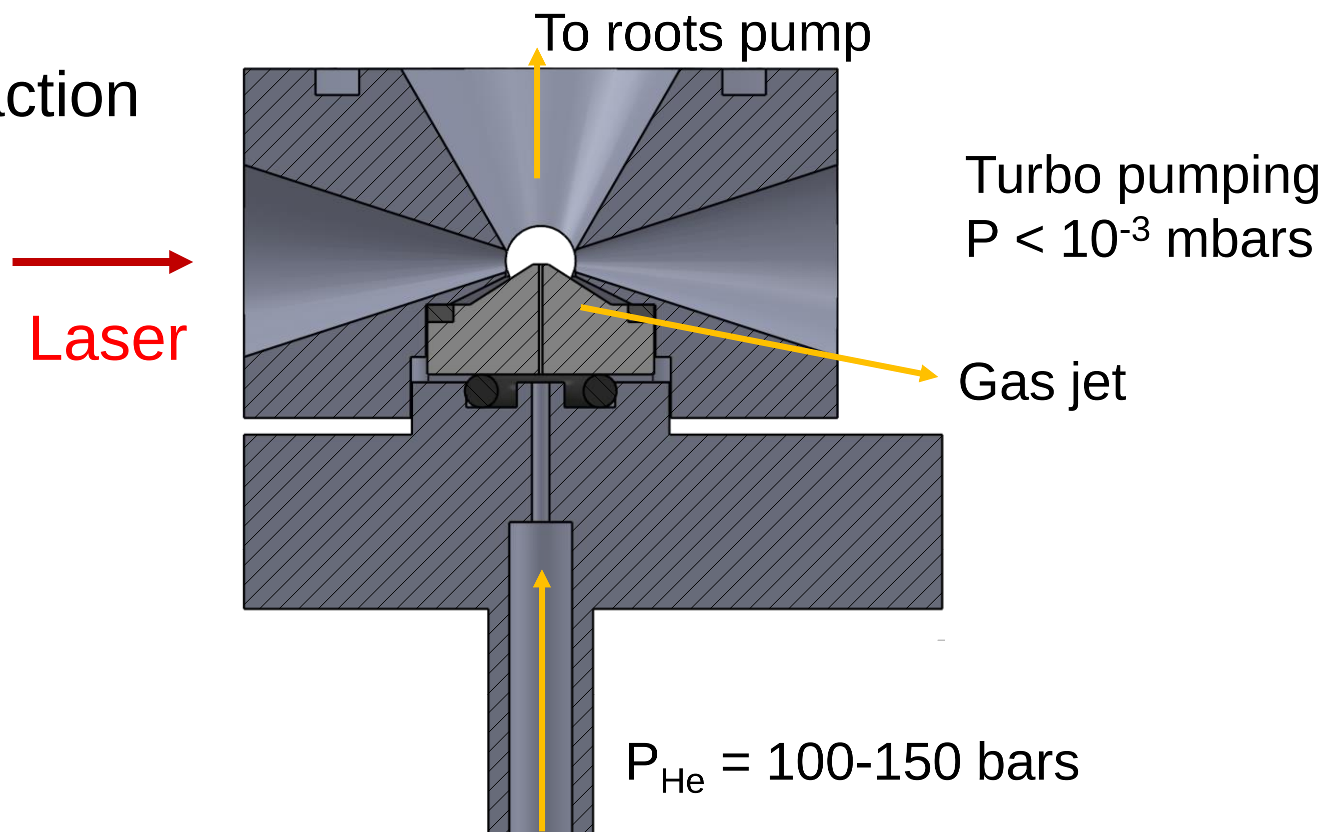
L. Rovige et al., PRAB **23**, 093401 (2020). Similar stability in Maier et al, PRX **10**, 031039 (2020)

Differential pumping for using lighter gases

N_2 provides 10 electrons → operation at 20 - 30 bars backing pressure
The problem with Nitrogen: ionization induced defocusing

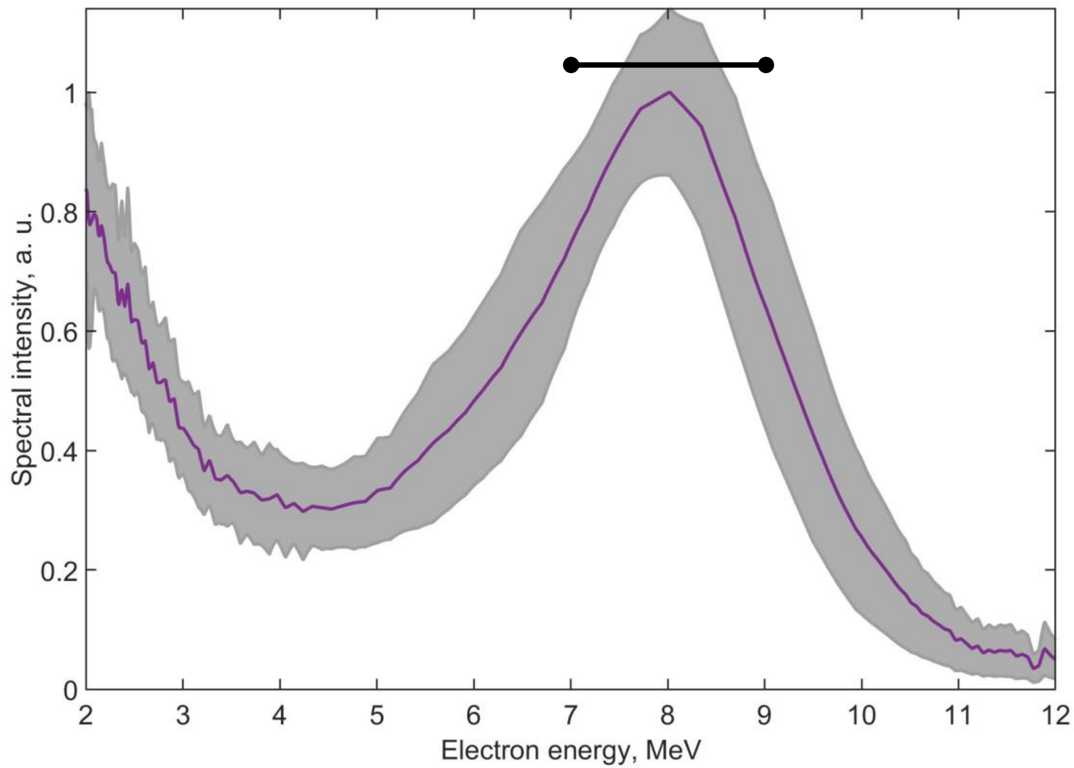
He or H_2 only provides 2 electrons → requires 100 - 150 bars: challenging

Miniature interaction chamber

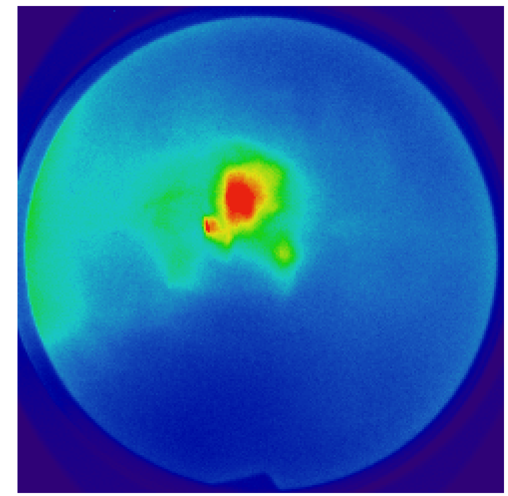


Higher energy acceleration in Helium now possible

Electron spectrum in He plasma



Beam profile
averaged over 30 shots

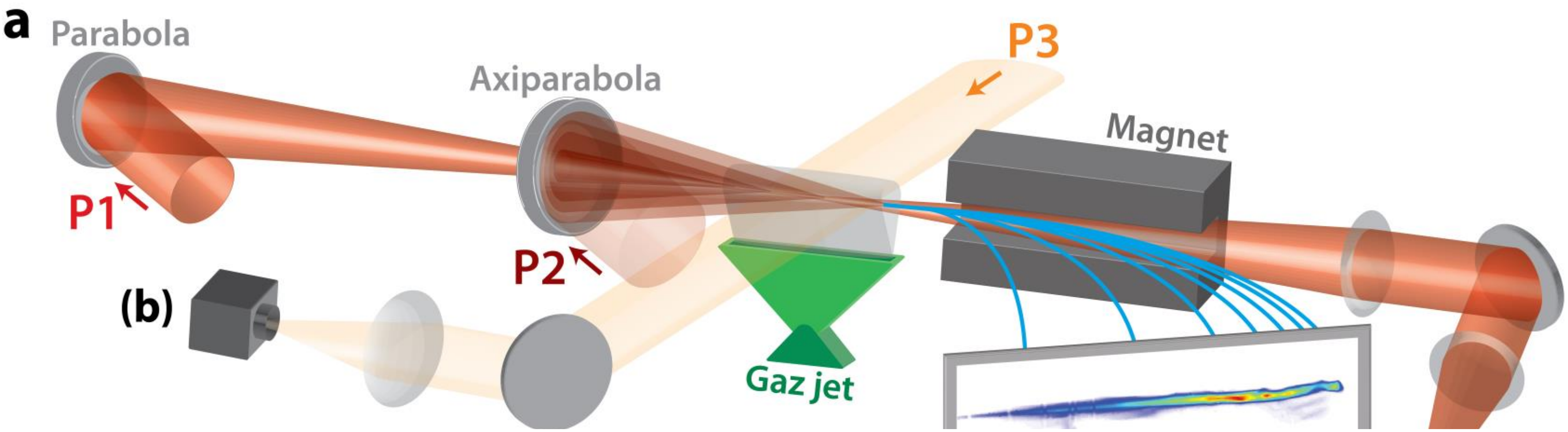


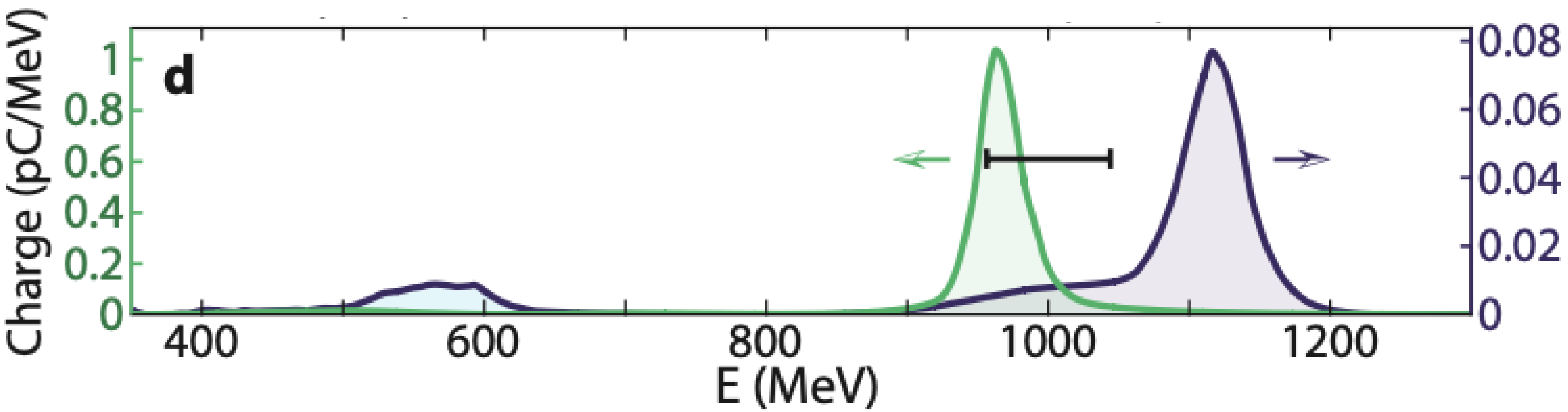
20 mrad FWHM
1.3 pC/shot

Acceleration in H_2 pending: > 10 MeV expected* & running at kHz

* see F. Salehi *et al*, PRX **11**, 021055 (2021)

GeV beams using a guided 50 TW laser (C. Thaury)



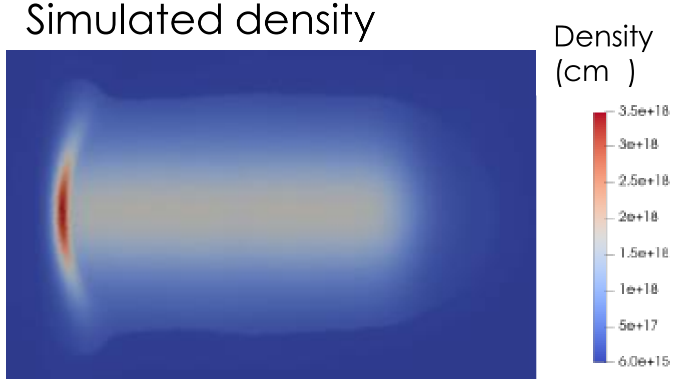


→ Demonstrated using shock injection

Accepted in Light Science & Applications (2022)

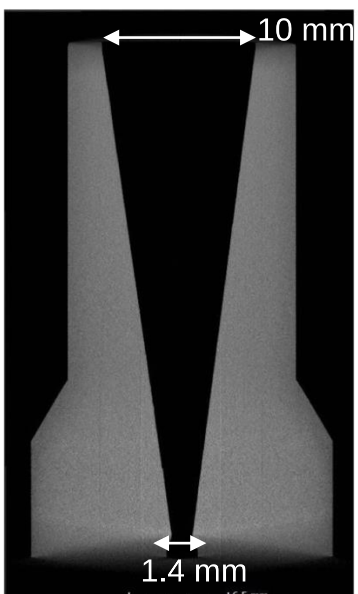
10 mm slit shocked nozzles for injection & guiding

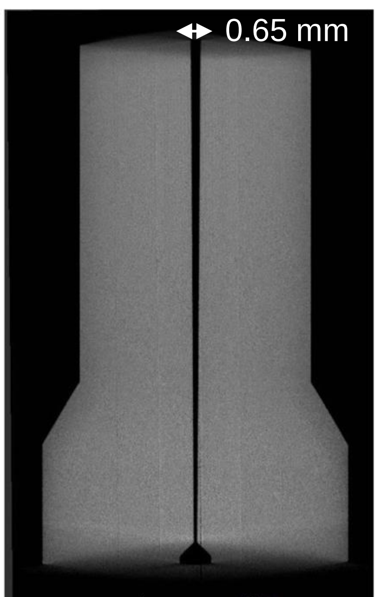
Simulated density



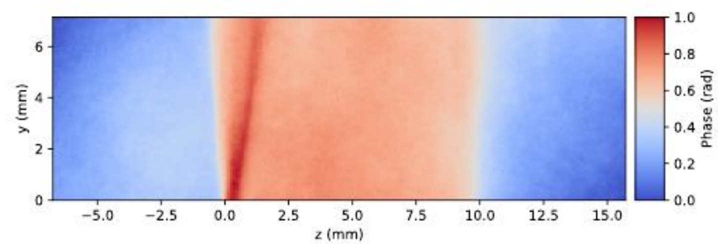
Still in progress

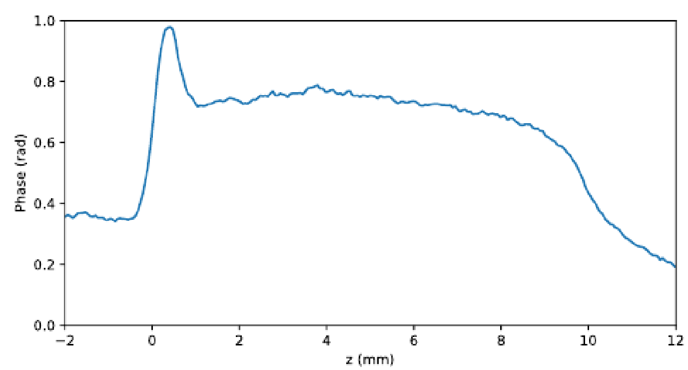
→ Shock not large enough for injection
→ Quick damage





Measured phase map





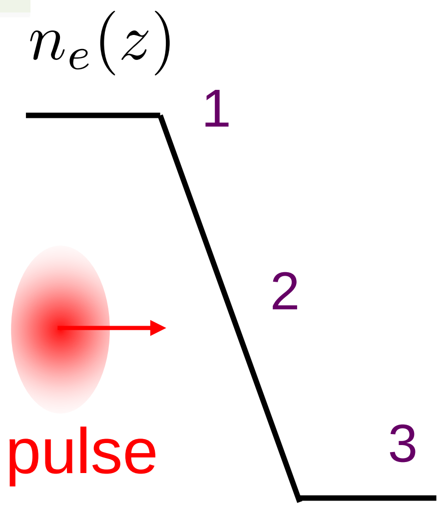
Conclusions

- **Micron-scale glass nozzles very successful:**
  - Injection in one sided shocked nozzles
  - Long term operation at kHz
- **Centimeter scale glass nozzles still in progress**
  - Promising but better design needed
- **Next: investigate new nozzle concepts…**
- **Investigate the robustness and durability of jets** for 100 W scale laser systems at 100 Hz – 1 kHz

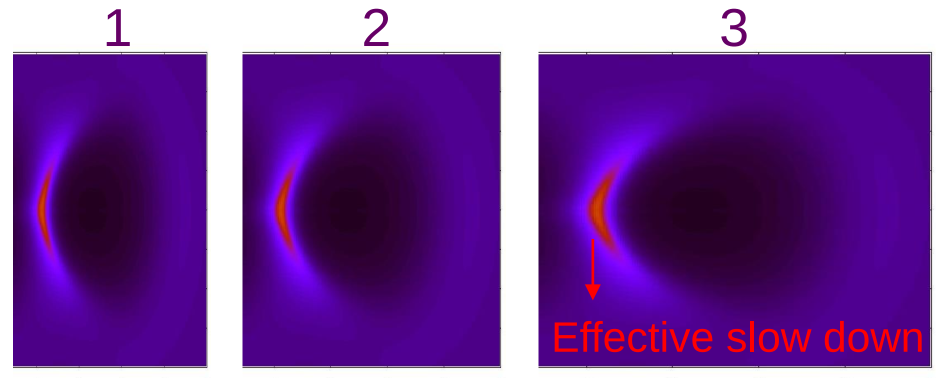
→ Recent application to CREATE funding on this topic with IJCLAB, France (gas cell targets) and DESY (capillary discharge targets)

EXTRAS

Structured density for downramp injection

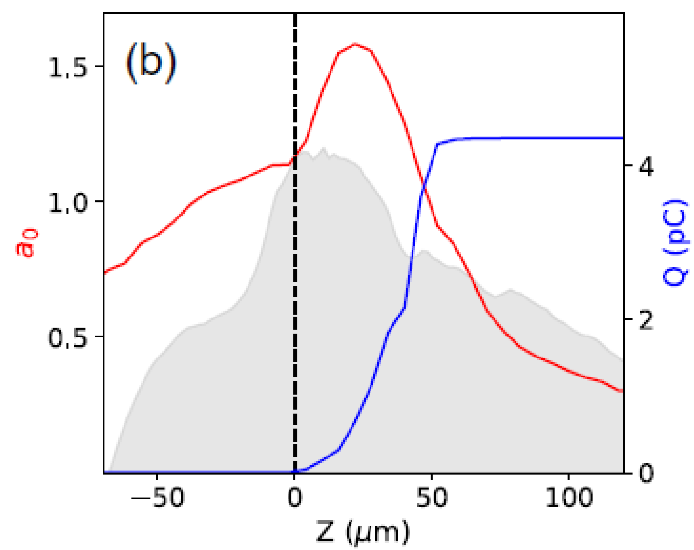


$$\lambda_p(z) \propto 1/\sqrt{n_e(z)}$$



The idea: slowing down the accelerating structure

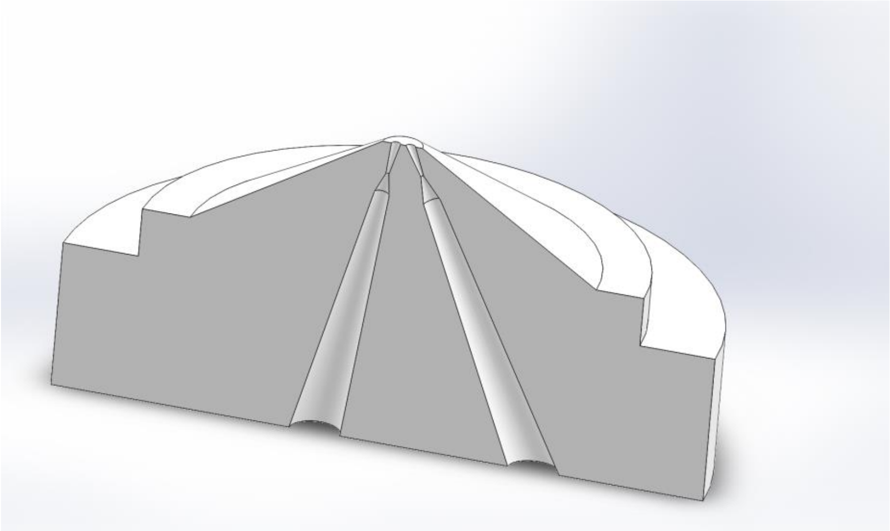
Simulations confirm that electrons are injected in the gradient

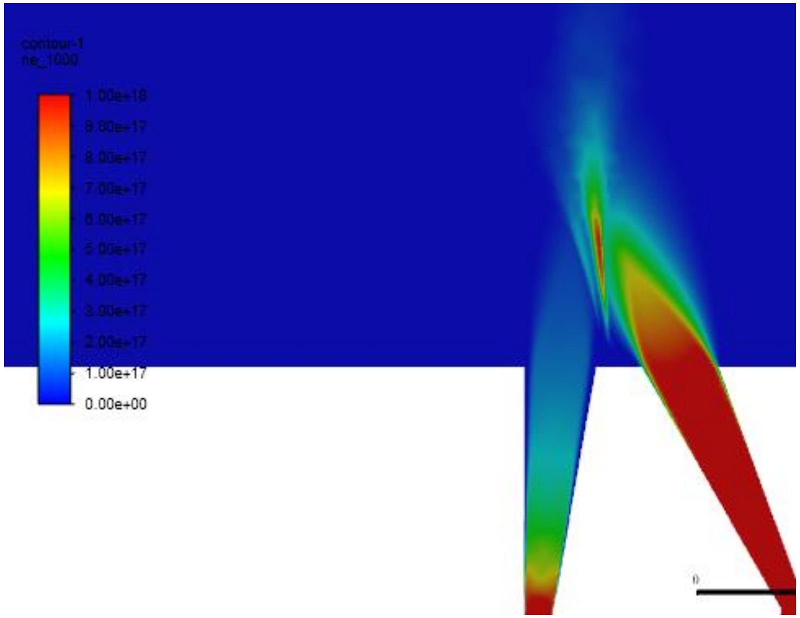


L. Rovige et al., PRAB **23**, 093401 (2020)

Novel jet concepts: double jet

- Advantage: two independently controllable gas inlets
- Current problem: a shard density spike at the transition between the flows





Related publications:

"Controlled acceleration of GeV electron beams in an all-optical plasma waveguide"; K. Oubrerie, A. Leblanc, O. Kononenko et al., accepted in Light Science and Applications (2022)

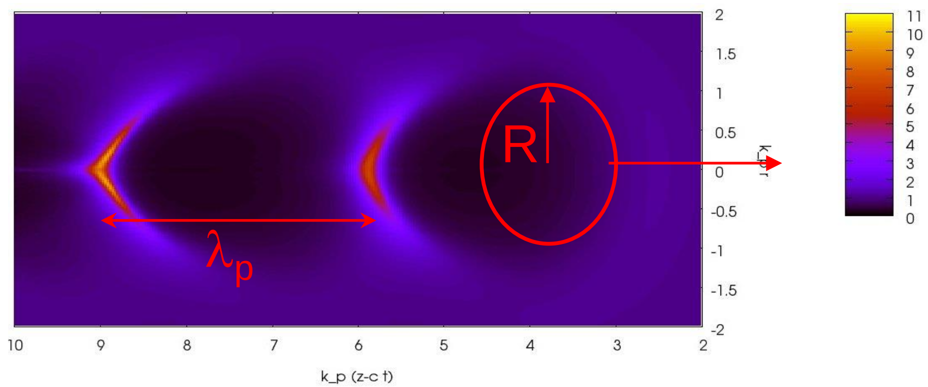
"Waveform control of relativistic electron dynamics in laser-plasma acceleration"; J. Huijts, L. Rovige, I.A. Andriyash et al., Phys. Rev. X **12**, 01136 (2022)

"Symmetric and asymmetric shocked gas jets for laser-plasma experiments"; L. Rovige, J. Huijts, A. Vernier et al., Rev. Sci. Inst. **92**, 083302 (2021)

"Optimization and stabilization of a kilohertz laser-plasma accelerator"; L. Rovige, J. Huijts, I.A. Andriyash et al., Phys. Plasmas **28**, 033105 (2021)

"Demonstration of stable long-term operation of a kilohertz laser-plasma accelerator"; L. Rovige, J. Huijts, I. Andriyash et al., Phys. Rev. Acc. & Beams 23, 093401 (2020)

Scaling laws and kHz lasers: resonance condition



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 $\Delta E \propto \tau^2 \propto \lambda_p^2$

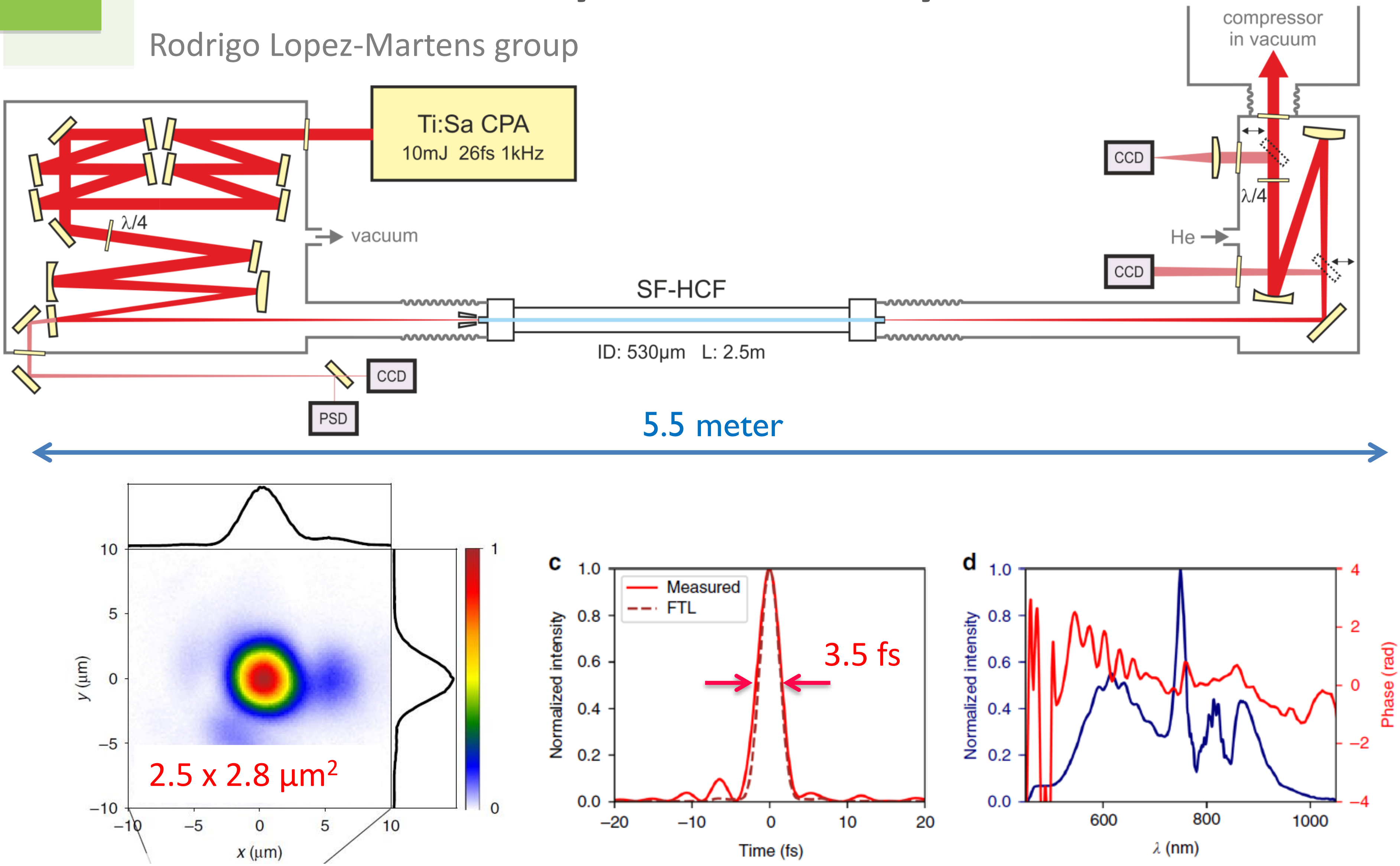
30 fs → 1 J → 100 MeV - 1 GeV @ 1 kHz: BRUTE FORCE method

3 fs → mJ → 1-10 MeV @ 1 kHz DELICATE method

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

1 TeraWatt few-cycle kHz laser system

Rodrigo Lopez-Martens group

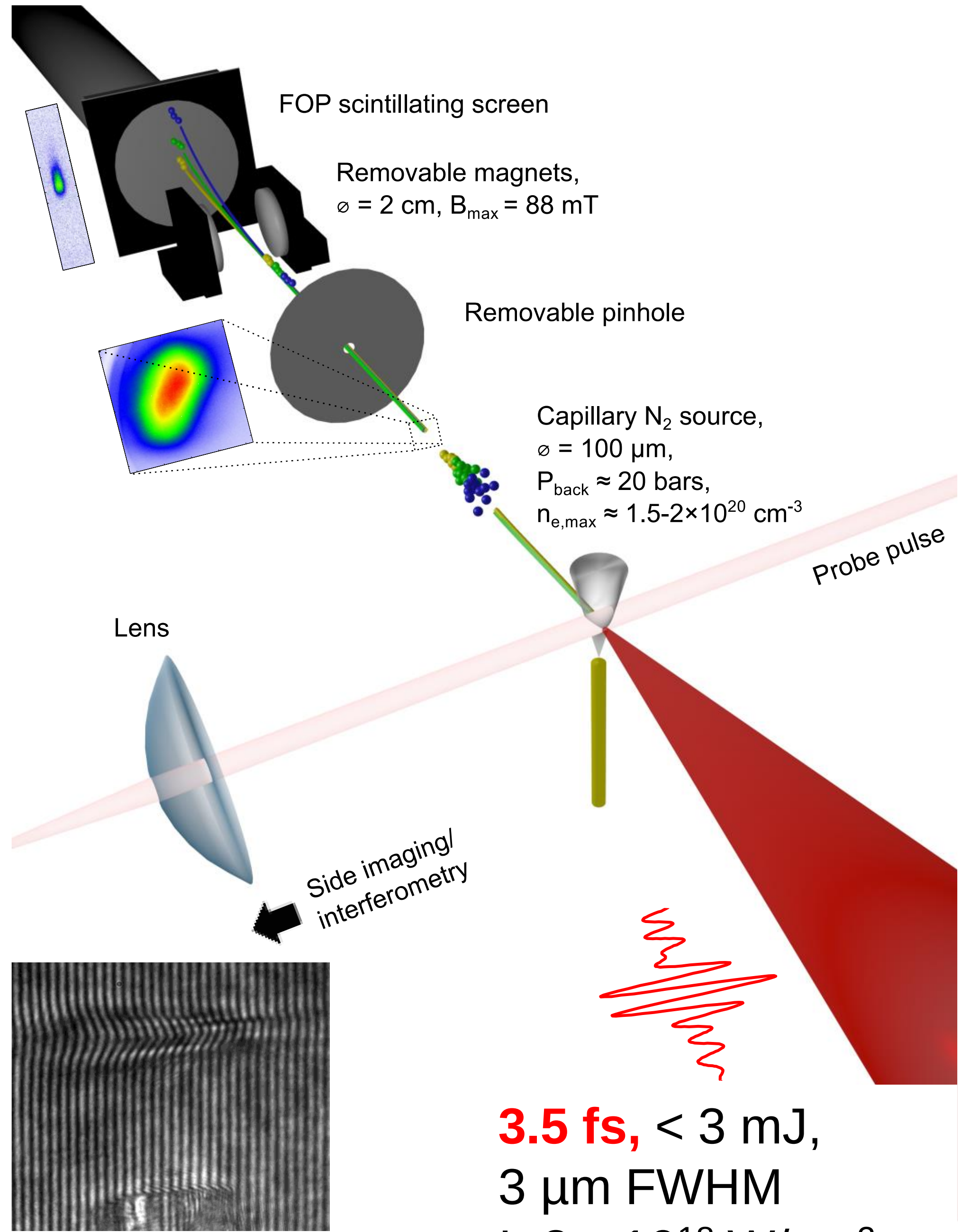


M. Ouillé et al., Light: Science & Applications, **9**, 47 (2020)
F. Böhle et al., Laser Physics Letters, **11**, 9 (2014)

Experimental set-up

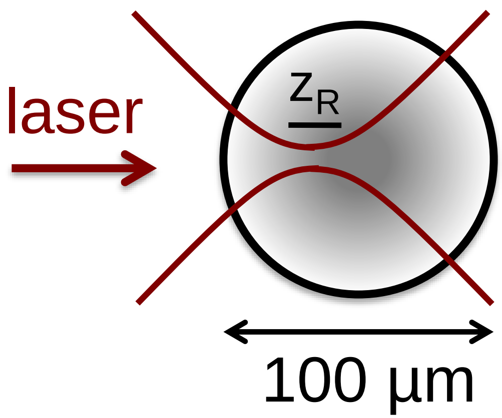
Gas target is a continuously flowing capillary N_2 gas jet

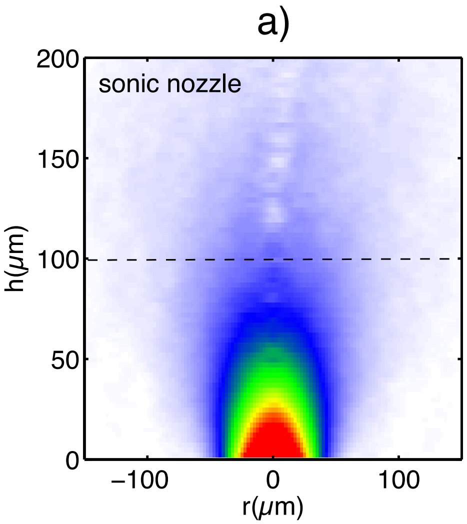
→ kHz operation !



3.5 fs, < 3 mJ,
3 µm FWHM
I=3 × 10^{18} W/cm^2

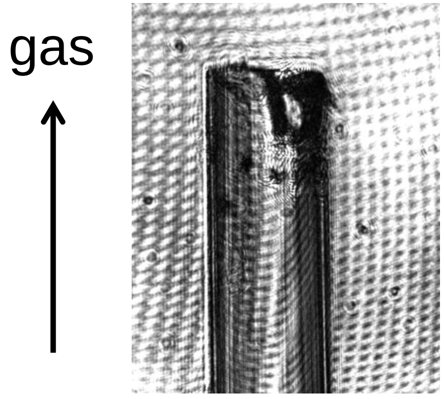
Microscale accelerator: complex regime





High density: > 10^{20} cm^{-3}

Rayleigh length: 50 µm
Depletion length: < 50 µm
Acceleration length: 20 µm



Glass capillary

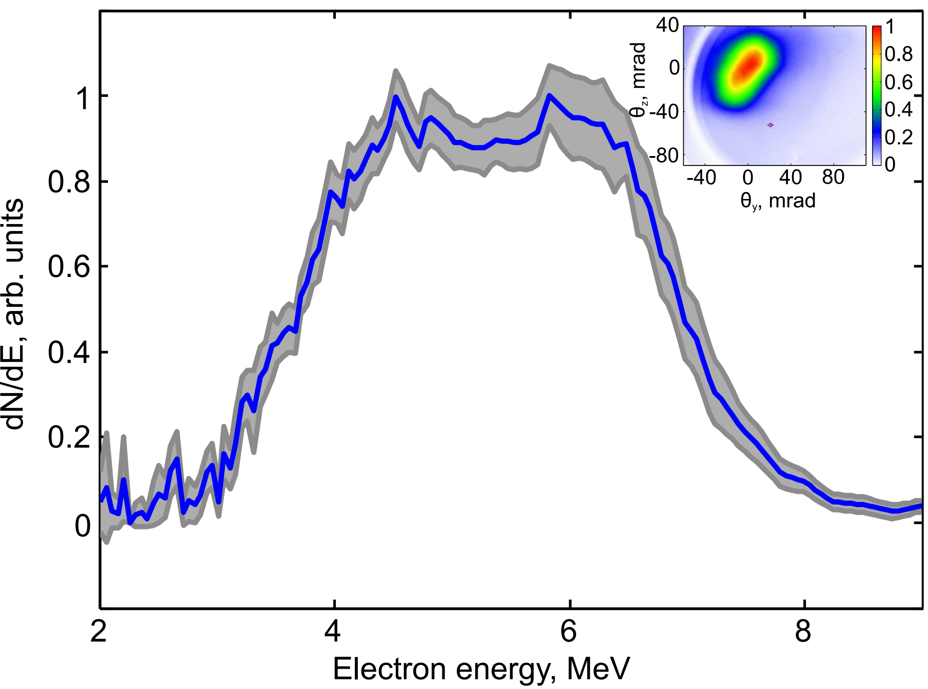
Supersonic jet

D. Gustas et al., PRAB 21, 013401 (2018)

MeV beams at kHz repetition rate

With subsonic jet

$n_e = 10^{20}$ cm^{-3}, $I = 3 \times 10^{18}$ W/cm^2



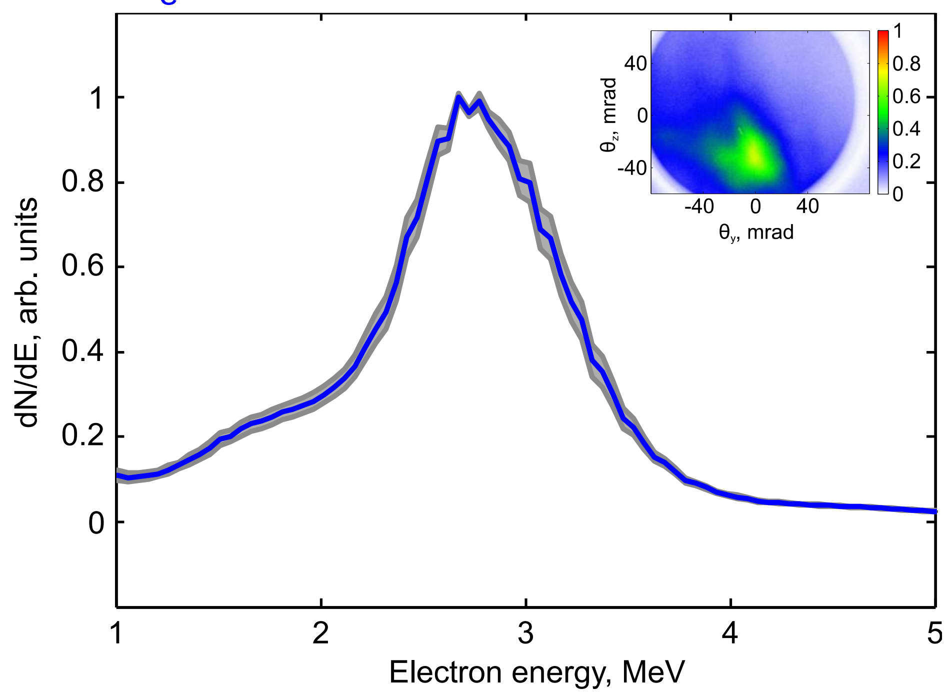
~40 mrad divergence

~100 fC - 1 pC, 30% rms fluc

Guénot et al., Nat. Phot. **11**, 293 (2017)

With supersonic jet

$n_e = 1\text{-}2 \times 10^{20}$ cm^{-3}, $I = 5 \times 10^{18}$ W/cm^2

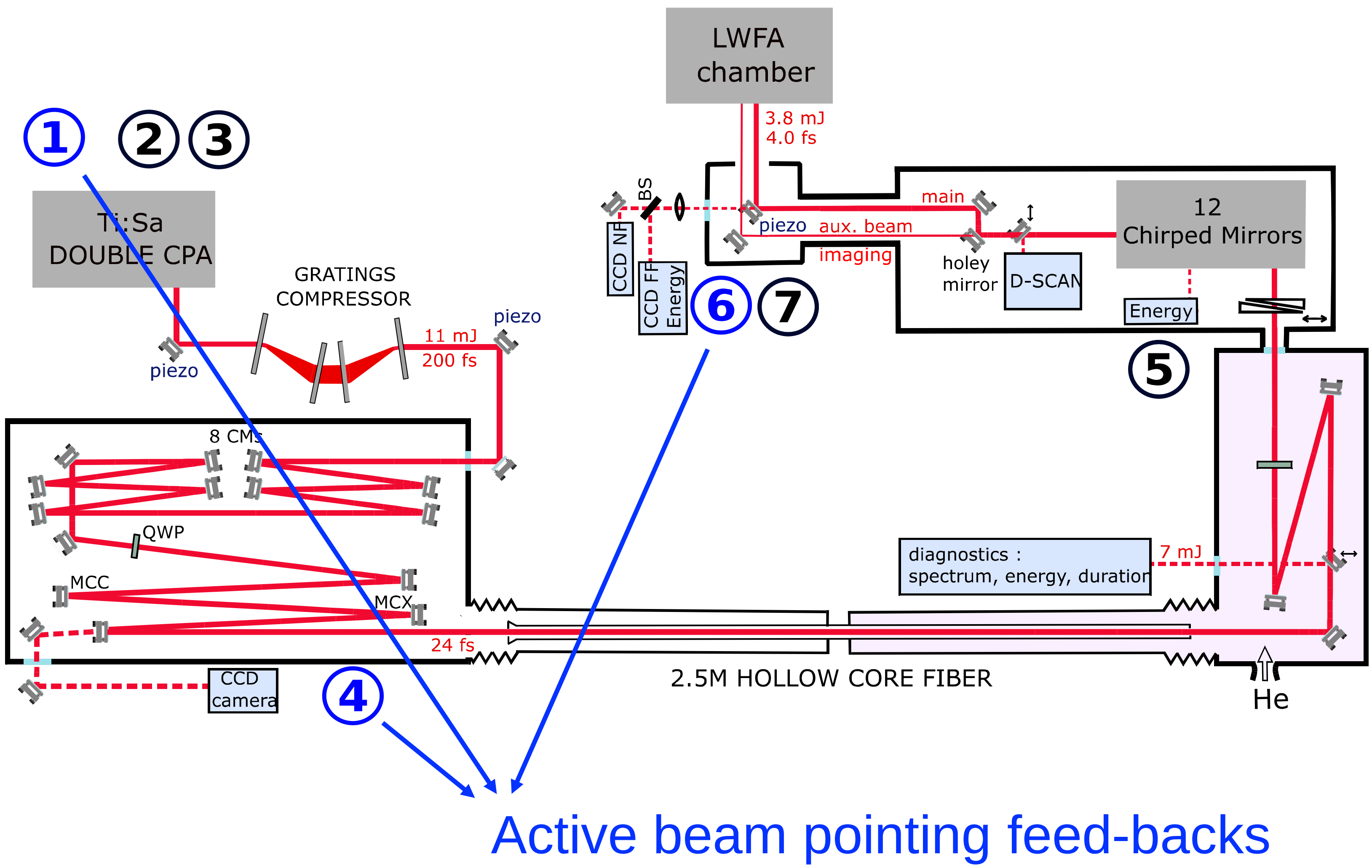


100 times more charge

~20 pC, 10% rms fluc

D. Gustas et al., PRAB 21, 013401 (2018)

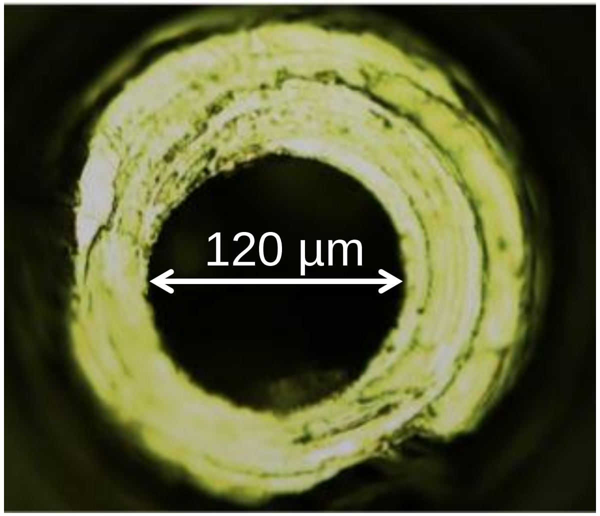
Laser feed-backs and diagnostics



+ many near/far fields measurements / energy meters…

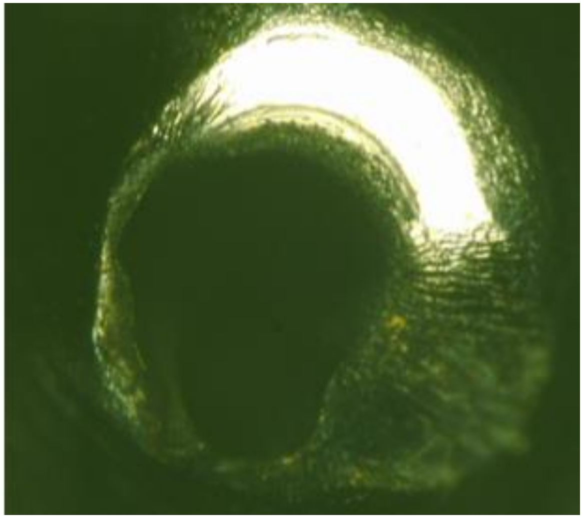
The challenge of long term stability
Micro-nozzle damage @ kHz

Before experiment



Top view of jet

After 7 days, 4-6 hours/day @ kHz



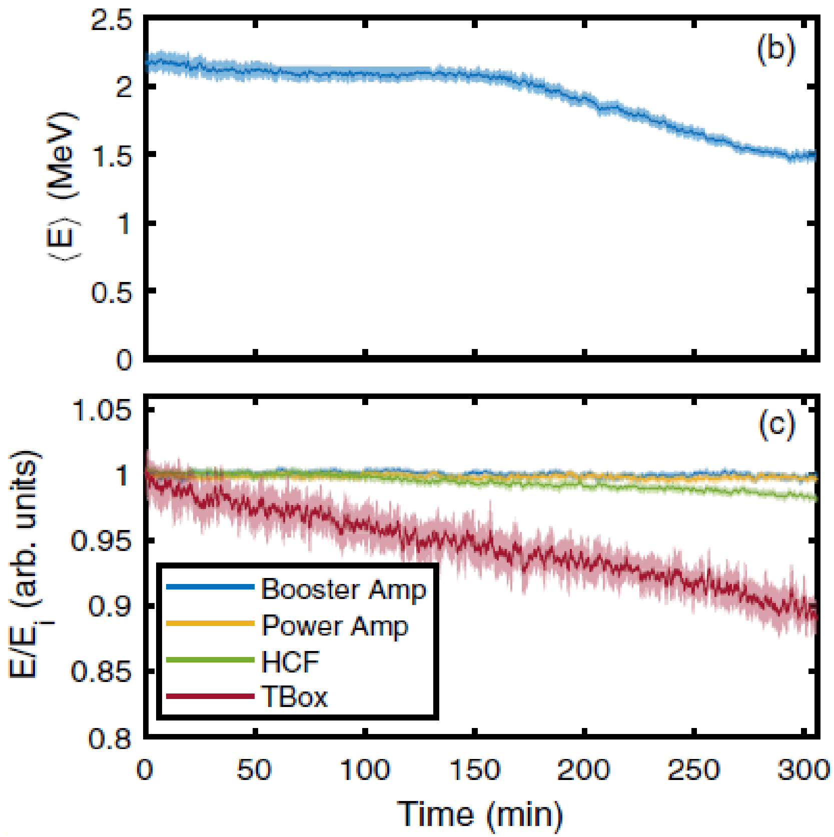
Damaged orifice

Shooting at less than 150 µm causes rapid damage

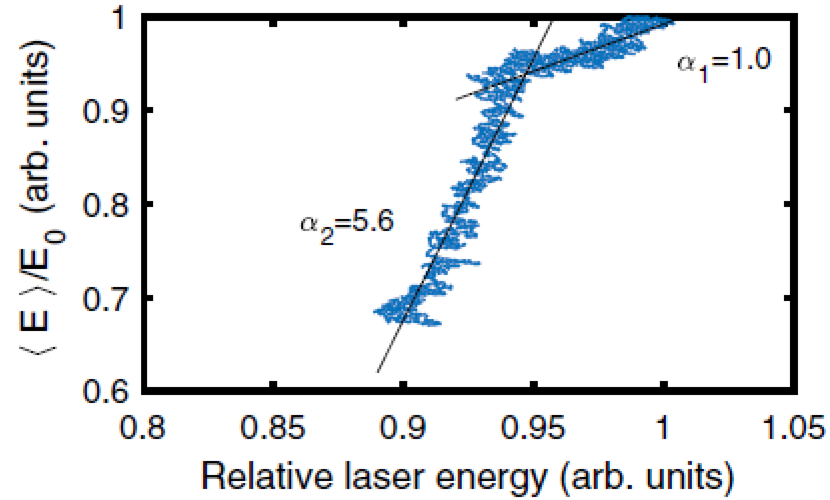
Slow damage causes evolution of the beam on minutes/hour scale

5-Hour Hands-Off Operation

Decrease probably due to a slowly appearing damage on a mirror in compressor



correlation

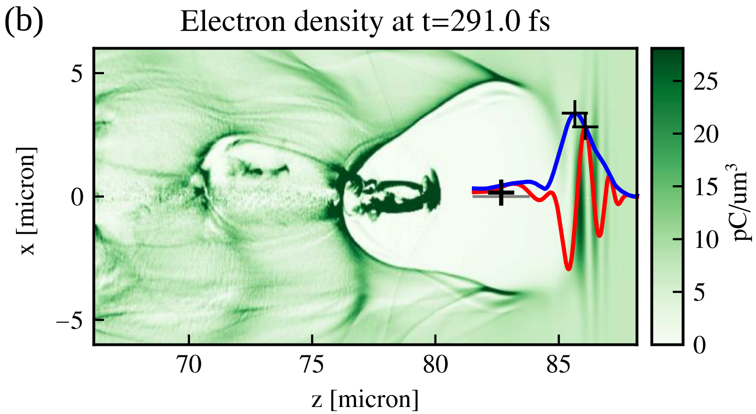


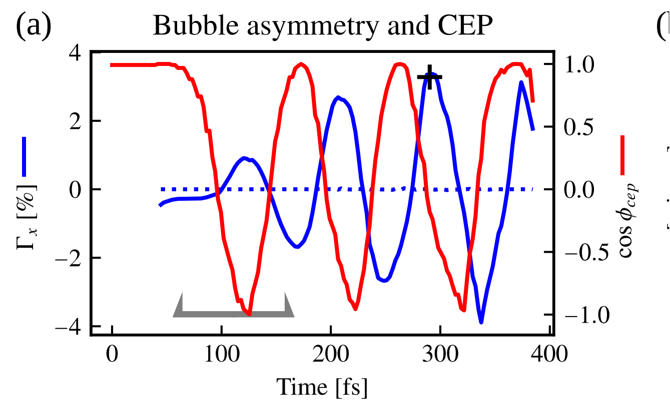
→ Stable operation for multiple hours possible using the shocked jets

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

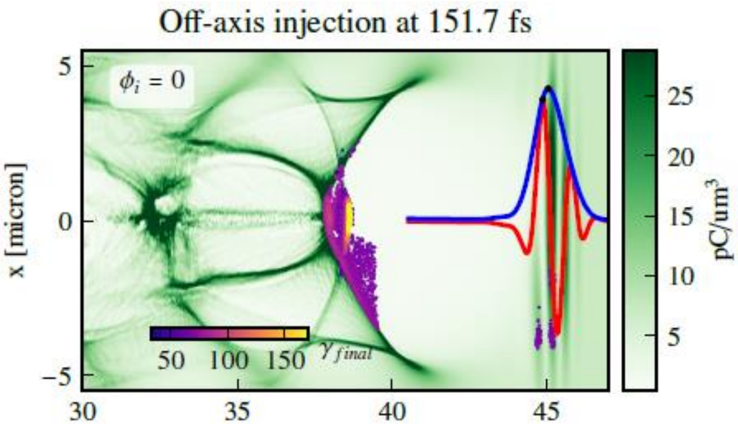
Other possible reasons of CEP dependent pointing

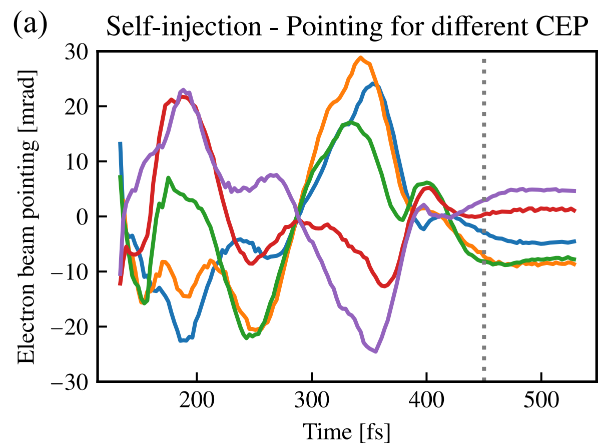
Few cycle pulse → asymetric bubble





→ Asymetric / off-axis injection

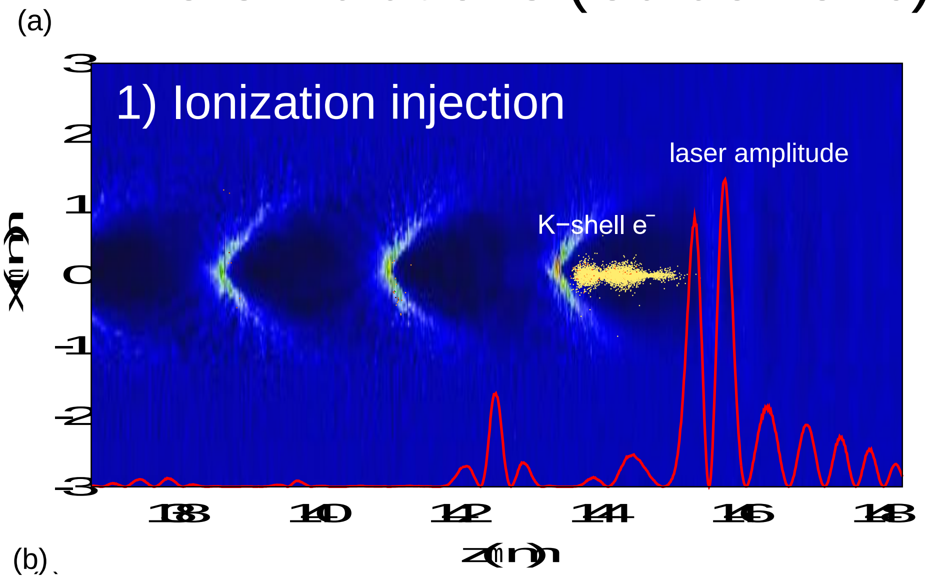




Nerush & Kostyokov, PRL 103, 035001 (2009)
J. Huijts et al. arXiv:2006.10566 (2020)

Different injection processes

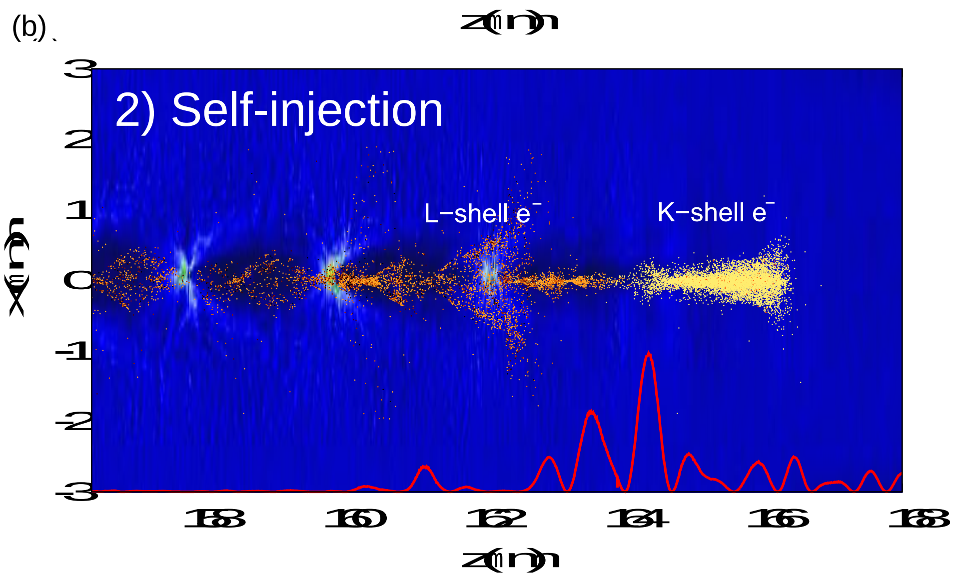
PIC simulations (Calder-Circ)



« low density » operation (subsonic jet)

$n_e = 10^{20}$ cm^{-3}

→ 5-7 MeV
→ <1 pC
→ 1 bucket: fs bunch



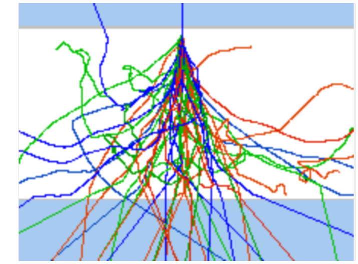
« high density » operation (supersonic jet)

$n_e > 1.5 \times 10^{20}$ cm^{-3}

→ 2-3 MeV
→ 20 pC
→ several buckets : longer electron bunches

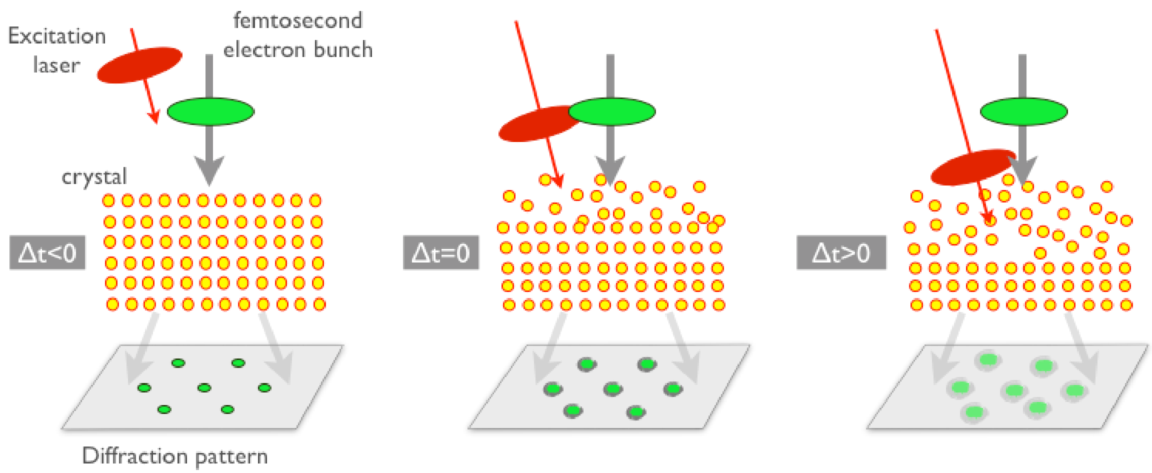
J. Faure et al., PPCF **61**, 14012 (2018)

"Low energy" applications

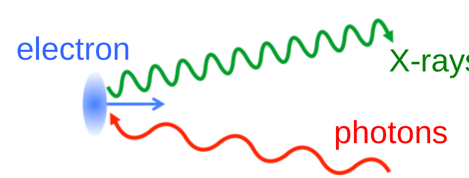


- **Electrons as a pump** for femtosecond irradiation:
  pulsed radiolysis (Muroya, Rad. Phys. Chem. 2008)
  radiobiology, radiation hardness

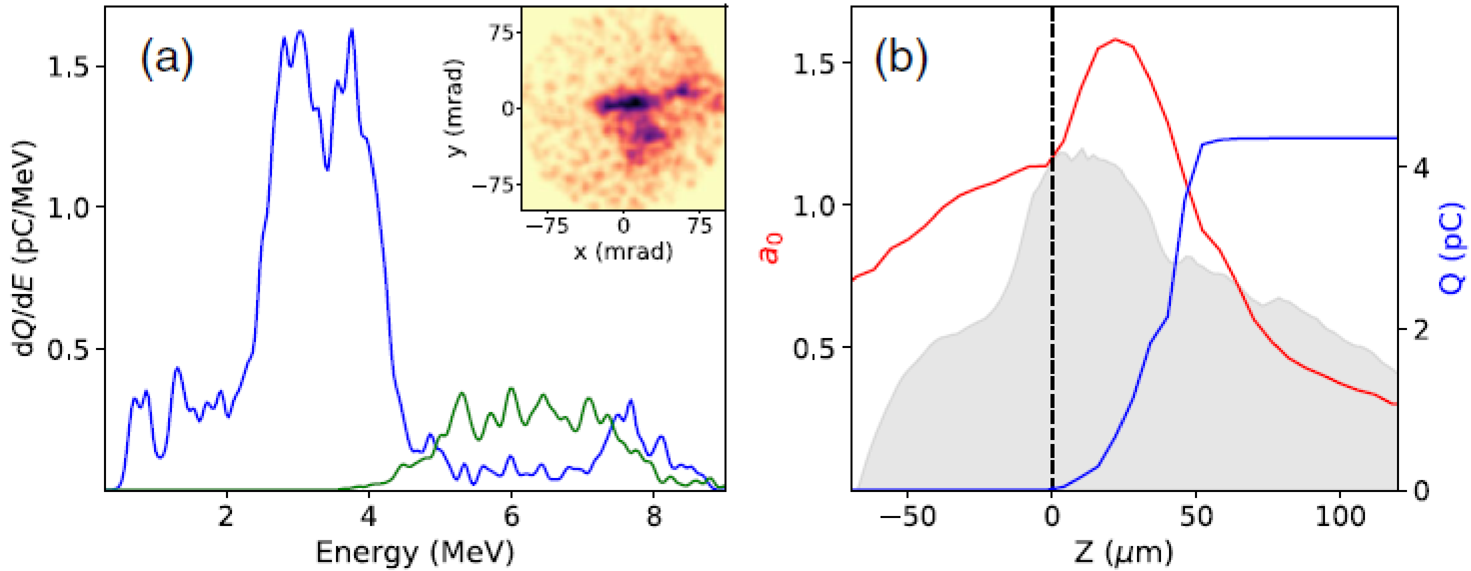
- **Electrons as a probe:** ultrafast electron diffraction for watching atomic motion in real time in complex materials
  (Mourou & Williamson, APL 41, 44 (1982), Miller, Science 343, 1108 (2014))



- **Electrons for driving a fs X-ray source @ kHz:**
  20 MeV electrons → 10 keV X-ray via Compton scatt.
  (Ta Phuoc, Nat. Phot. 2012)

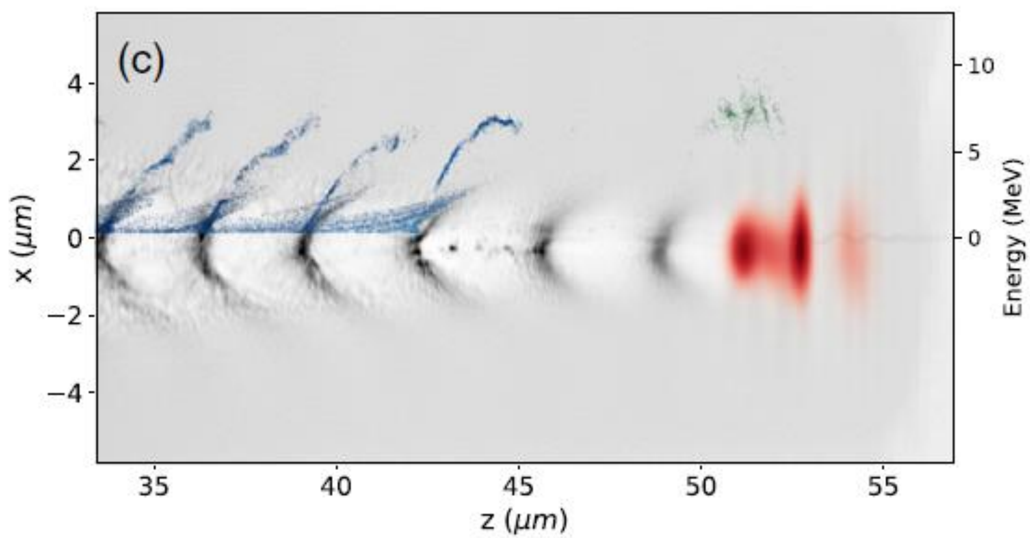


PIC simulation: gradient injection dominates

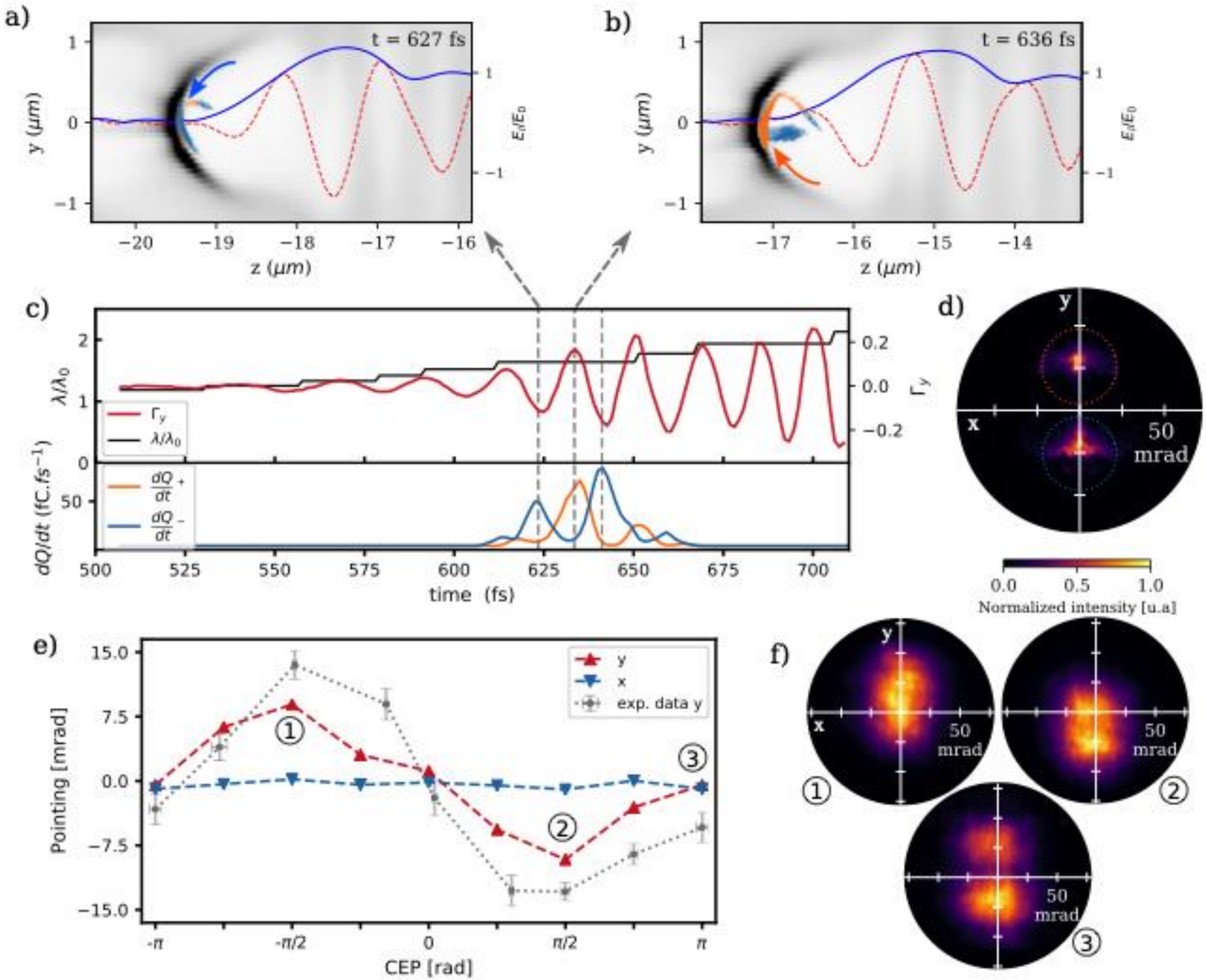


Density-gradient injection

(and some ionization injection)



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



a)
t = 627 fs
y (μm)
z (μm)
E_l/E_0
b)
t = 636 fs
c)
λ/λ_0
Γ_y
dQ/dt (fC.fs^{-1})
$\frac{dQ}{dt}_+$
$\frac{dQ}{dt}_-$
time (fs)
d)
y
x
50 mrad
Normalized intensity [u.a]
e)
Pointing [mrad]
CEP [rad]
y
x
exp. data y
①
②
③
f)