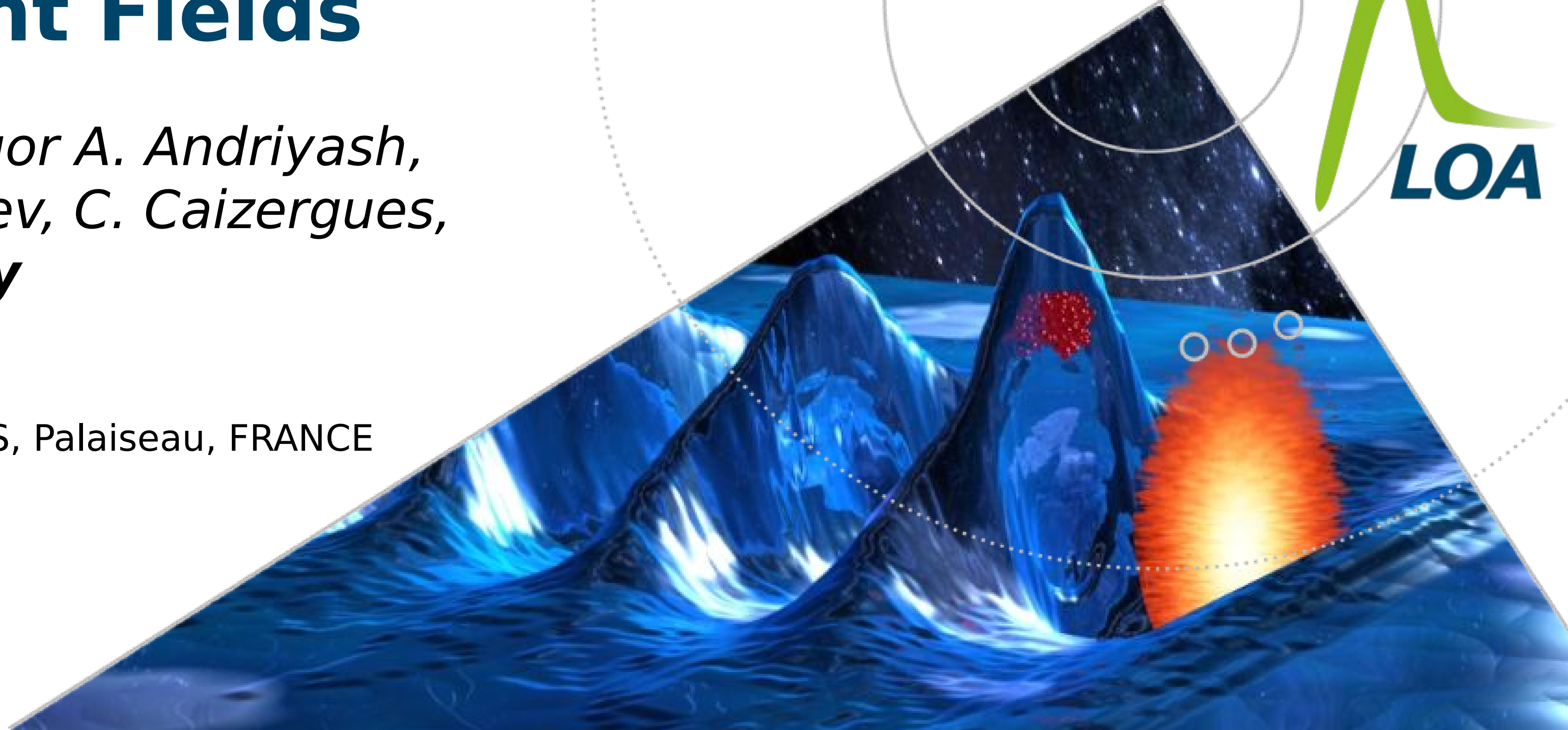
Overcoming the Limitations of Laser-Wakefield Acceleration with Structured Light Fields

*R. Lahaye, K. Oubrerie, Igor A. Andriyash, O. Kononenko, S. Smartsev, C. Caizergues, A. Leblanc and **C. Thaury***

Laboratoire d'Optique Appliquée,
Institut Polytechnique de Paris, CNRS, Palaiseau, FRANCE



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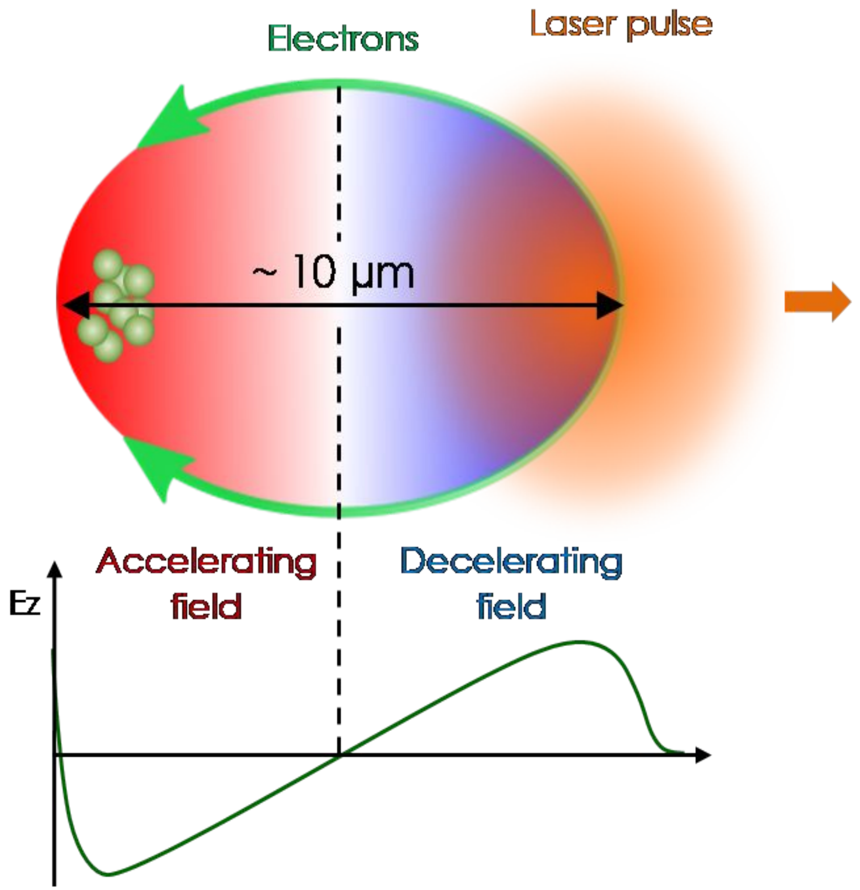
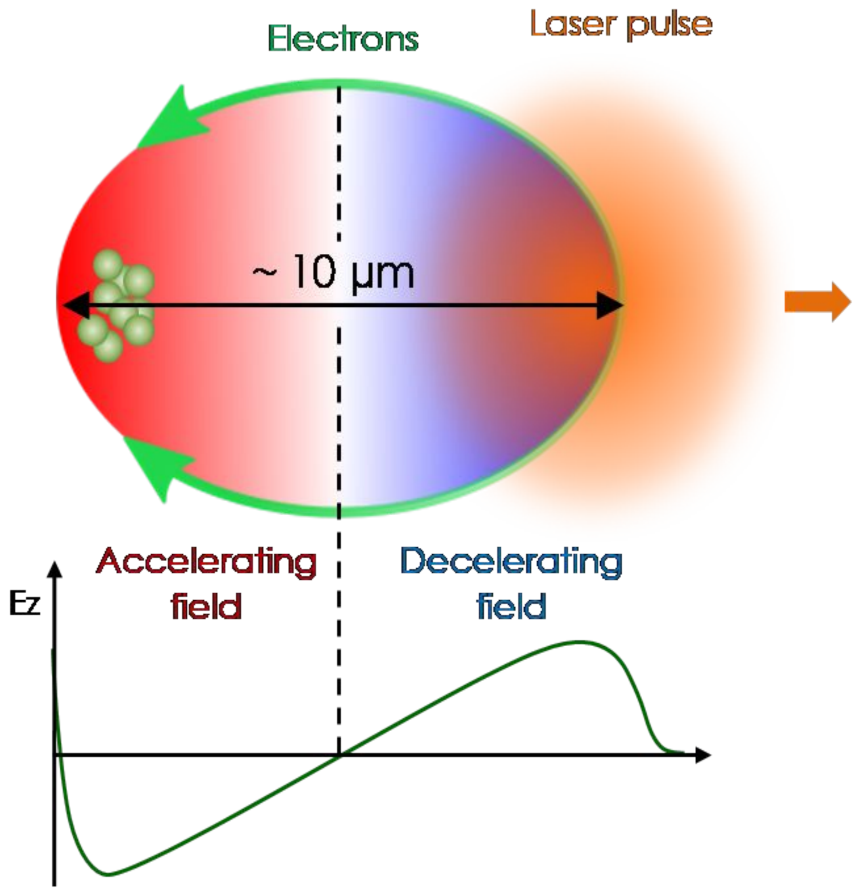
Challenge: Producing High-Energy, High-Quality Beams



- Achieving a **high quality beam** requires to control the trapping of an electron beam into a µm cavity that moves at c.

- **High energy** requires to sustain a high amplitude electric field and to keep the electron beam in this field over a long distance (>cm).

Challenge: Producing High-Energy, High-Quality Beams



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  → **controlled injection**

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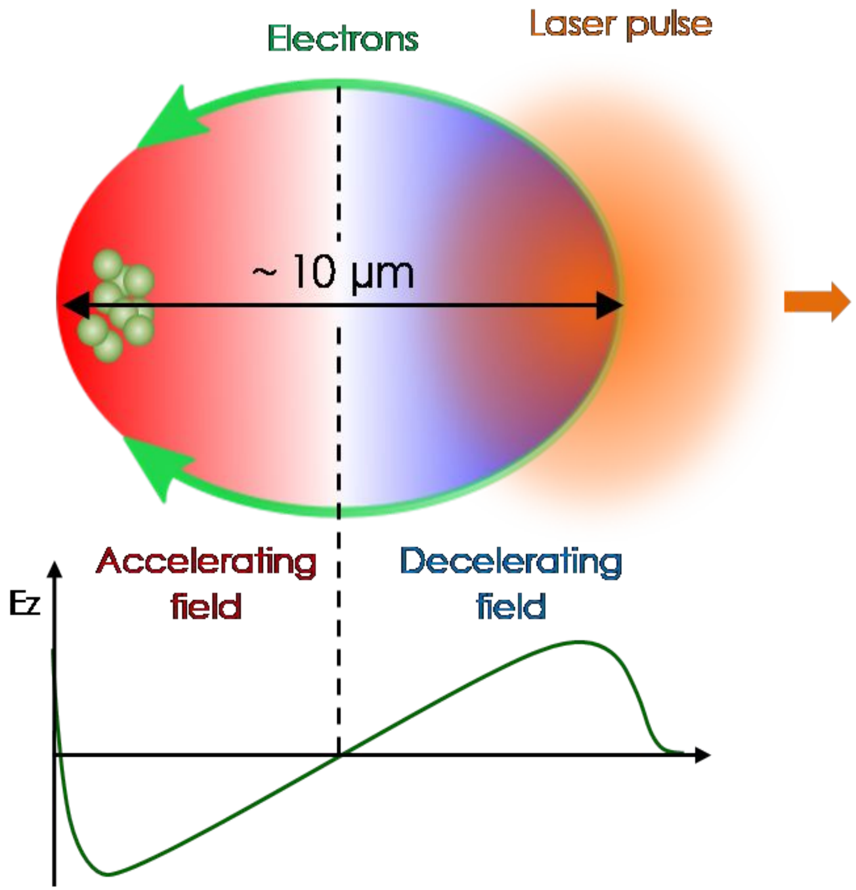
Challenge: Producing High-Energy, High-Quality Beams



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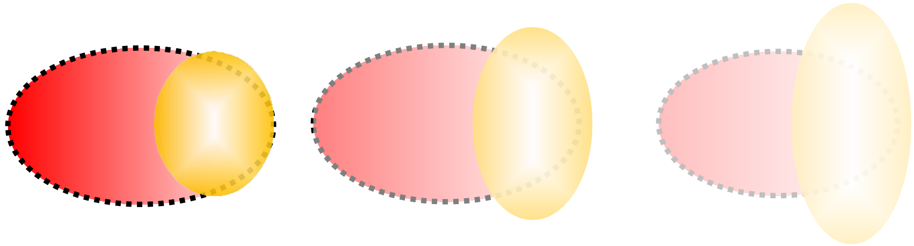
- **High energy** requires to sustain a high amplitude electric field and to keep the electron beam in this field over a long distance (>cm).
  → **laser guiding**

Two basic ingredients in a LPA: the laser and the plasma.
→ We propose to use structured light to shape both the laser and the plasma.

Energy Limits in Laser Wakefield Accelerators

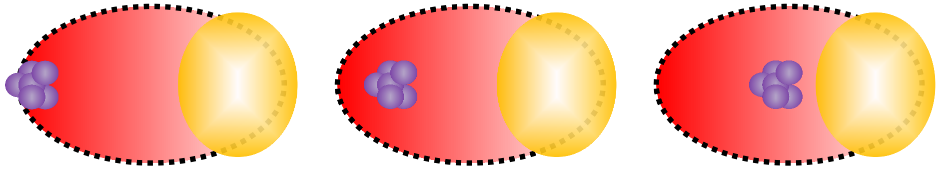
Diffraction



Laser intensity decreases because the laser diverge.

⇒ high plasma density (self-focusing)

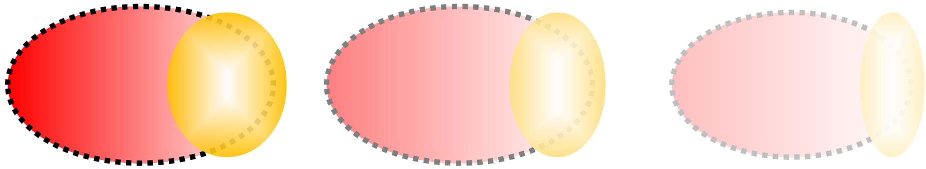
Dephasing



The electron beam does not remain in the accelerating field because it is faster than the laser.

⇒ low plasma density

Depletion



Laser intensity decreases as the laser gives its energy to the plasma.

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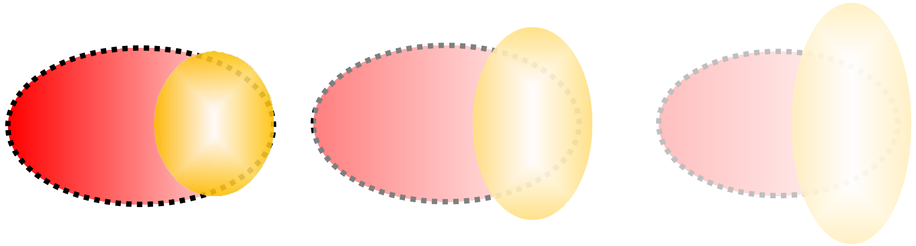
Energy Limits in Laser Wakefield Accelerators

Diffraction



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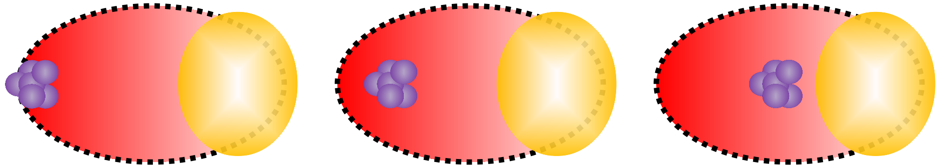

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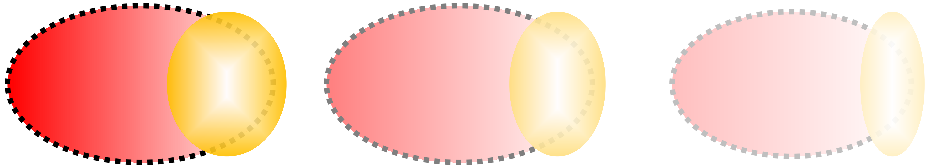
An additional degree of freedom is needed → guiding

Depletion



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⇒ low plasma density

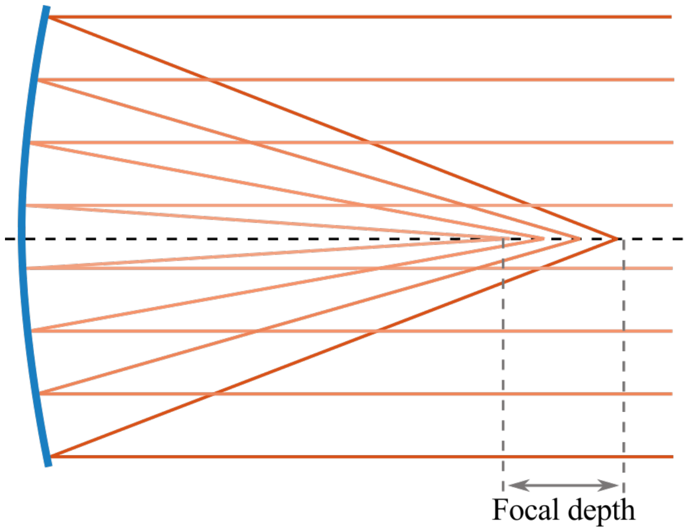
A New Optics for All-Optical Guiding: Axiparabola

An **axiparabola** is a reflective optic that generates a long and high-intensity focal line with a small waist.

$$f(r) = f_0 + \delta(r)$$

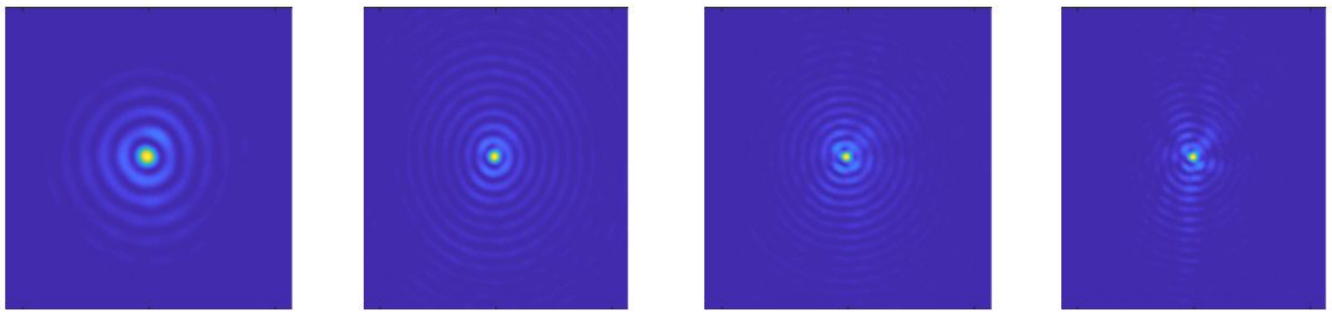
Top hat beam and constant intensity line :

$$f(r) = f_0 + \delta_0 \frac{r^2}{R^2}$$



Laser focal spot along the line

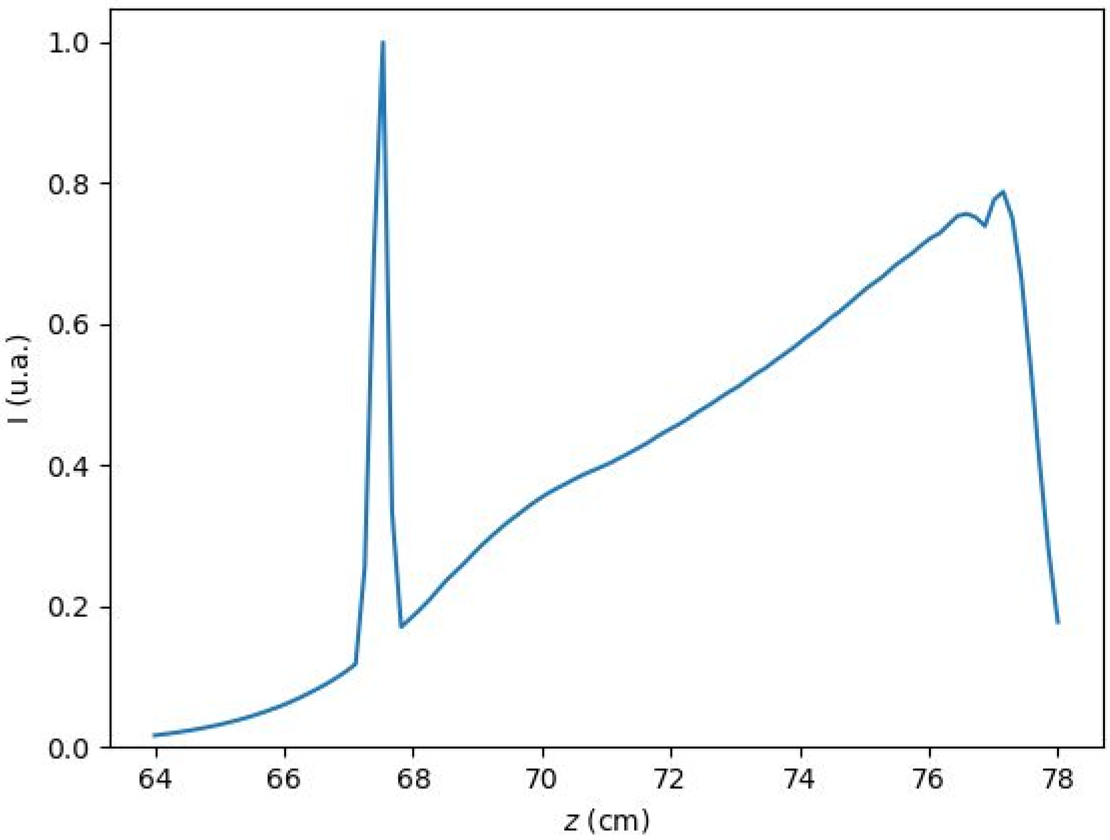
z = 2 mm *z = 5 mm* *z = 7.5 mm* *z = 10 mm*

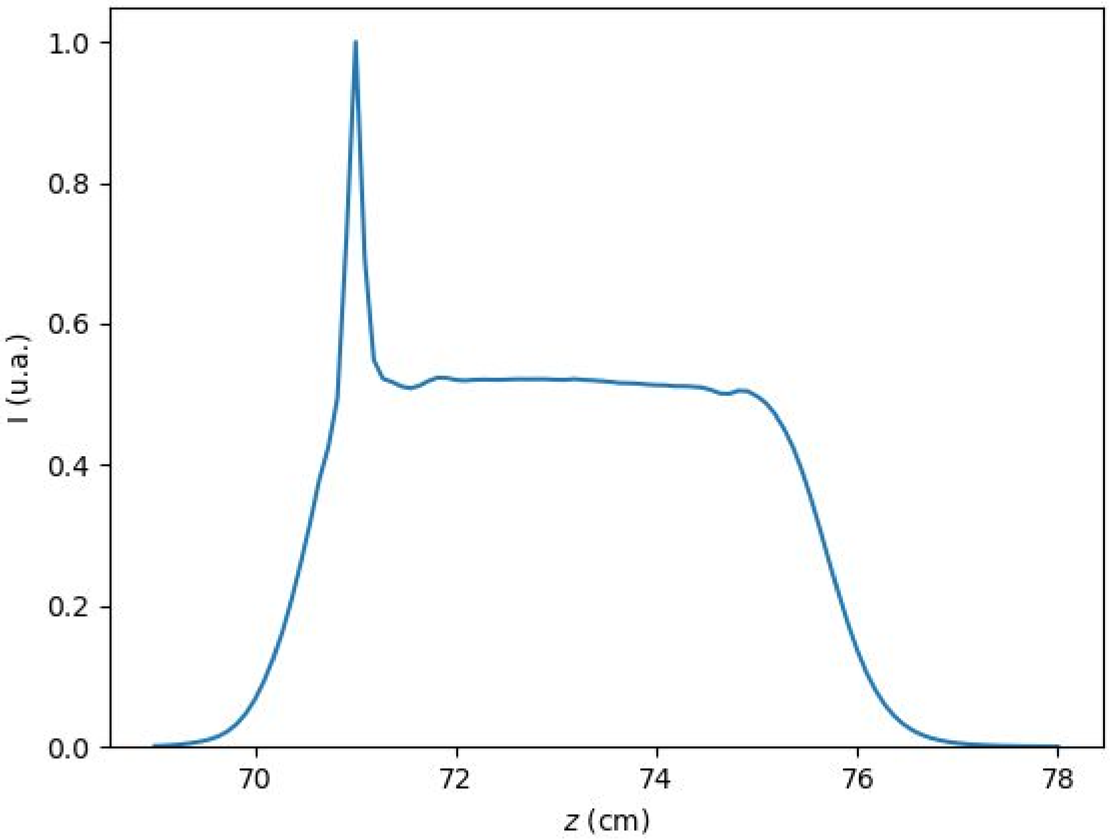


The surface can be shaped to get non-monotonic intensity profiles, curved lines...

Smartsev et al Optics Letters **44**, 3414-3417 (2019)

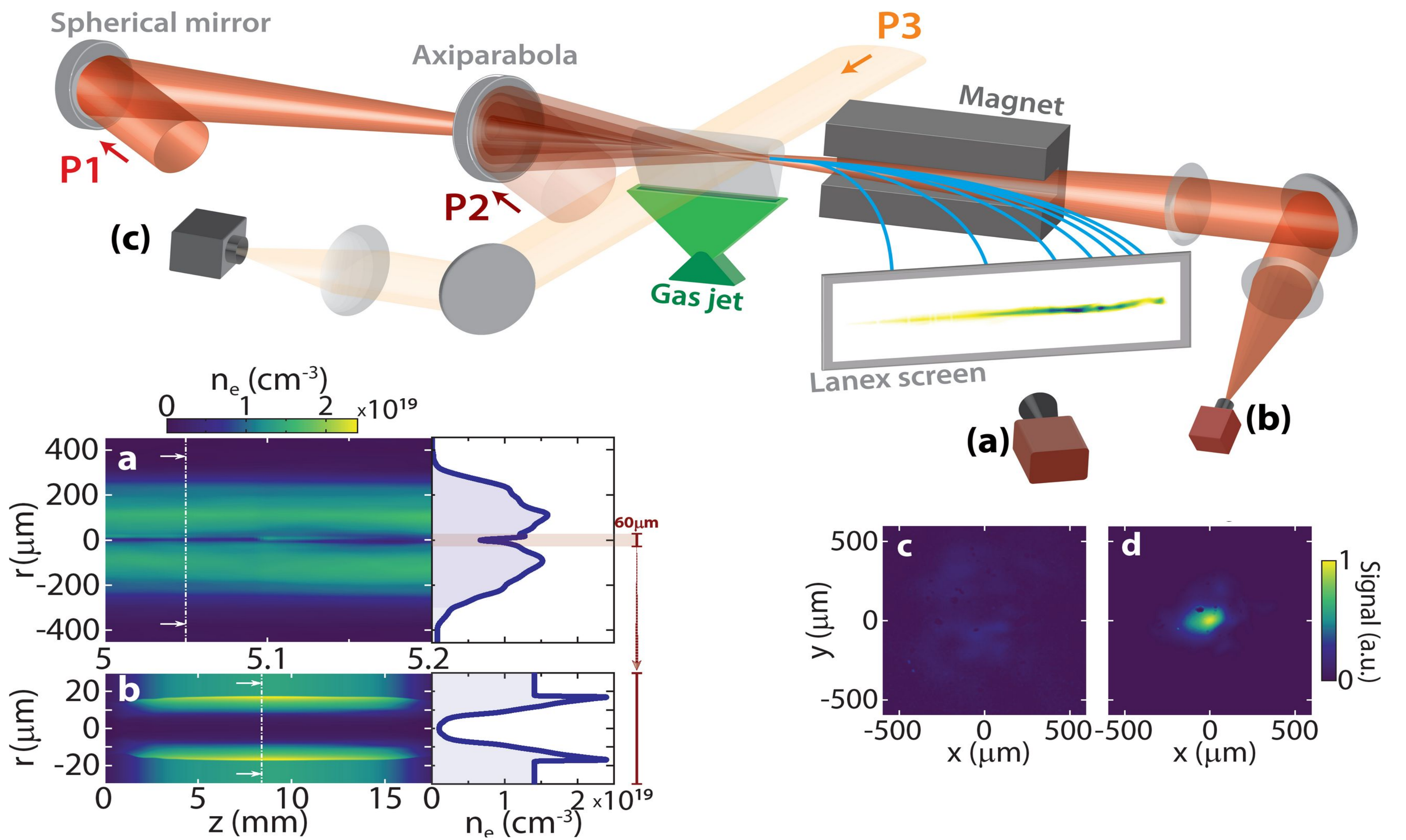
Intensity shaping





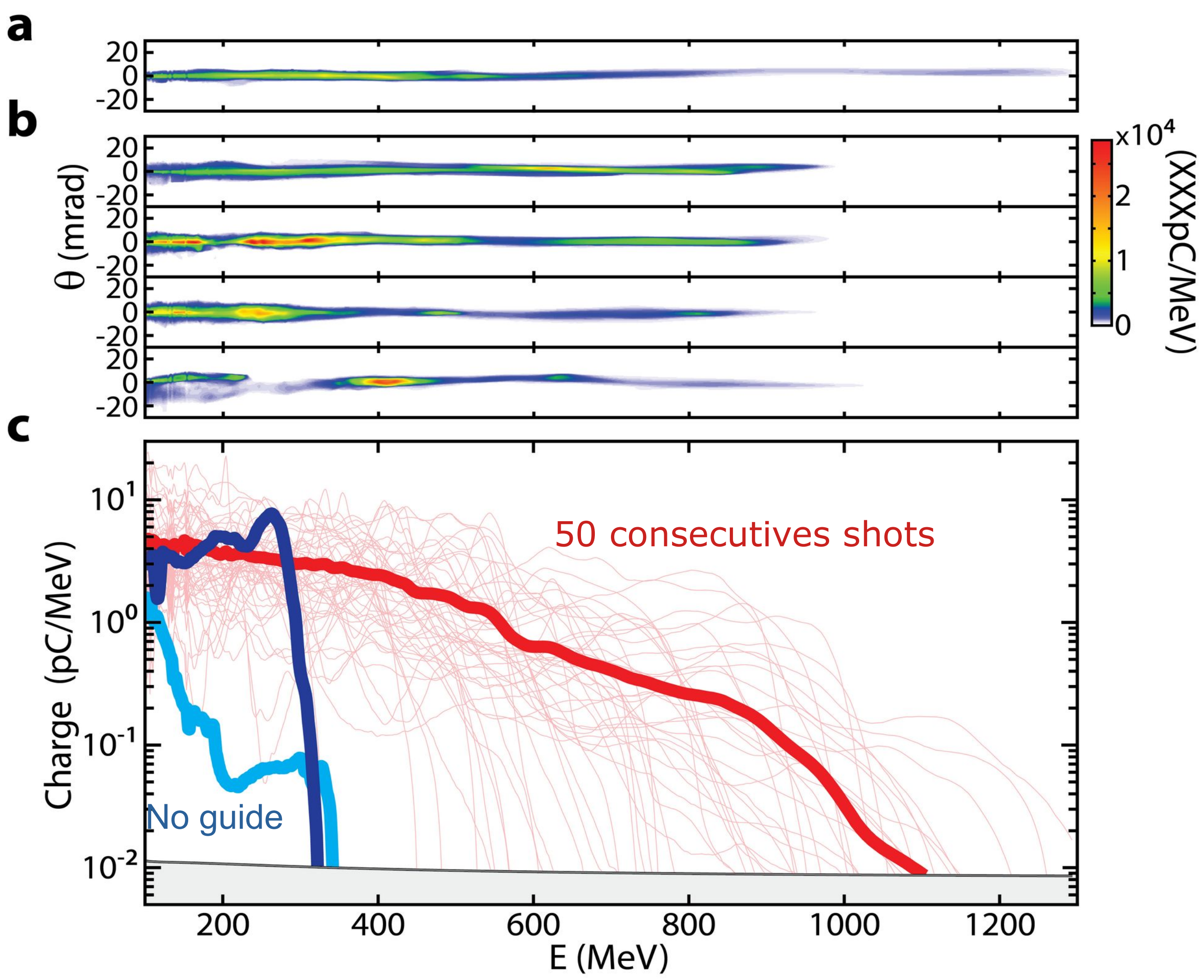
Axiprop module : https://github.com/hightower8083/axiprop

Acceleration in a Laser-Generated Waveguide



Acceleration in a Laser-Generated Waveguide

Ionization injection (gas= Hydrogen + 1% Nitrogen)

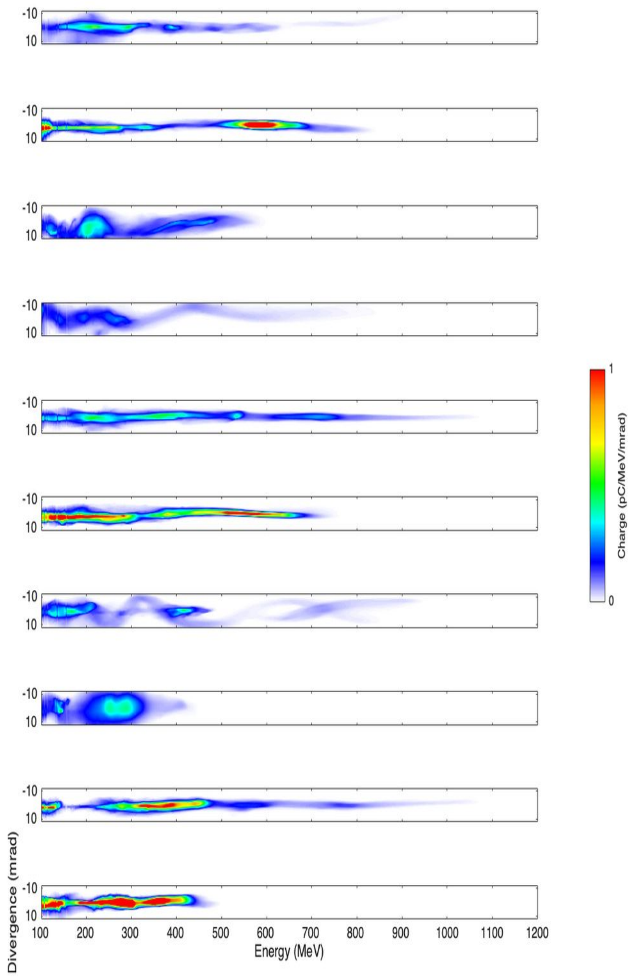


- 1.7 J – 30 fs laser for aceleration
- 15 mm gas jet
- 5 mJ for generating the waveguide
- Up to ~1.1 GeV electron energy

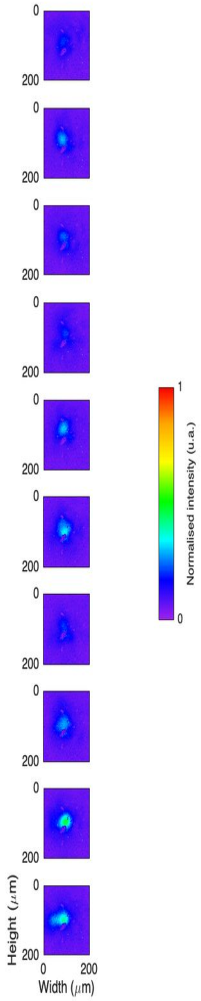
- 70% of shots with guiding and electron energy > 600 MeV
- 50 pC above 350 MeV (2% conversion efficiency)

Laser Pointing and Beam Stability

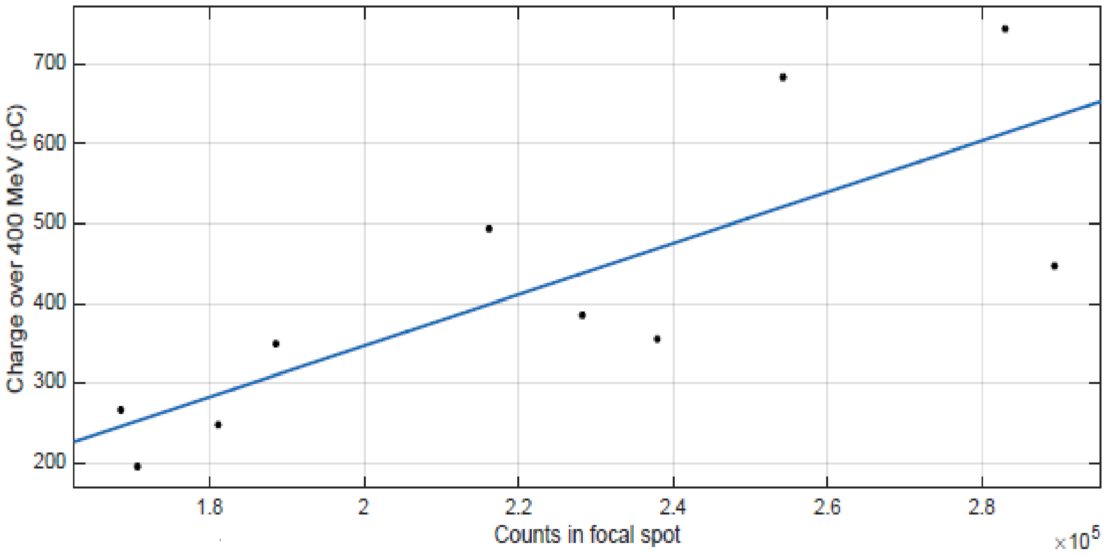
Consecutive electron spectra



Focal spots



Correlation between guiding quality and injected charge

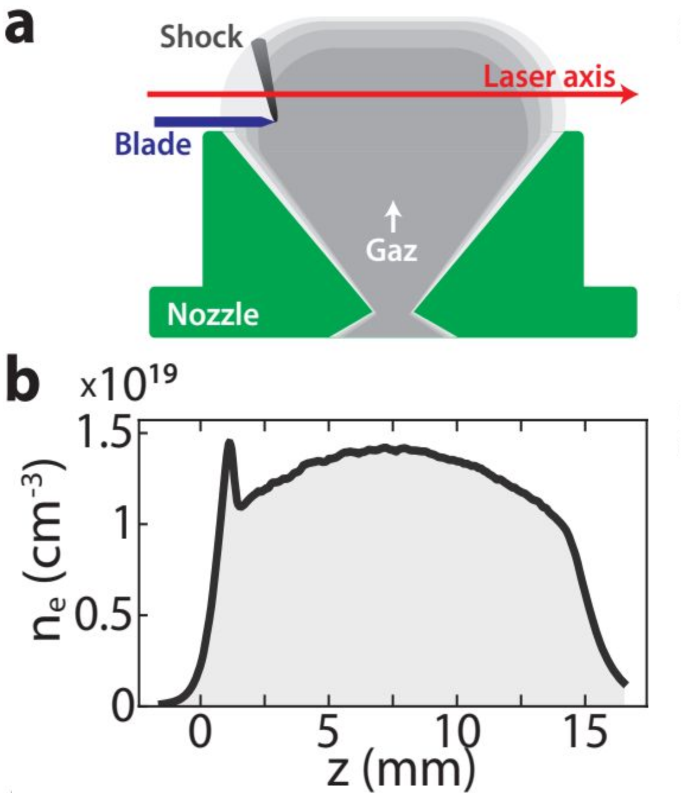


Laser pointing has to be controlled to stabilize the accelerated charge.

Oubrerie et al. Light Sci Appl 11, 180 (2022)

Controlled Injection in a Laser-Generated Waveguide

Density transition injection



Guided laser ➡ peaked spectra > 600 MeV

Oubrerie et al. Light Sci Appl 11, 180 (2022)

Controlled Injection in a Laser-Generated Waveguide

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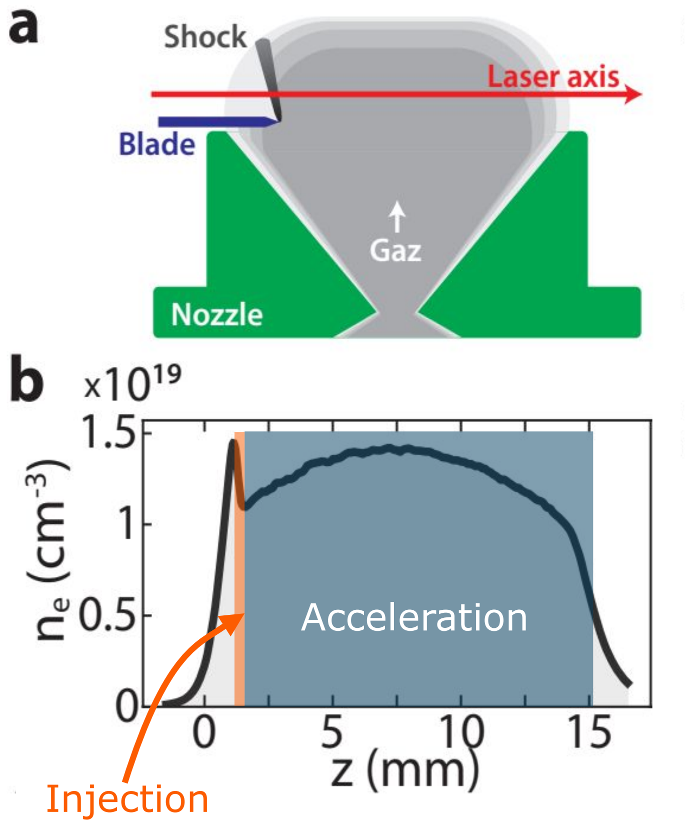
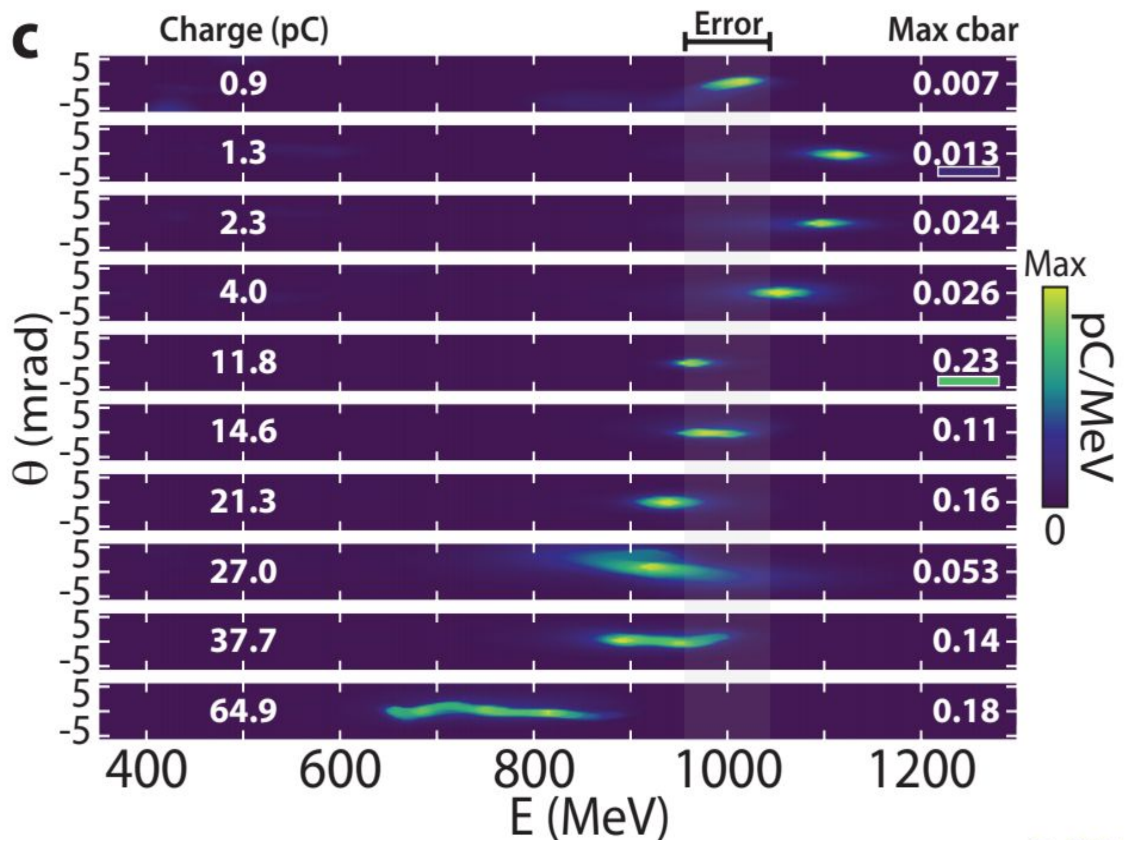


10 shots selected from a series of 14 sorted by charge



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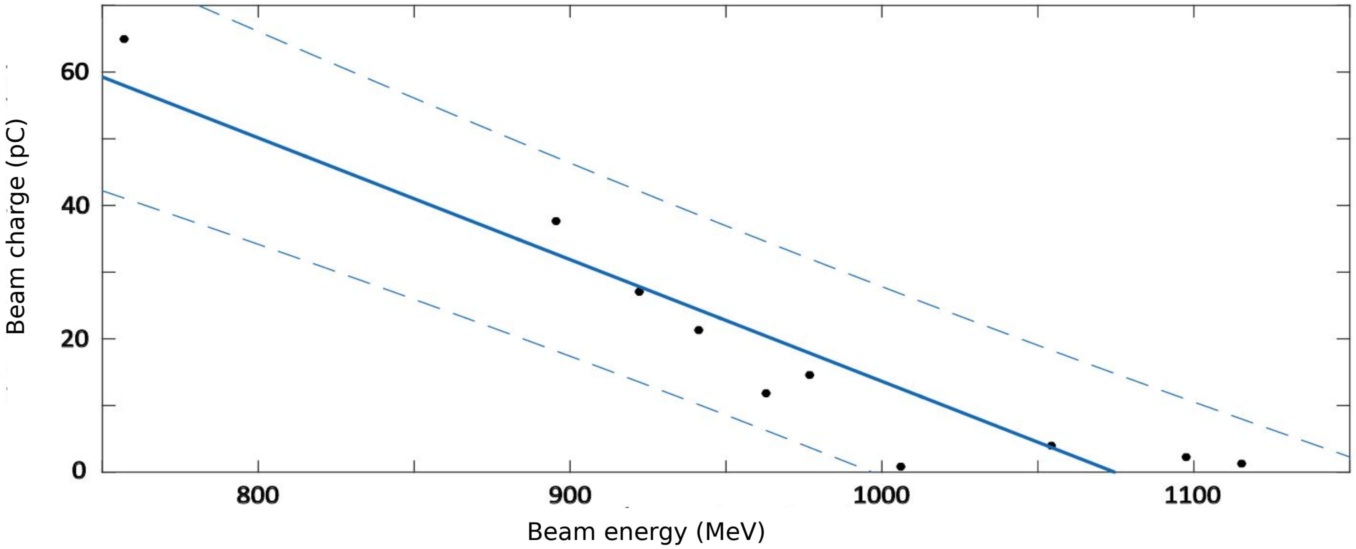
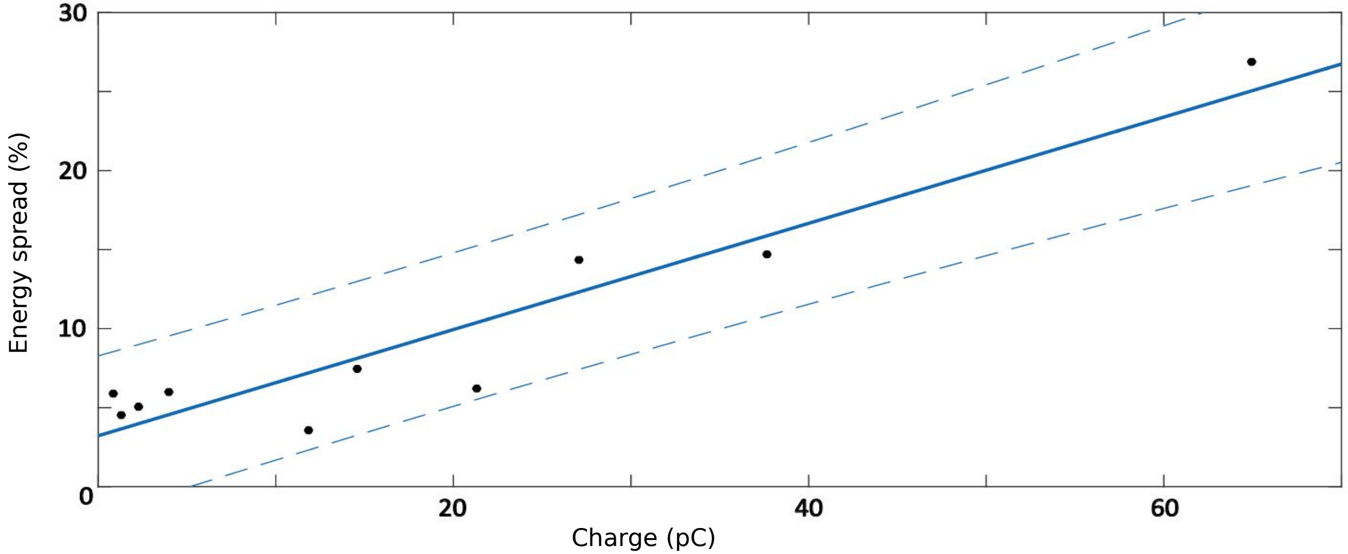
Oubrerie et al. Light Sci Appl 11, 180 (2022)

Guiding and Beam-Loading





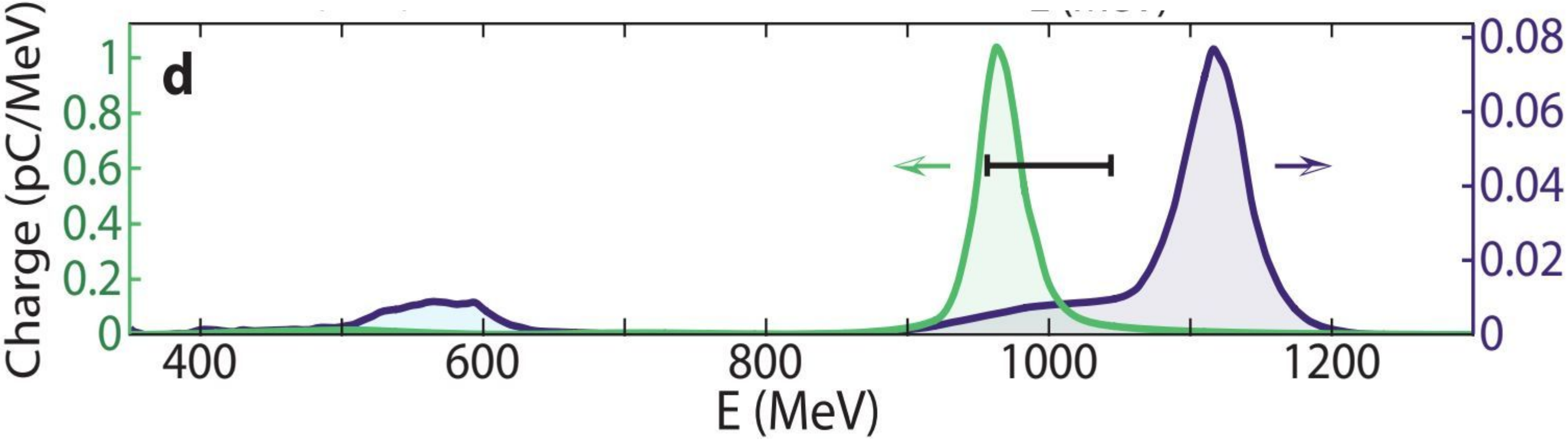
Beam charge ↗ ➡ { - Beam energy ↘ / - Energy spread ↗

⬇

Laser pointing ➡ fluctuations in charge, energy and energy spread

Oubrerie et al. Light Sci Appl 11, 180 (2022)

Guiding and Beam-Loading



◆ Down to 2% energy spread (3.6% without divergence deconvolution)

◆ Conversion efficiency of 1% for GeV beams and up to 6% for the most loaded ones.

Oubrerie et al. Light Sci Appl 11, 180 (2022)

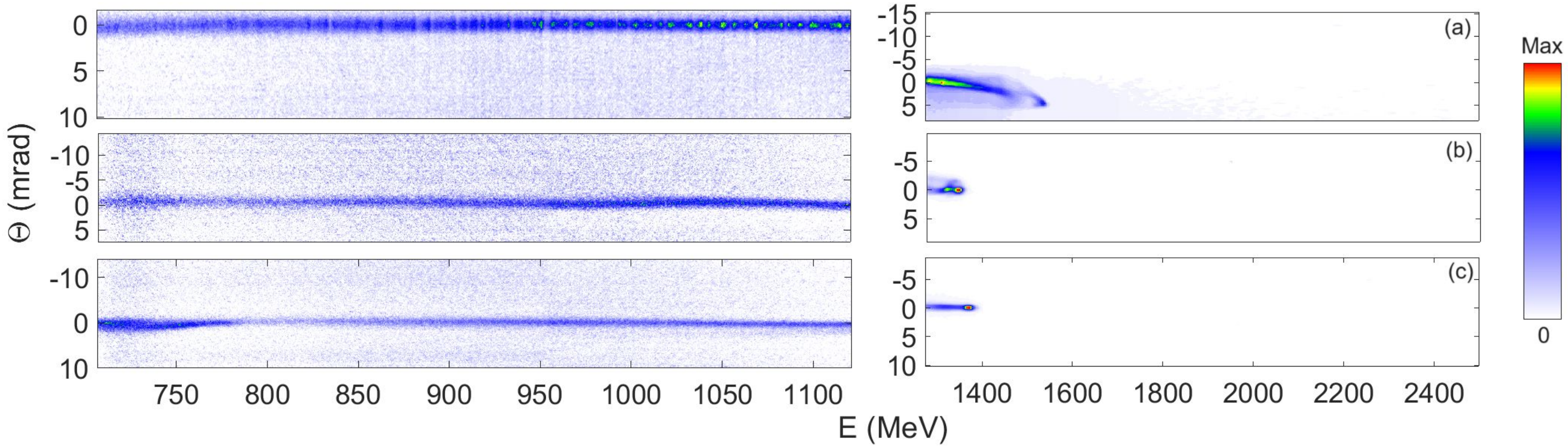
Increasing the Laser Energy with a PW-class Laser

View of the experiment

Target (6 cm long nozzle + blade)

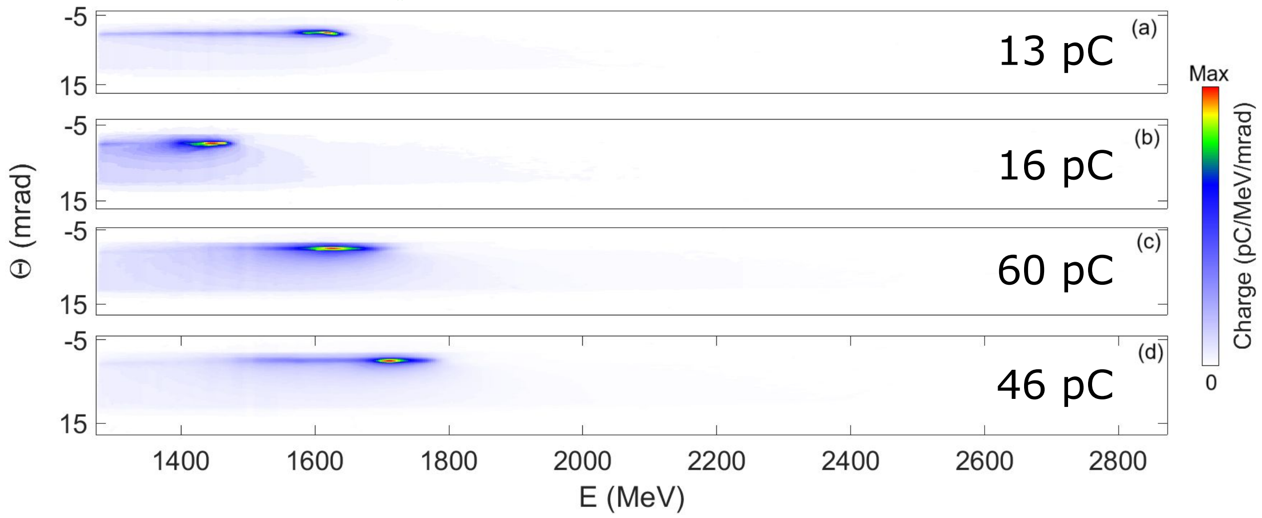
Apollon laser ~ 10 J on target, 25 fs
Helium gas

No blade, no guiding
→ Continuous spectra
→ Max energy ~ 1.4 GeV



Increasing the Laser Energy with a PW-class Laser

Blade



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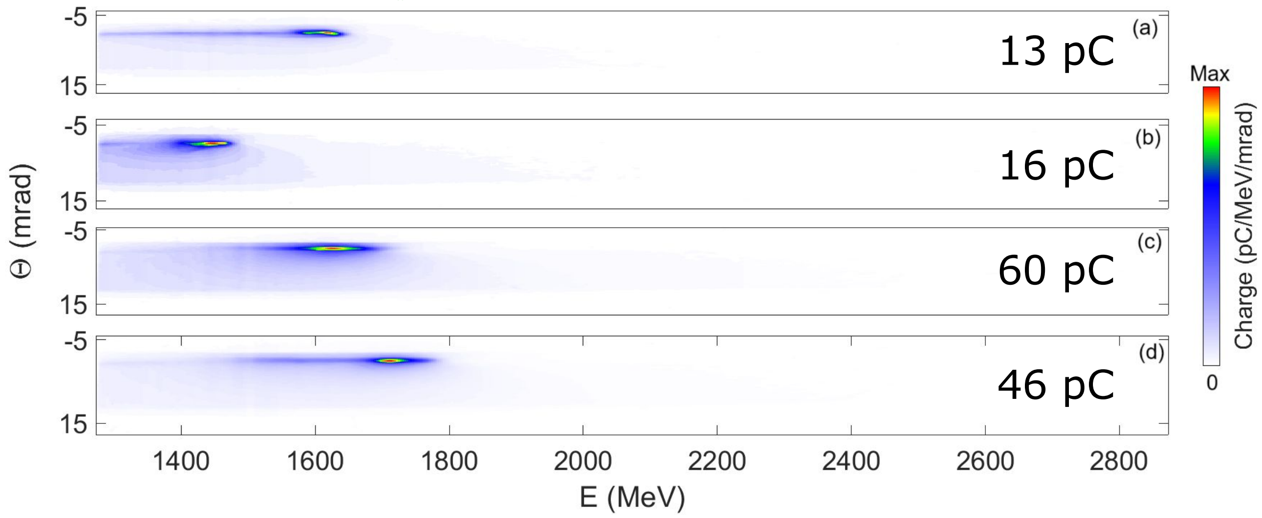
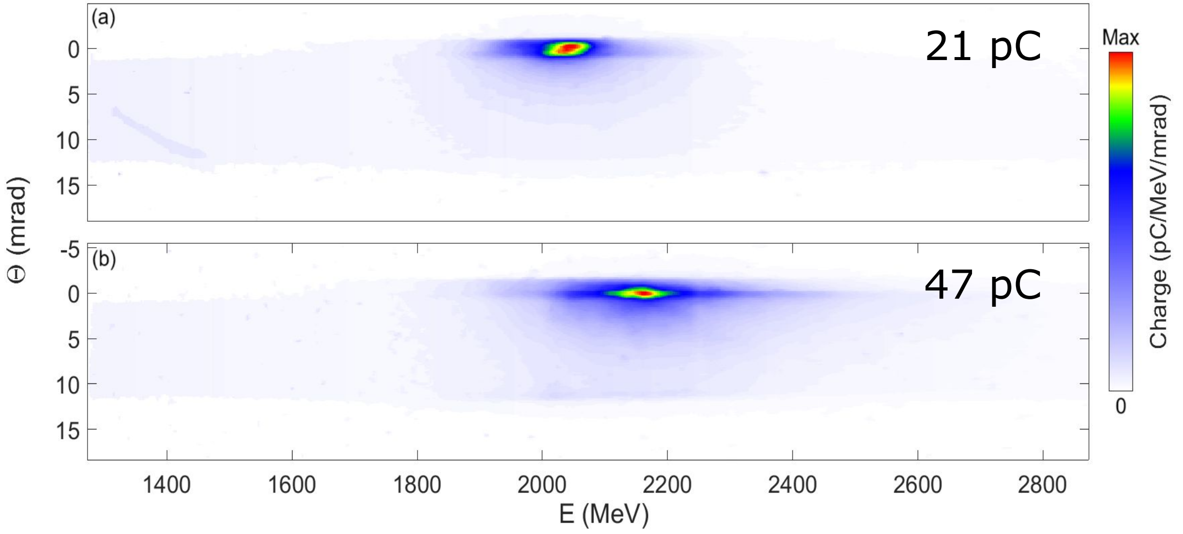
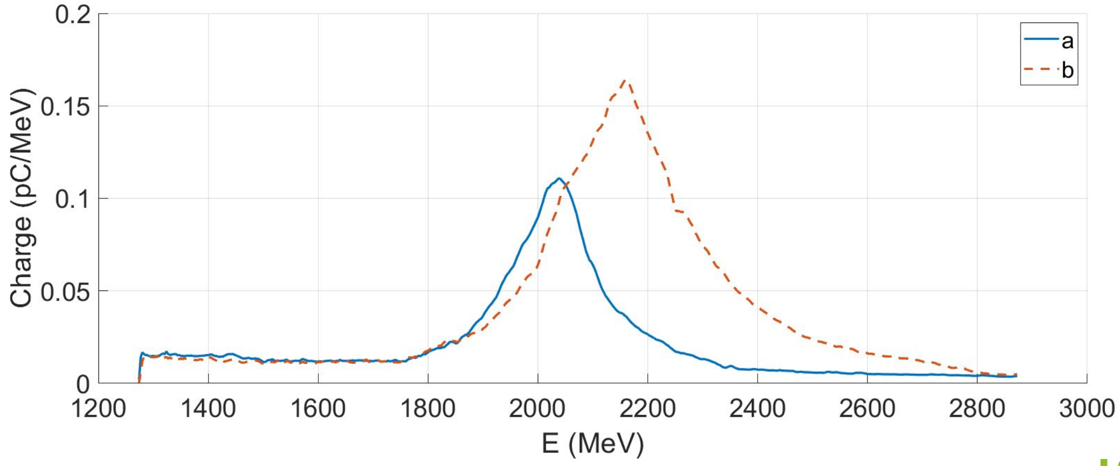


Blade + guiding





- 2.2 GeV
- 1% conversion efficiency
- 10% energy spread

Up to 5 GeV, w/o controlled injection in Miao et al. PRX 12, 031038 (2022)

Energy Limits in Laser Wakefield Accelerators

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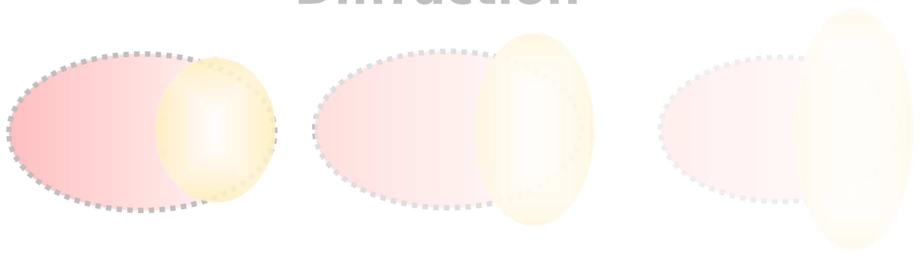

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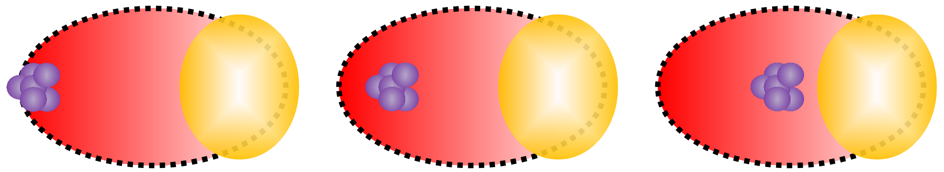

The electron beam does not remain in the accelerating field because it is faster than the laser.

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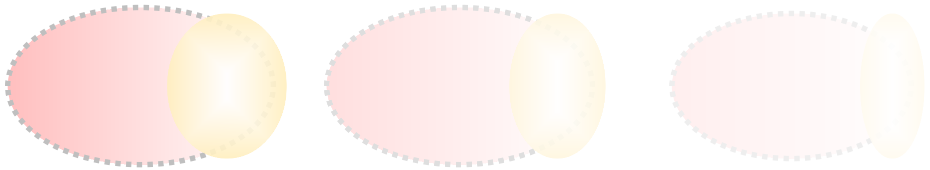
Depletion

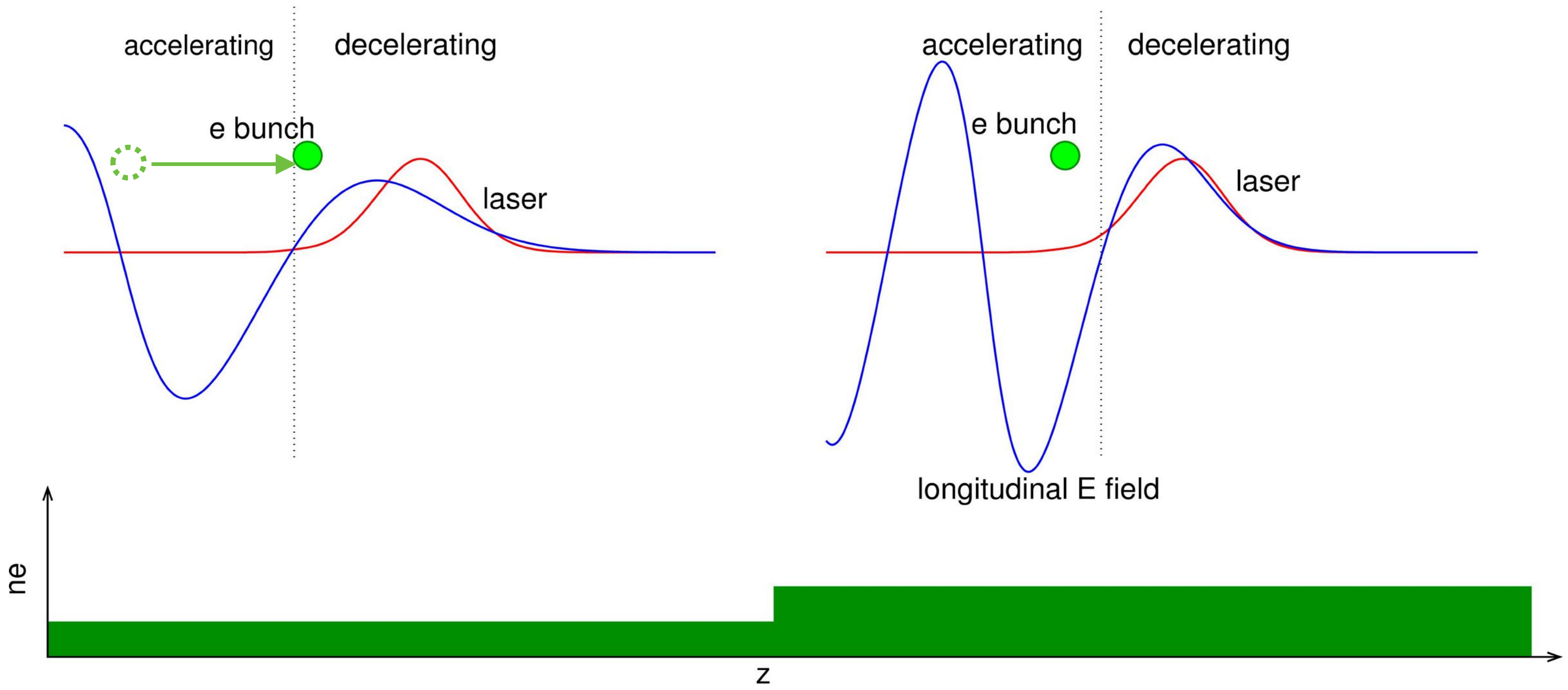


Laser intensity decreases as the laser gives its energy to the plasma.

⇒ low plasma density

The Rephasing Technique

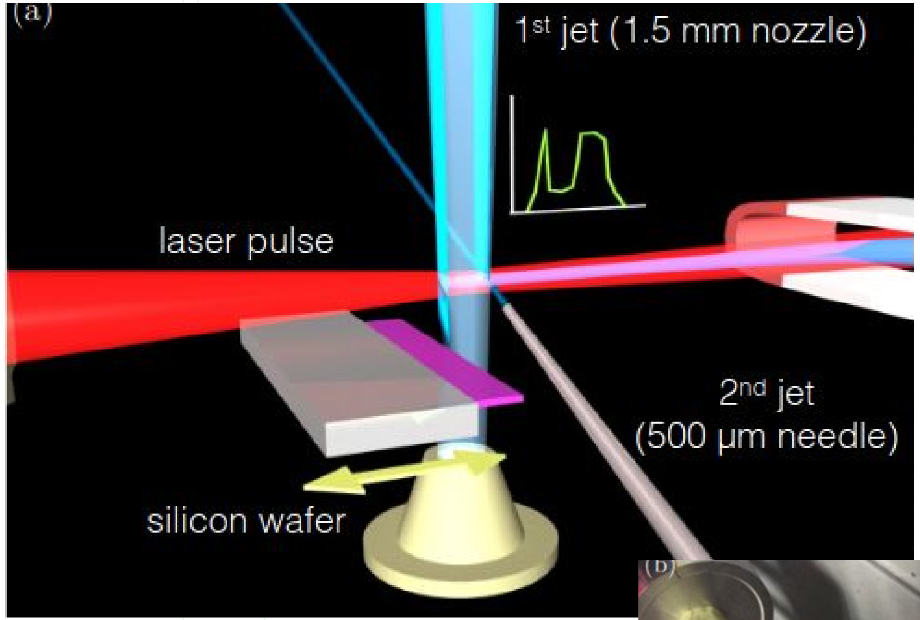
Idea: use plasma shaping to counter dephasing

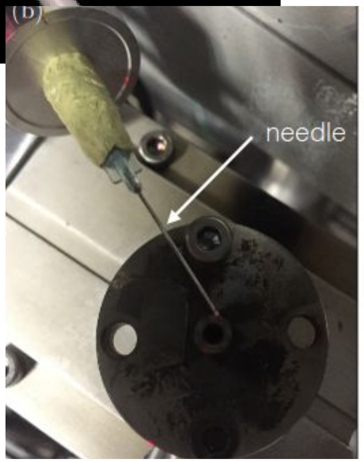


A density step is used to rephase the electron bunch

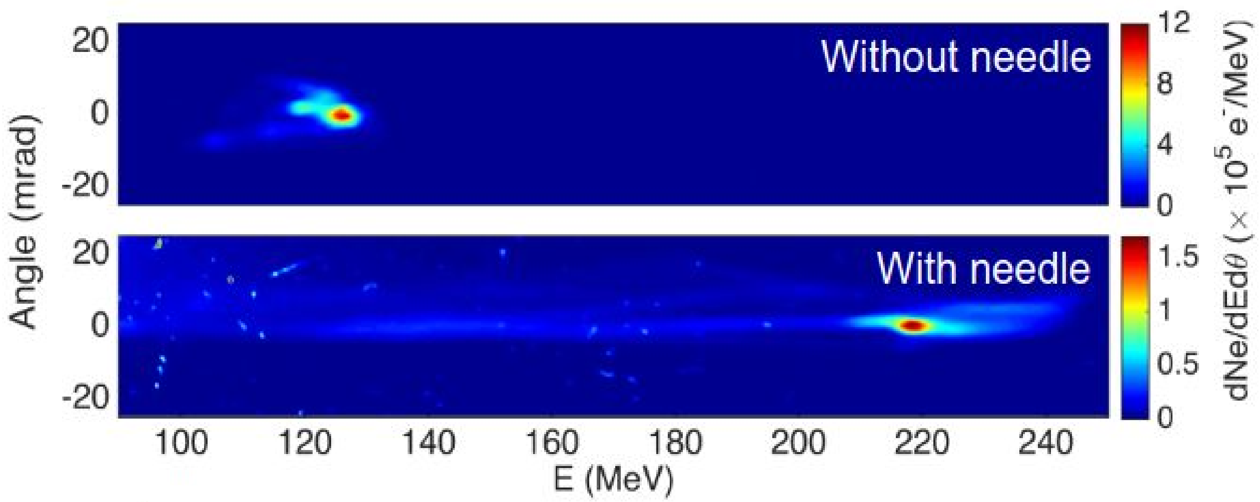
A. Döpp et al. Physics of Plasmas **23**, 056702 (2016), E. Guillaume et al. Phys. Rev. Lett. **115**, 155002 (2015)

The Rephasing Technique





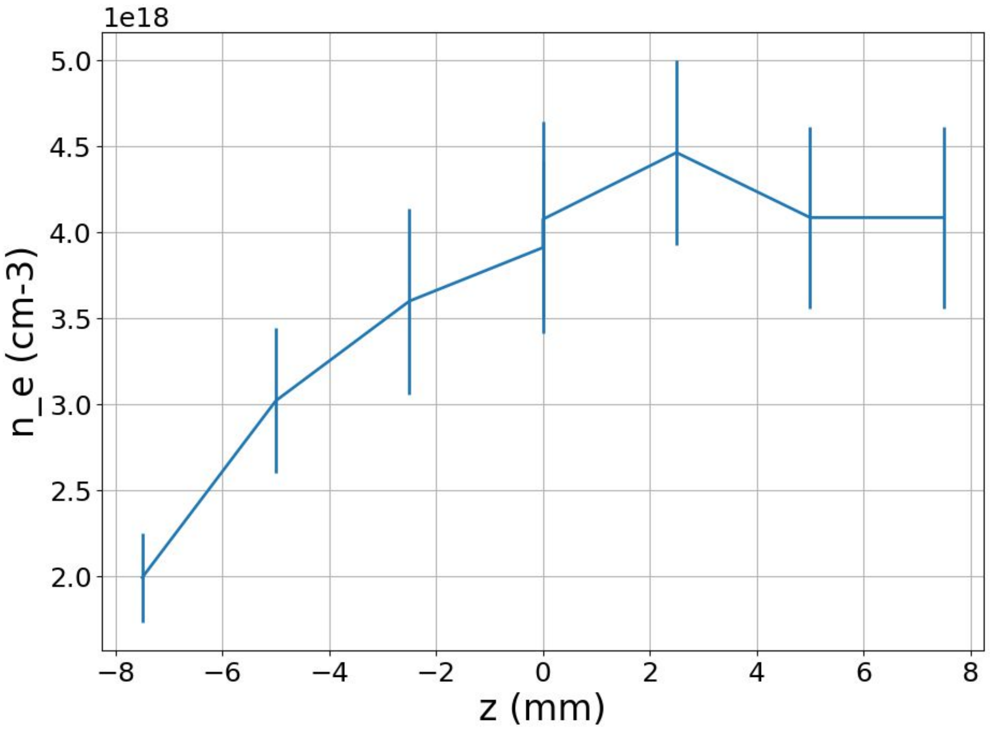
60% energy gain



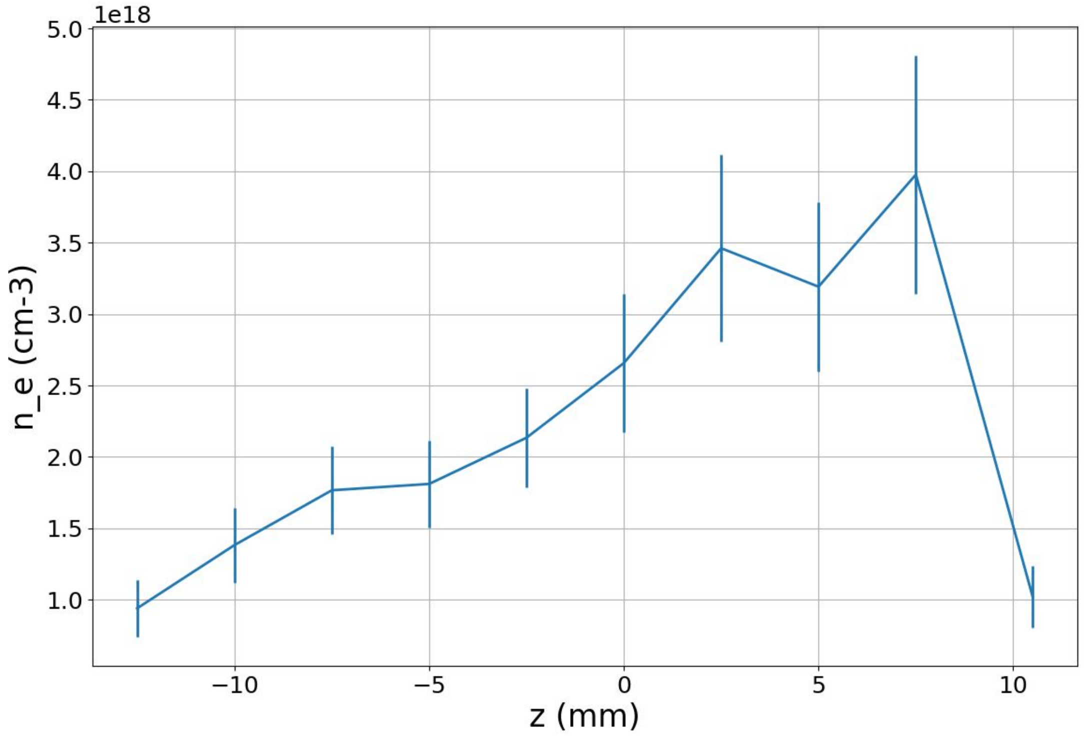
Guillaume et al. Phys. Rev. Lett. **115**, 155002 (2015)

Guiding and rephasing

Rising density profiles



V-shaped nozzle

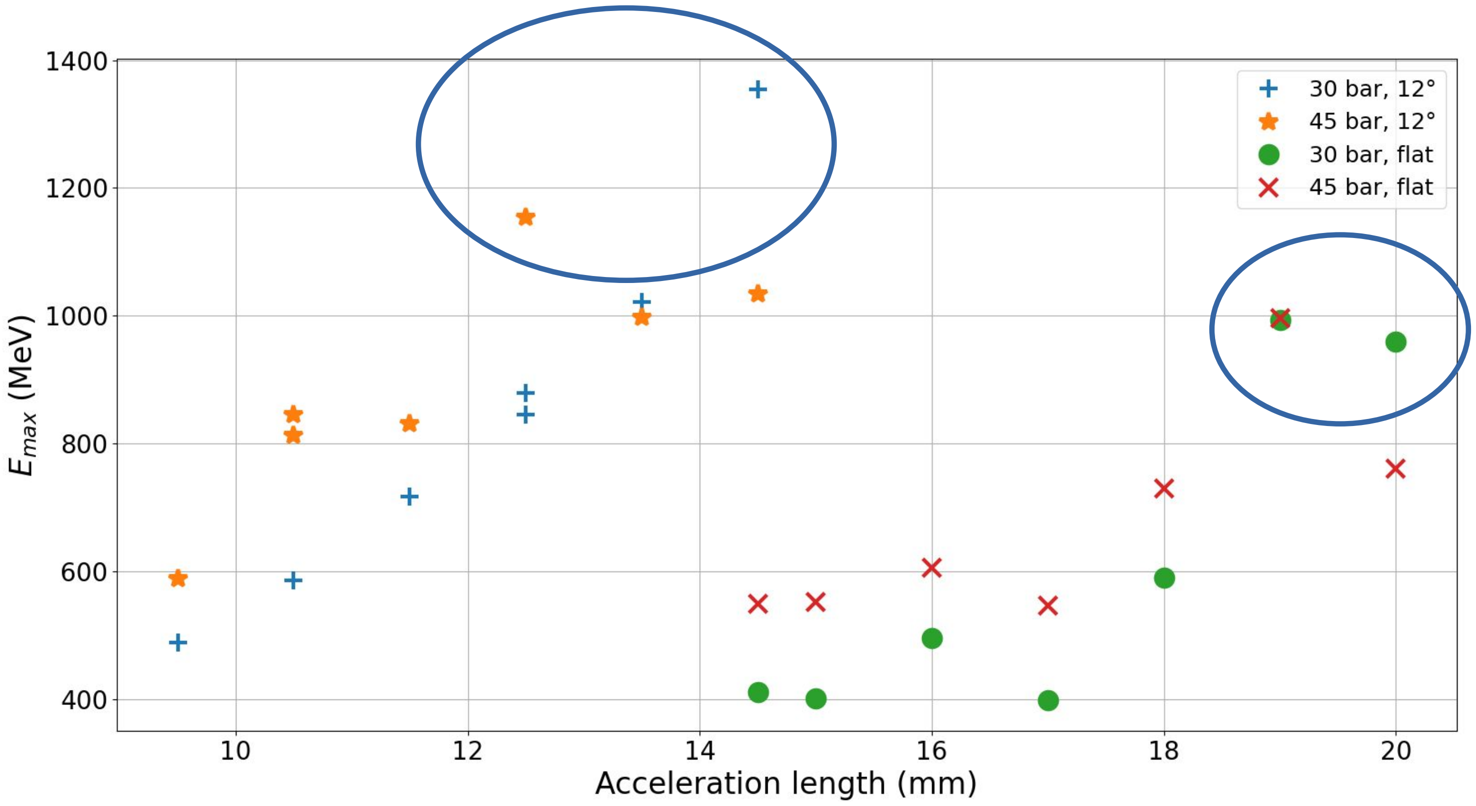


Tilted nozzle

Guiding and rephasing

Preliminary results

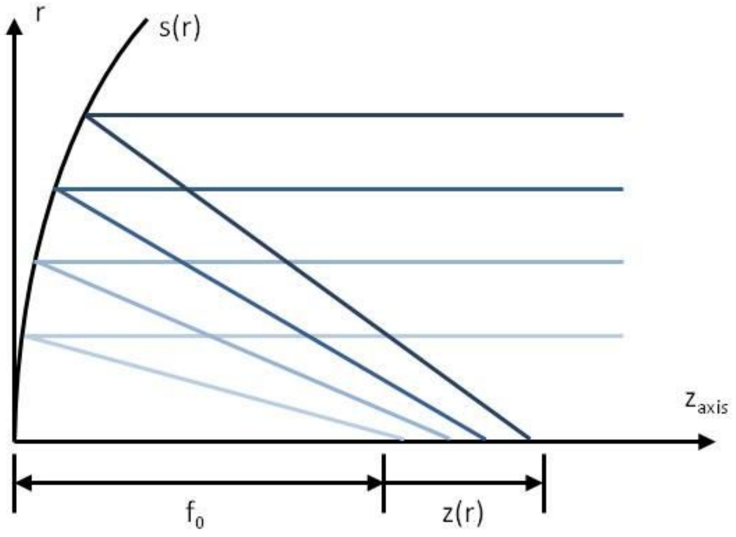
Rising gradient



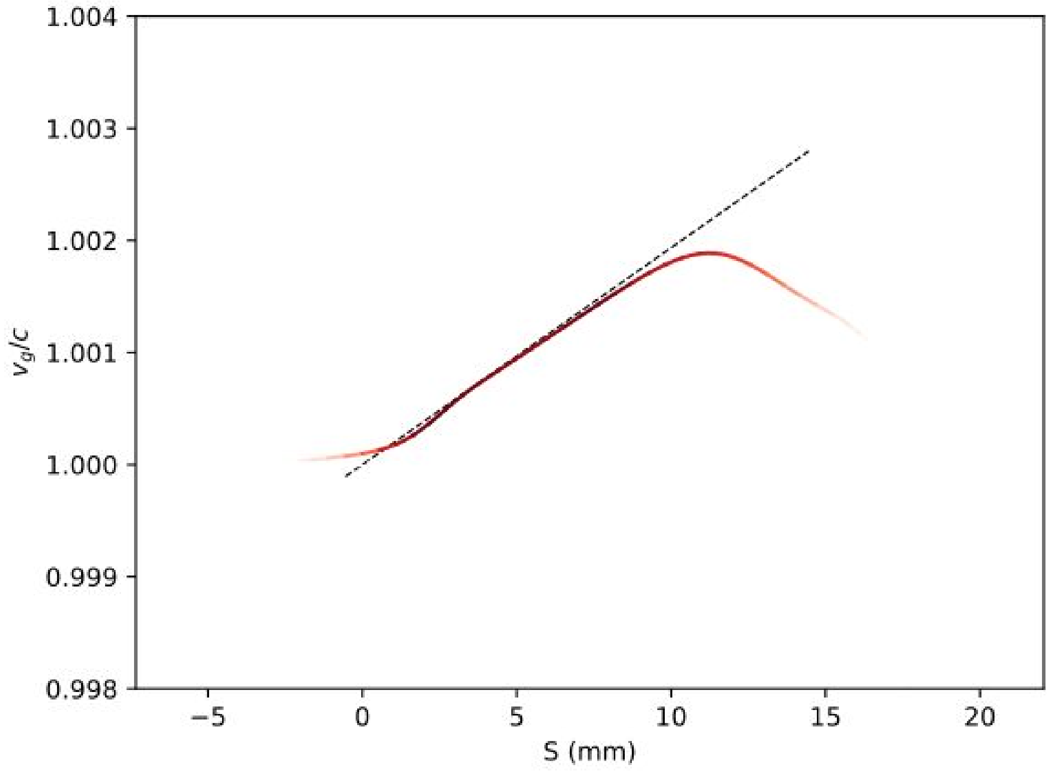
Flat profile

Up to ~1.4 GeV with the density gradient, vs ~1 GeV with a flat profile

Axiparabola: Control of the Velocity - Theory



$$\frac{v}{c} = 1 + \frac{r^2}{2f^2}$$

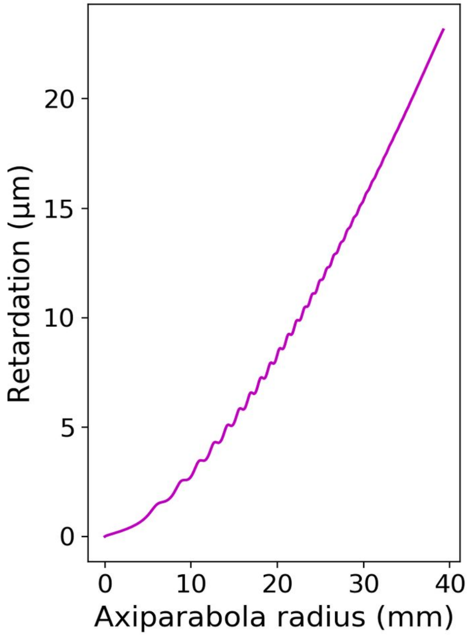


Intensity peak goes faster than c along the optical axis

Oubrerie et al.J. Opt. 24 045503 (2022)

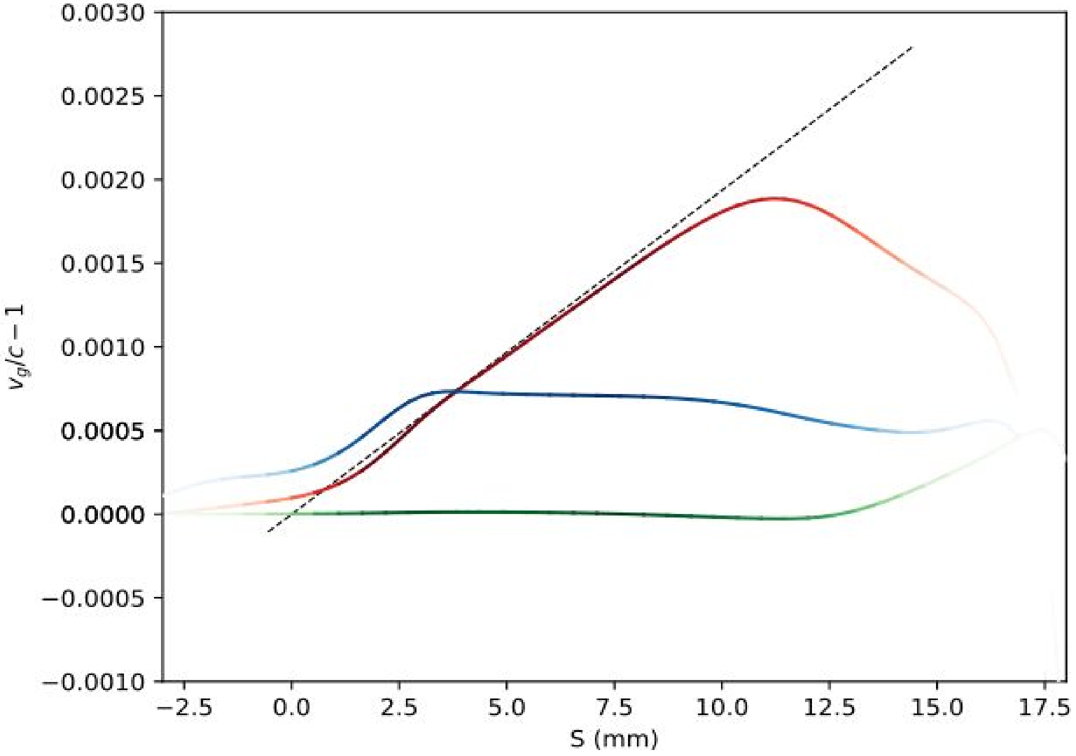
Axiparabola: Control of the Velocity - Theory

Spatio-Temporal Couplings can be used to modify the arrival time of the beamlets on the axis and thus control the light velocity.



$$c\tau \simeq \frac{P_0}{\lambda_z R^2}\left(-\frac{v_0}{c}r^2 + \frac{1}{2f^2}\left(\frac{v_0}{c}+\frac{1}{2}\right)r^4\right) + o(r^5)$$

Velocity along the focal line



A. Kabacinski et al J.. Opt. 23 06LT01 (2021)

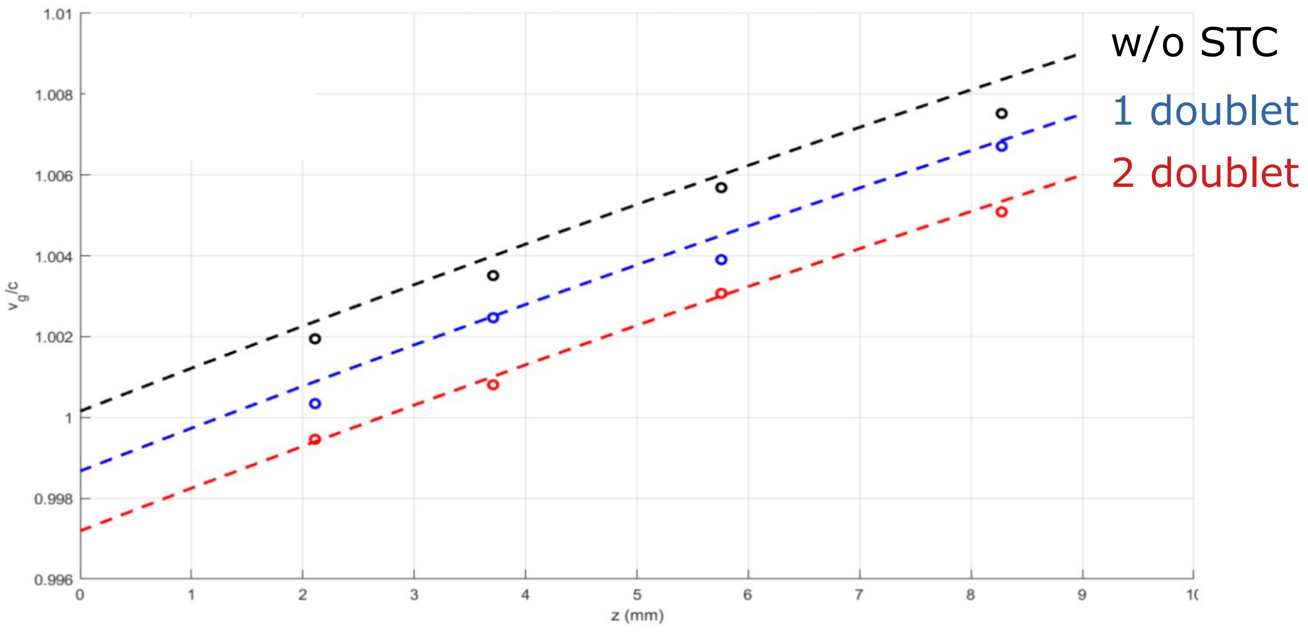
K. Oubrerie et al.J. Opt. 24 045503 (2022)

Axiparabola: Control of the Velocity - Experiment

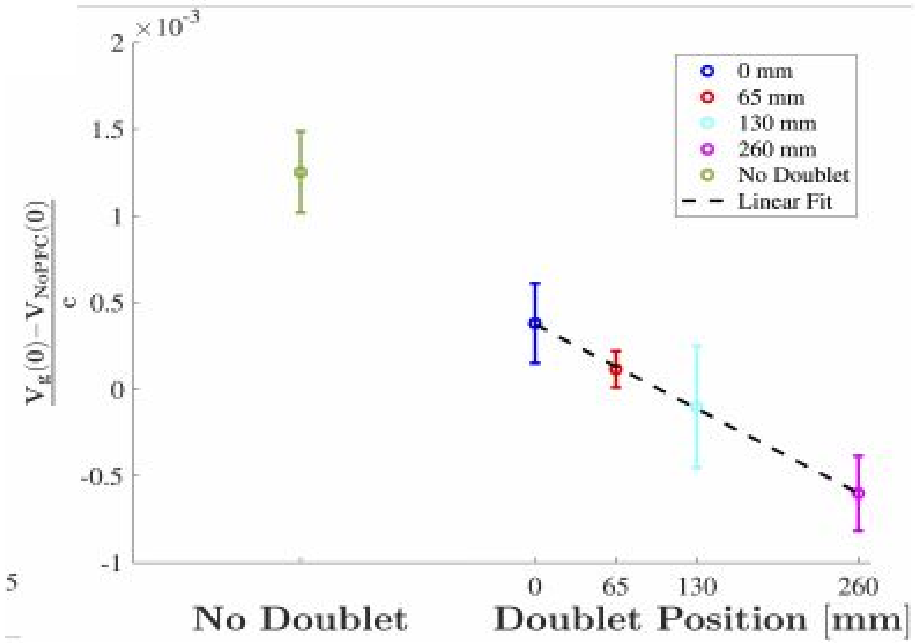
Weizmann Institute of Science

We used a chromatics doublet of infinite focal length to introduce Pulse Front Curvature and modify the velocity.

Velocity along the line for ≠ STC



Velocity shifts for ≠ positions of the doublet

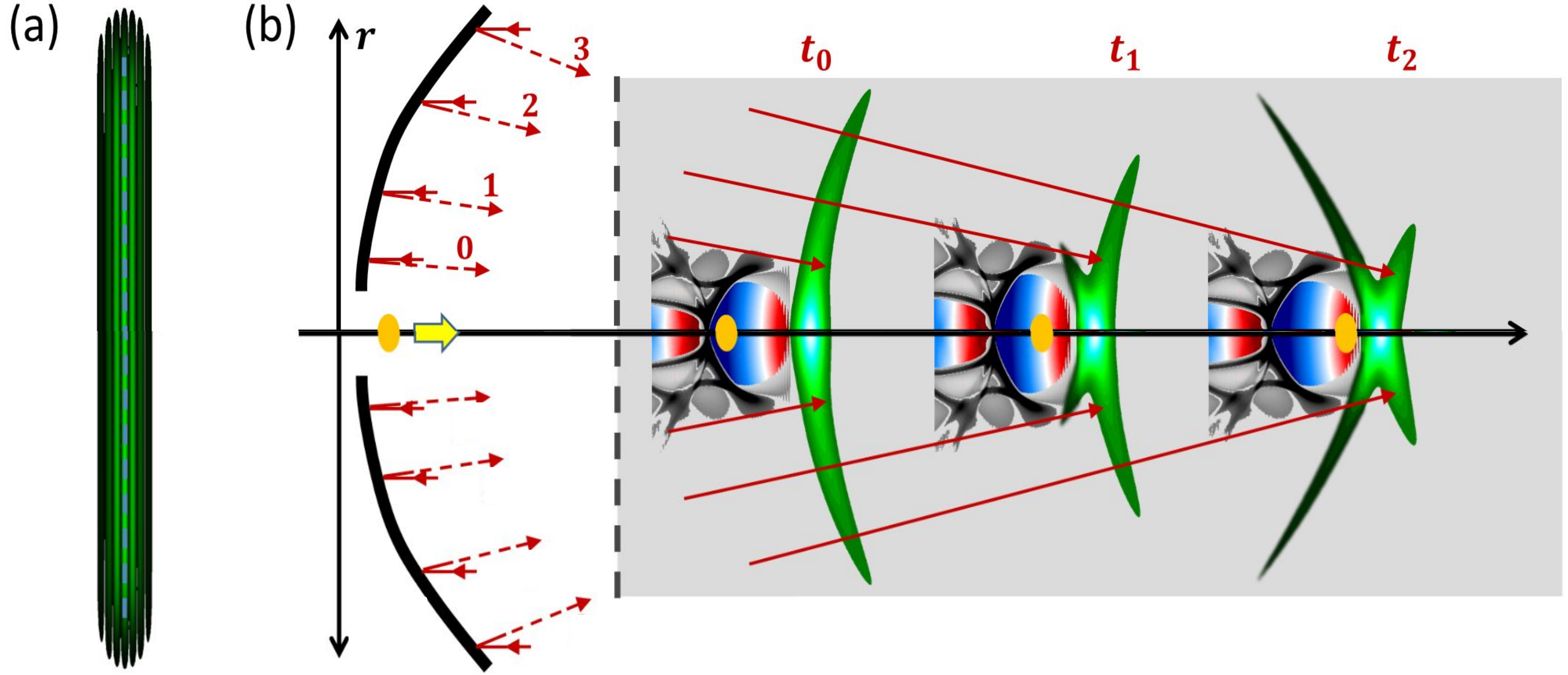


Proper delay can be introduced by using chromatic optics

A. Kabacinski et al J.. Opt. 23 06LT01 (2021), A. Liberman et al *arXiv:2306.14327* (2023)

Superluminal Acceleration - Principle

The wake field is driven by an axiparabola which focuses the laser in line at a_0~1.5, in a single laser beam experiment.
→ Diffraction-free acceleration.



C. Thaury *et al.*, Proc. SPIE 11037 (2019)

C. Caizergues et al. Nature Photonics **14**, 475–479 (2020)
J.P. Palastro, Phys. Rev. Lett. 130, 159902 (2020)

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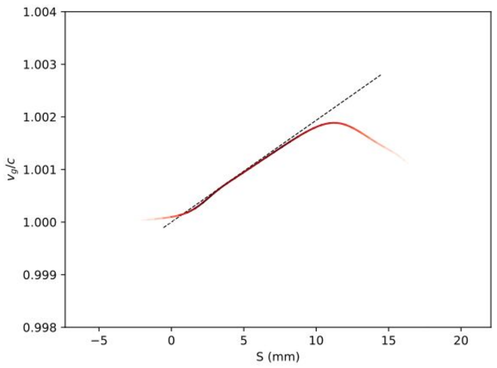

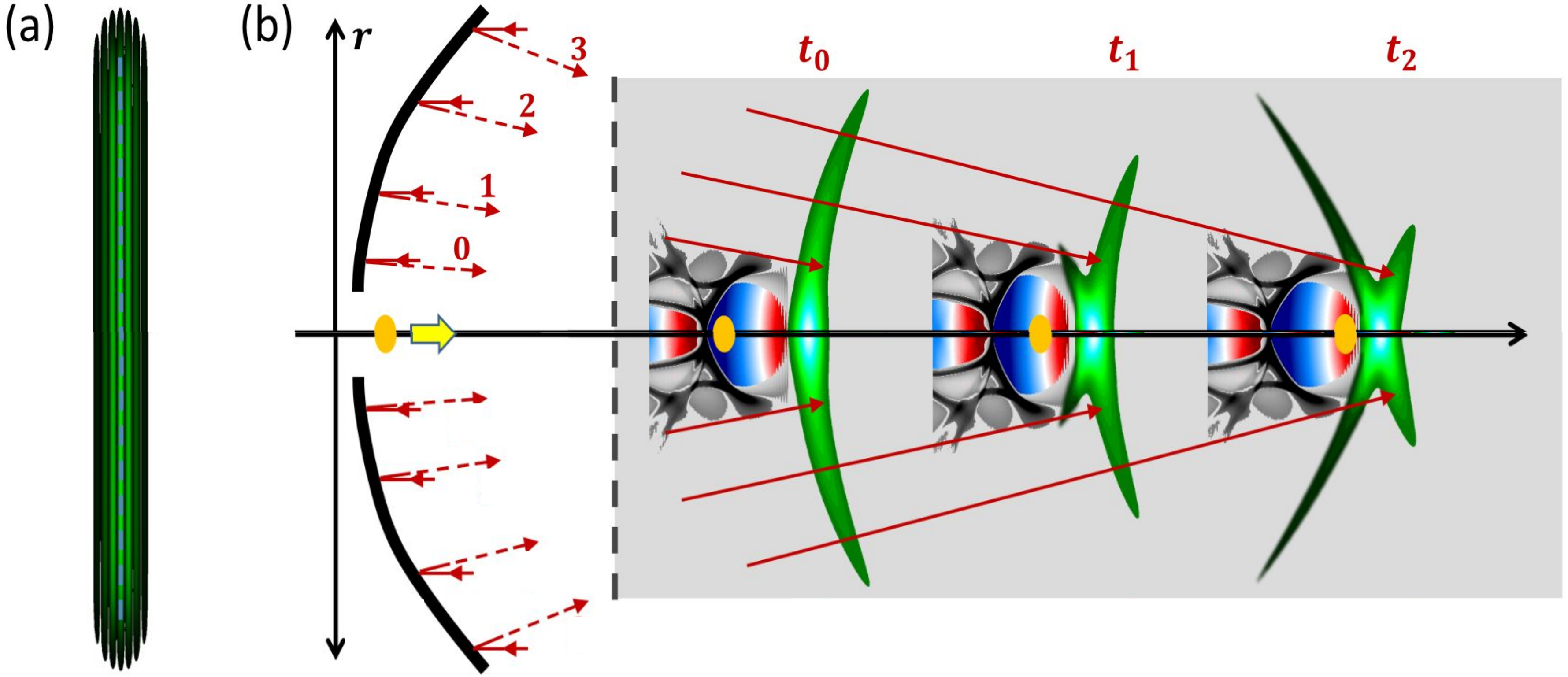

w/o STC
laser velocity
≠ electron beam velocity

C. Thaury *et al.*, Proc. SPIE 11037 (2019)

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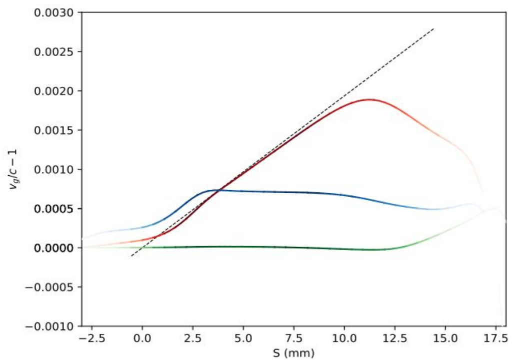
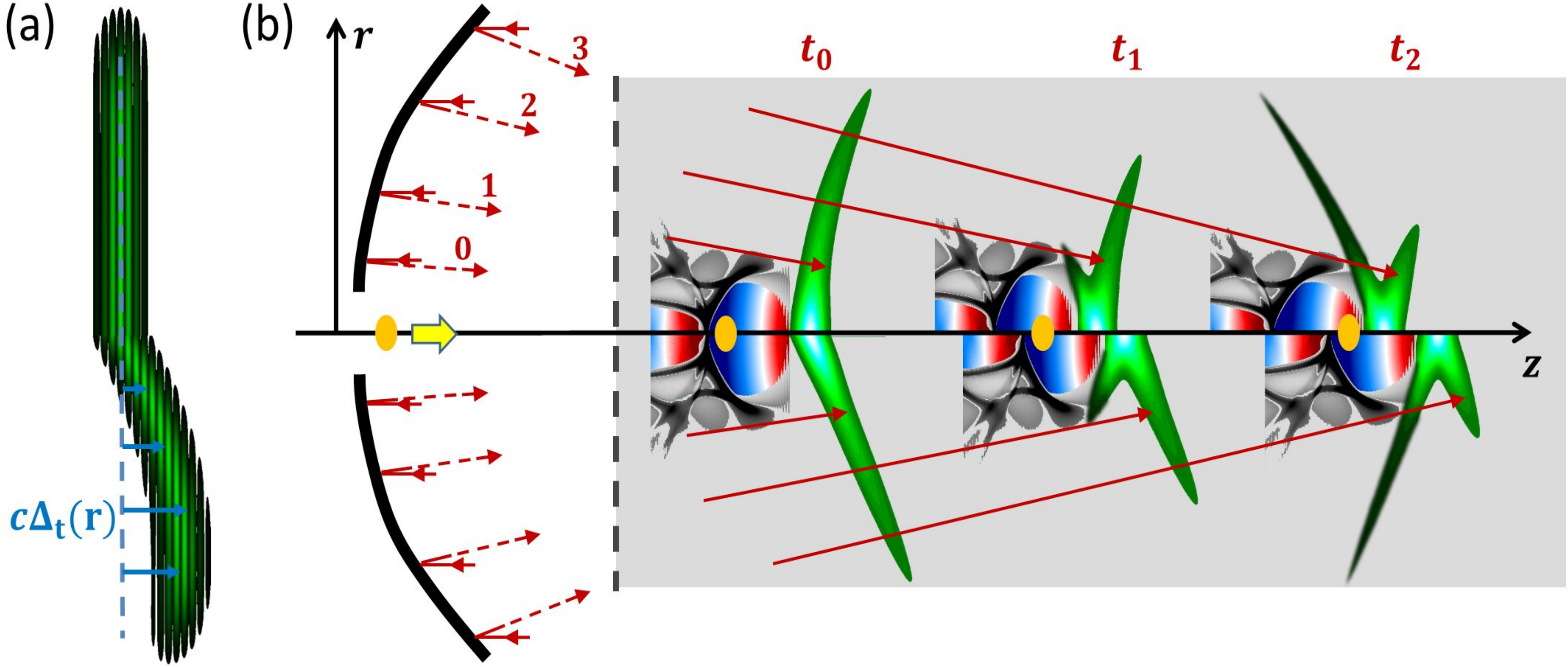
Superluminal Acceleration - Principle

- Acceleration with a diffraction-free superluminal laser beam.
- Overcoming diffraction, dephasing and depletion.





w/o STC
laser velocity
≠ electron beam velocity

with STC
the laser velocity is locked to that of the electron beam

C. Thaury *et al.*, Proc. SPIE 11037 (2019)

C. Caizergues et al. Nature Photonics **14**, 475–479 (2020)
J.P. Palastro, Phys. Rev. Lett. 130, 159902 (2020)

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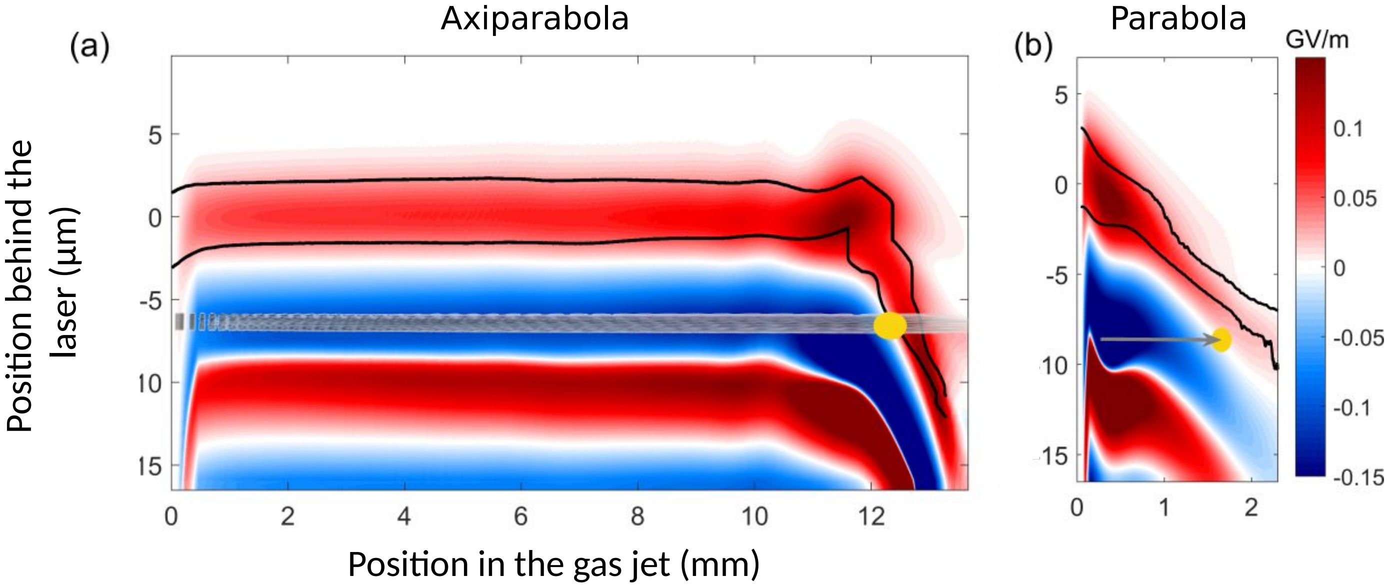
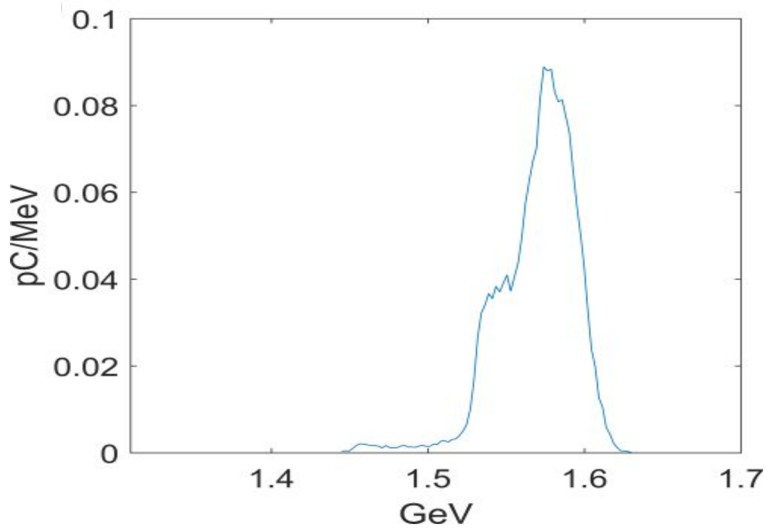
Accelerating fields





1.6 GeV with a 1 J, 15 fs laser pulse.

The electron beam remains in the region of strongest field over 12 mm.

C. Caizergues et al. Nature Photonics **14**, 475–479 (2020)

Superluminal Acceleration - Principle

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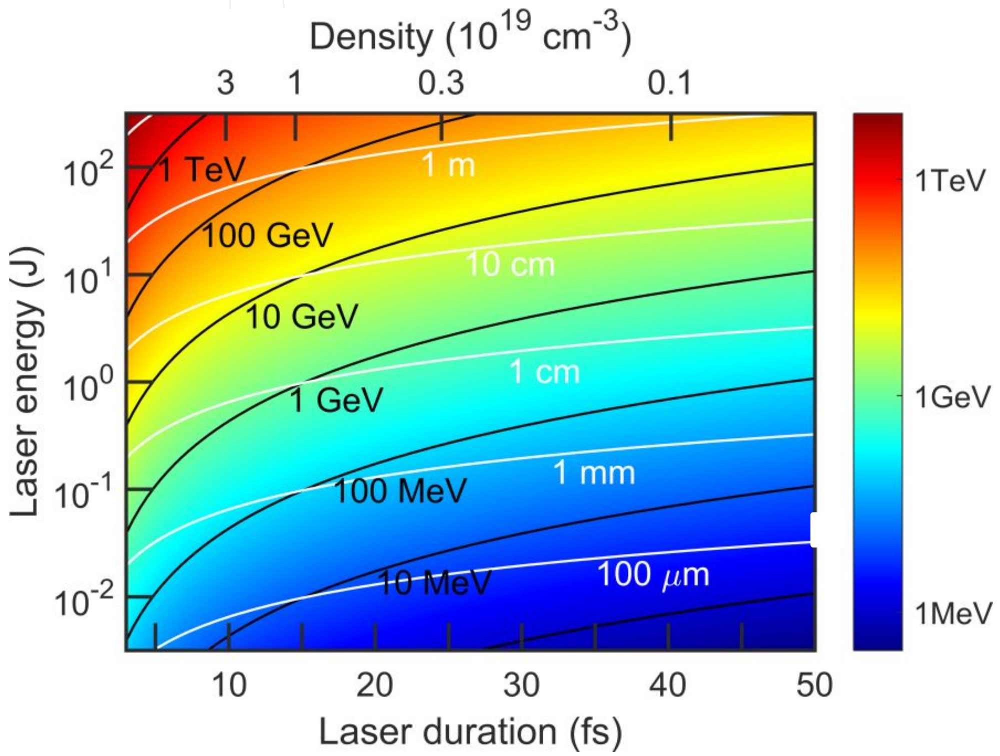
- Overcoming diffraction, dephasing and depletion.

Beam energy according to Lu's model



$\gamma \propto 1 / \tau^2$

$\gamma \propto E_L$

➡

Best gain for the shortest and highest energy laser pulses.

Up to **50 GeV** with a 1 PW, 15 fs laser.

C. Caizergues et al. Nature Photonics **14**, 475–479 (2020)

Conclusion

Acceleration in a laser-generated waveguide

- Waveguiding + density transition injection
  → good quality beams up to 2.4 GeV
- Up to 6% conversion efficiency
- Down to 2% energy spread at 1 GeV, with J-class laser
- Plasma tapering → energy x 1.4

Acceleration with a superluminal beam

- Demonstration in simulations of a new acceleration scheme
  → potential increase of the energy gain by several orders of magnitude
- **Next:** - Injection, management of the dispersion of few-cycle laser pulses in simulations
  - Proof of principle experiment

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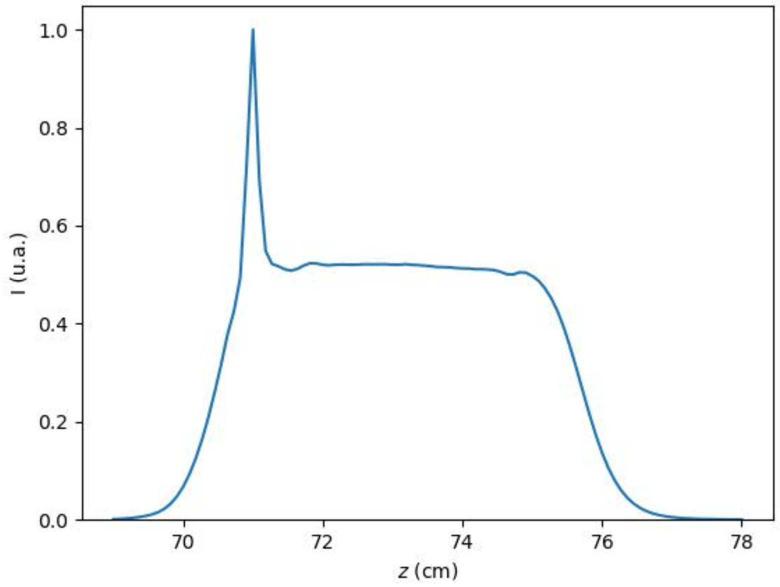
Using advanced intensity profile to control the injection without using a blade ?



Thank you for your attention

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