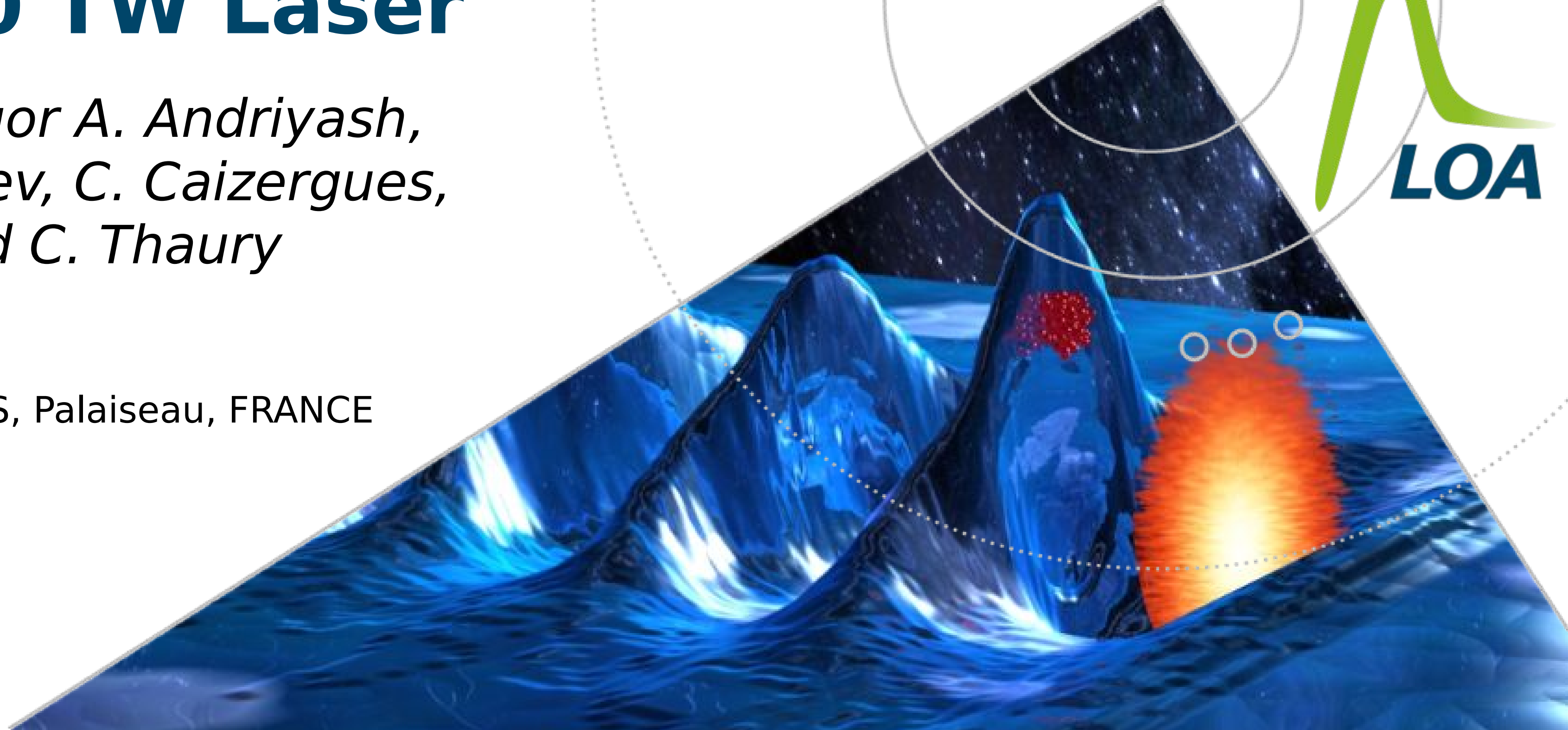
High-Quality 1 GeV Electron Beam with a 50 TW Laser

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

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

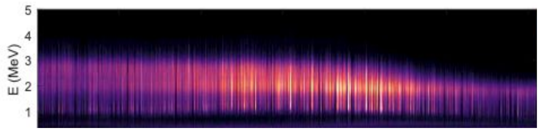


loa.ensta-paris.fr

Laser Plasma Acceleration at LOA

Salle Noire
1 kHz, 3 fs, 3 mJ laser
→ 1-15 MeV electron beams
Jérôme Faure

Physics and technology:
- Physics of the injection, role of the CEP
  *Huijts, PRX **12**, 011036 (2022)*
- Stable long-term operation
  *Rovige, PRAB **23**, 093401 (2020)*



Applications:
- Radiobiology
- Time resolved electron diffraction

Salle Jaune
2.5 J, 30 fs, 1 Hz laser
→ 5 MeV – 1 GeV electron beams

Particle beam driven wakefield acceleration
Sébastien Corde
- Staging laser-driven and beam-driven plasma acc. [*Kurz, Nature Comm.* ***12****, 2895 (2021)].*
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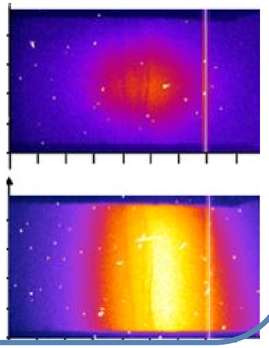

Laser wakefield acceleration
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  Oubrerie, LSA ***11****, 180 (2022)*
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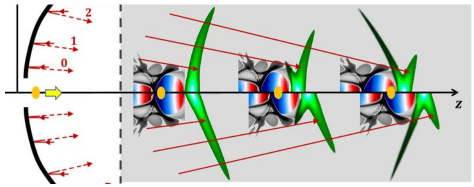
- *Industrial applications*



Quantum Electro Dynamics
Adrien Leblanc
- ERC project EXAFIELD: Probing experimental signatures of QED in the strong field regime

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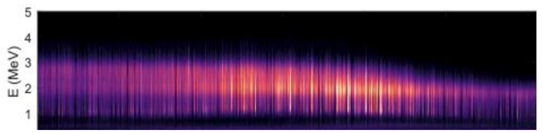

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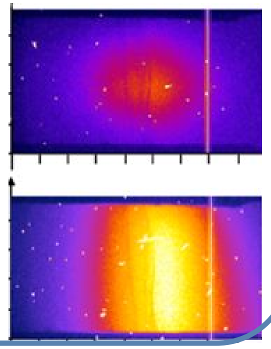

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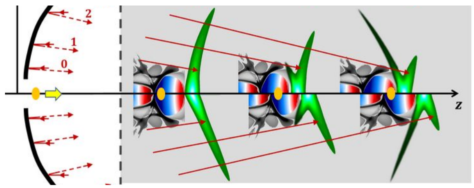

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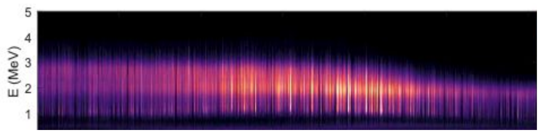

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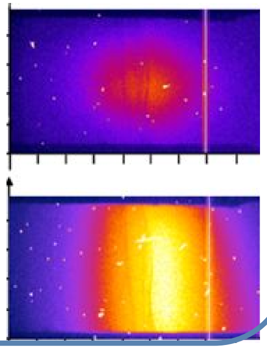

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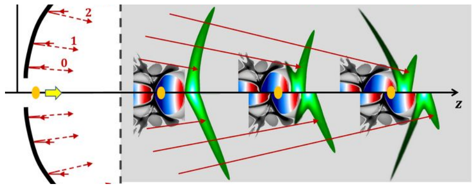
L. Martelli, Poster We



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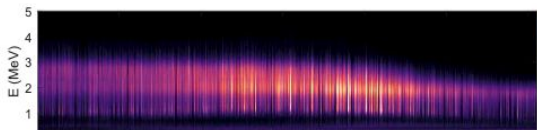

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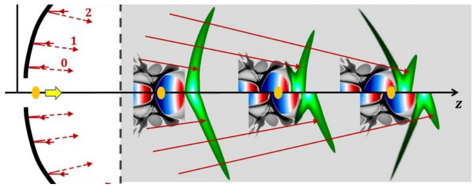

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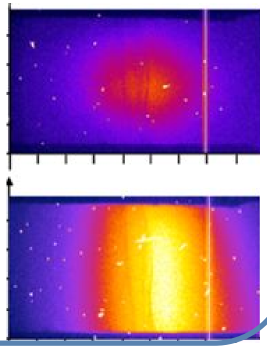

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H. Vincenti (CEA), Mo

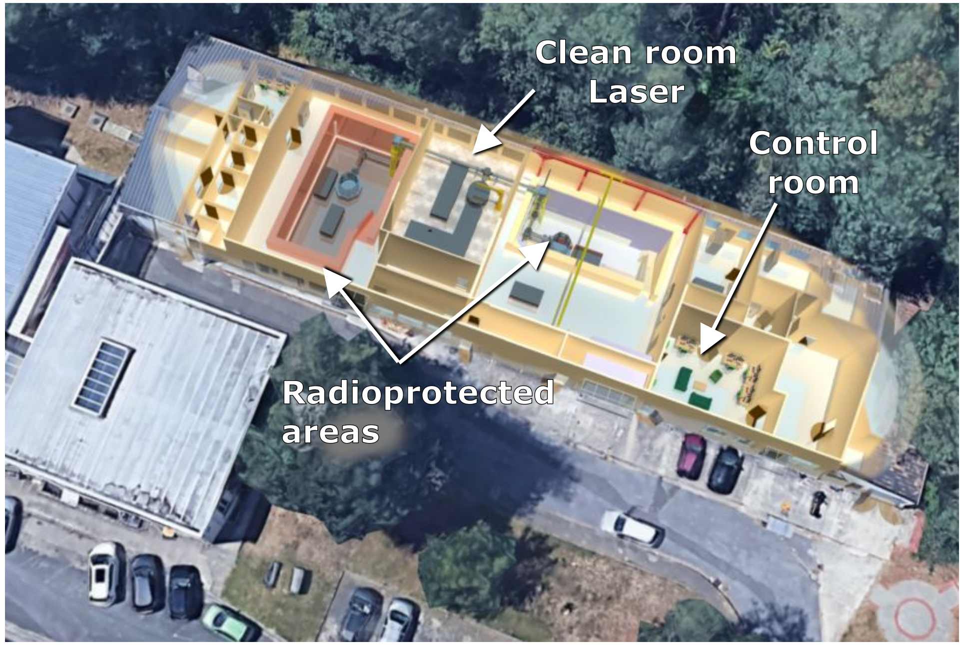
The LAPLACE Project

LAPLACE HC

- 80 m² clean room
- Laser 1 J @ 100 Hz
- 50 m² radioprotected area
- 2nd radioprotected area in option

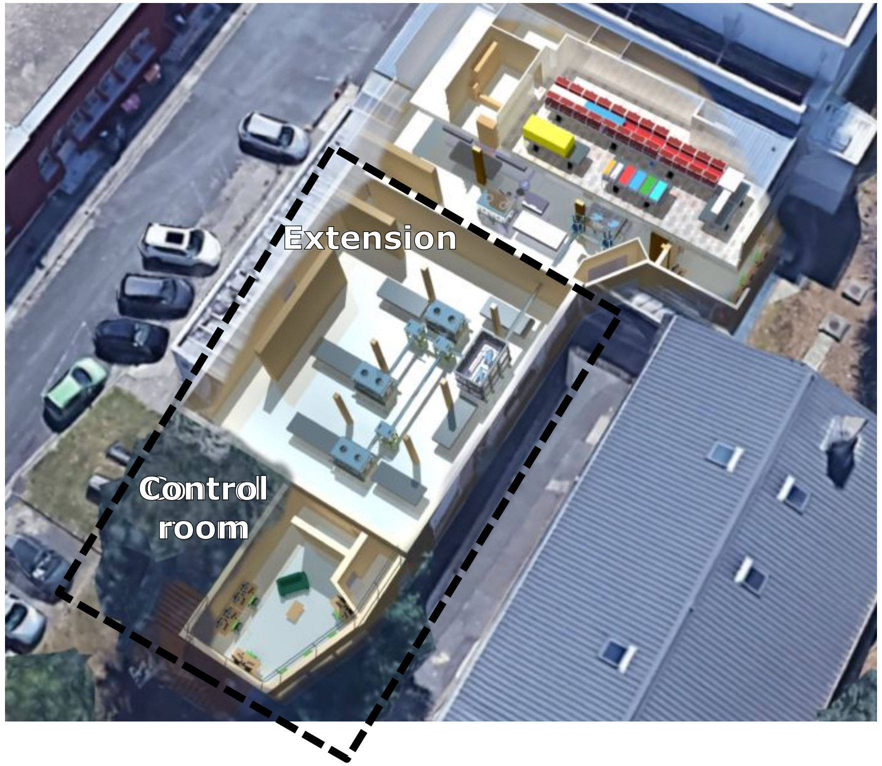
Average power of ~ 100 W (vs 1 W now)

O. Chalus , WG2 Th. (THALES LAS)



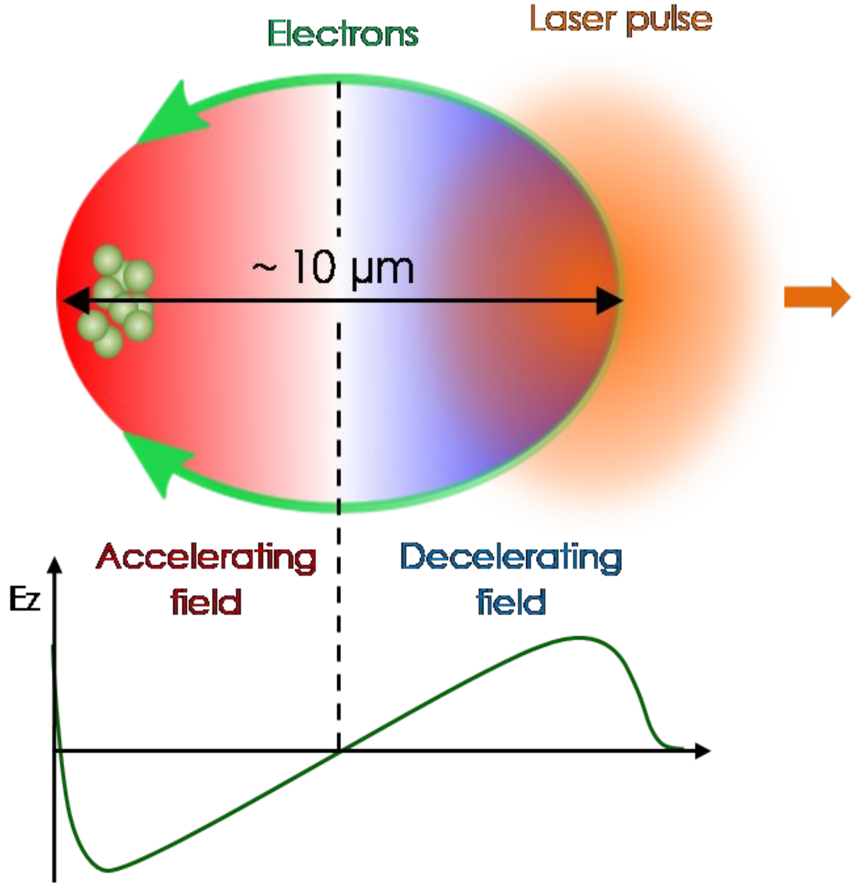
LAPLACE HE

- Doubling of the experimental area (>500m²)
- Doubling of beam time
- Upgrade to 300 TW (10 J)



http://laplace-loa.fr

Challenge: Producing High-Energy, High-Quality Beams

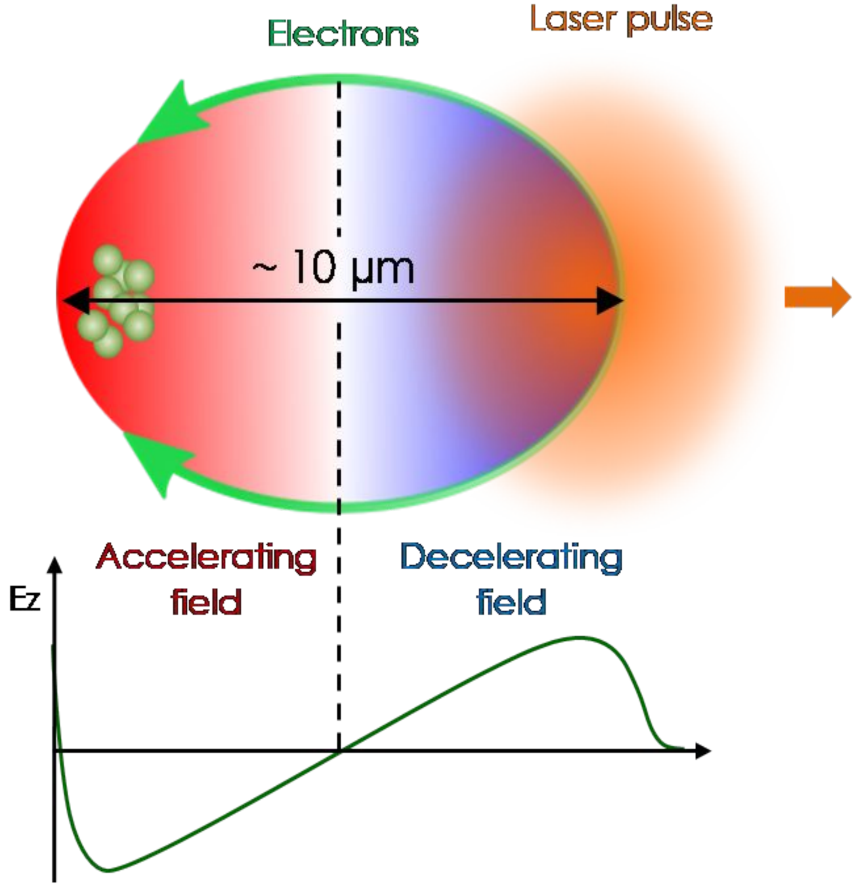


- Achieving a **high quality beam** requires to control the trapping of an electron beam into a μm cavity that moves at c.

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

- The **stability** suffers from the non-linearity of the interaction → requires a high level of stabilization of the laser and target parameters.

Challenge: Producing High-Energy, High-Quality Beams



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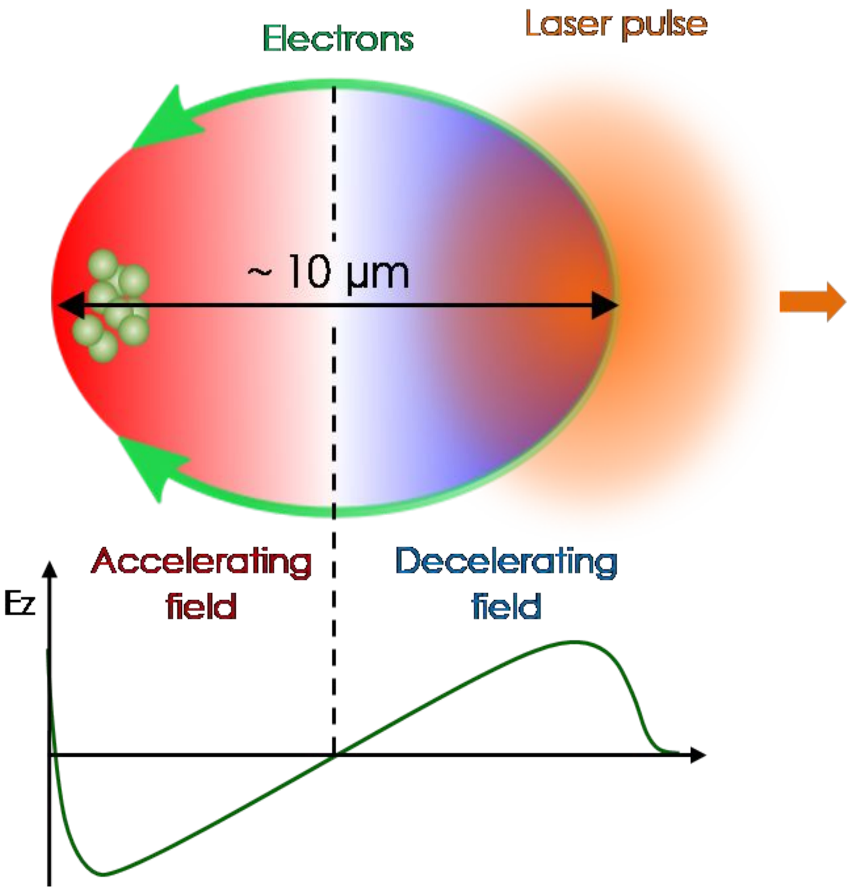

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- **High energy** requires to sustain a high amplitude electric field and to keep the electron beam in this field over a long distance (>cm).
  → **laser guiding**

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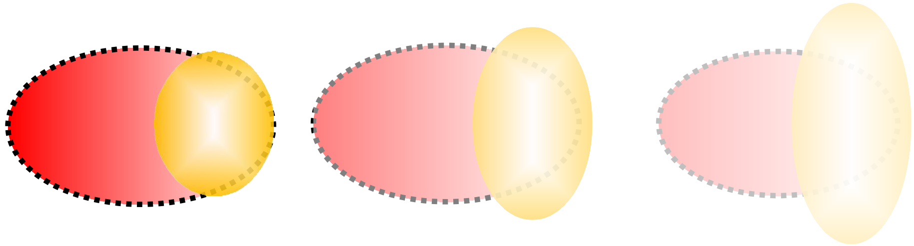
Energy Limits in Laser Wakefield Accelerators

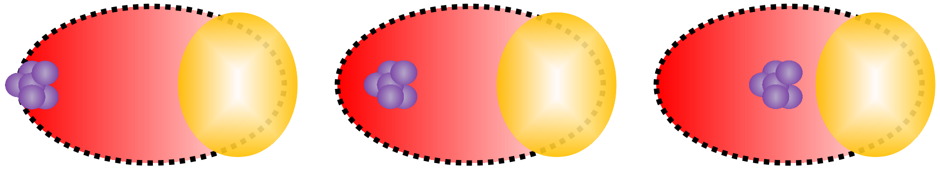
Diffraction



Laser intensity decreases because the laser diverge.

⇒ high plasma density (self-focusing)

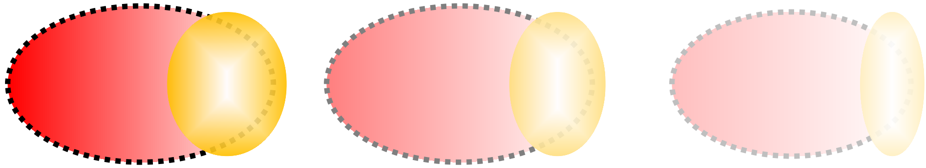
Dephasing



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.

⇒ low plasma density

Energy Limits in Laser Wakefield Accelerators

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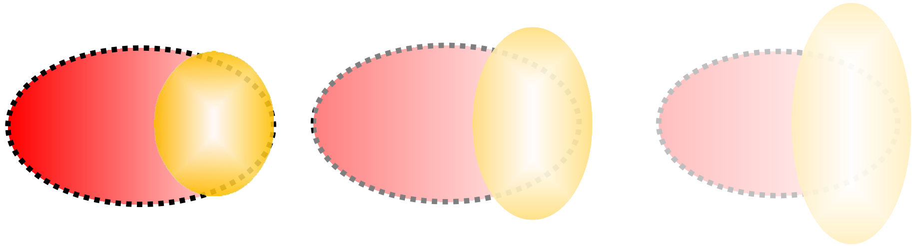

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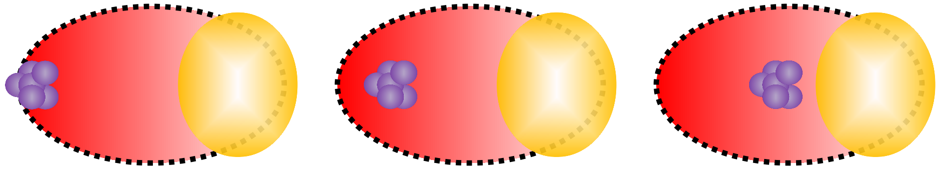

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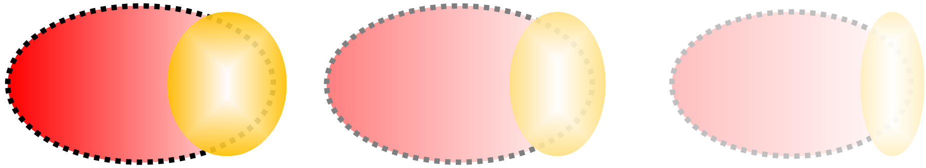
An additional degree of freedom is needed

Depletion



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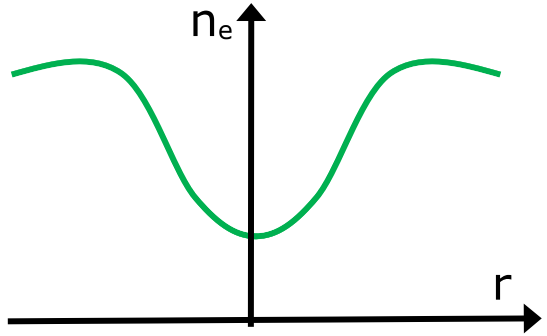
Plasma Wave-Guide



Refractive index $\eta = \sqrt{1 - n_e / n_c}$

➨ acts as a lens

➢ The channel results from the expansion of a hot plasma column.

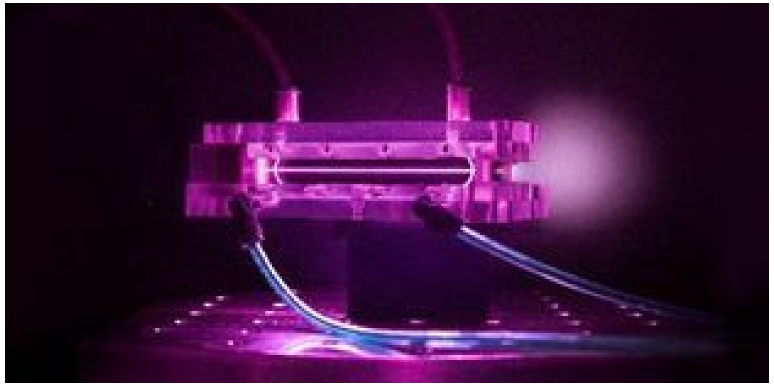
➢ It can be generated either by a discharge or by a laser.

Optical guide

Durfee *et al.* PRL **71**, 2409-2412 (1993)

Capillary discharge

Buttler *et al.* PRL **89**, 185003 (2002)



Capillary Discharge

Bella center at LBNL

nature physics | VOL 2 | OCTOBER 2006

⇒ **1 GeV** (acc. length ~ 1 cm)

PRL **113,** 245002 (2014)

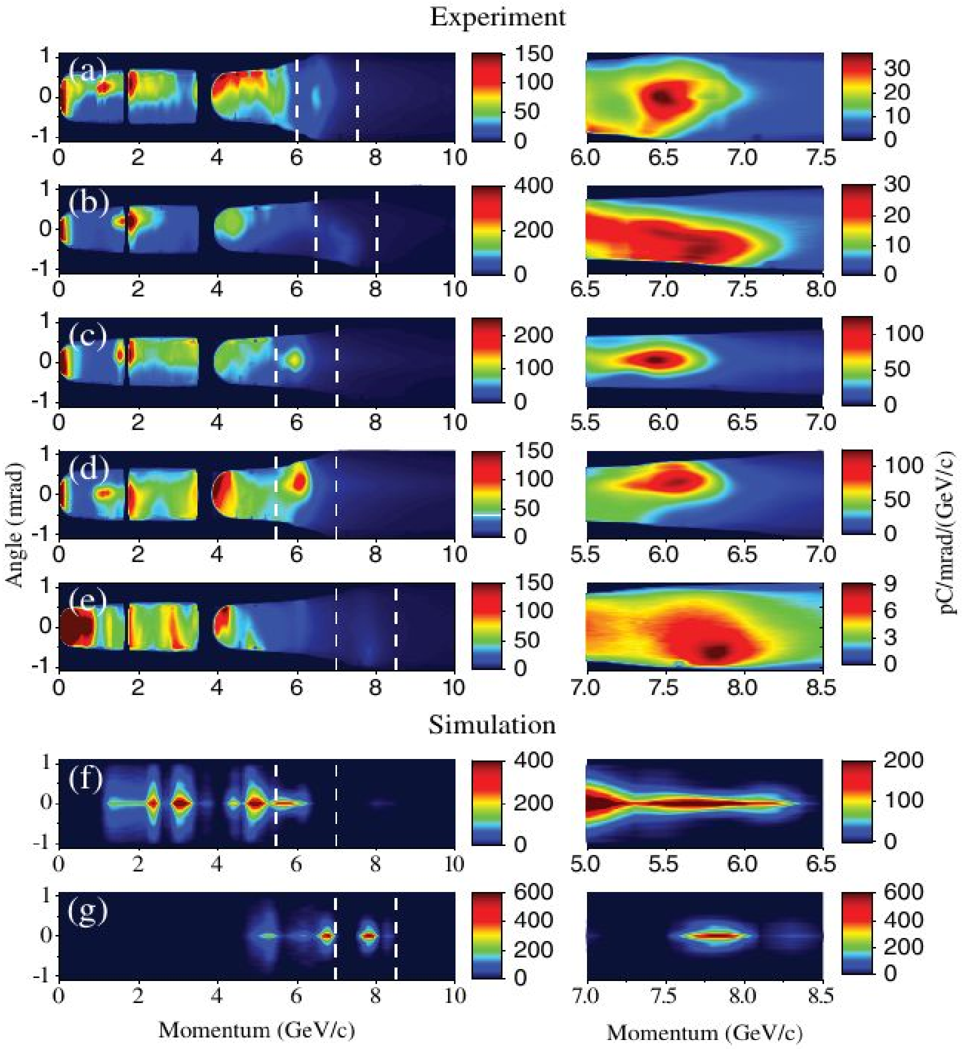
⇒ **4 GeV** (acc. length ~ 9 cm)

PHYSICAL REVIEW LETTERS **122,** 084801 (2019)

⇒ **8 GeV** (acc. length ~ 20 cm)

Main drawback:

- Plasma is encapsulated in a capillary
  - → difficult to shape the plasma
  - → risk to damage the capillary
- Operation at very low densities is challenging.



→ Hydrodynamic Optical Field Ionization → Aaron ALEJO talk on Monday

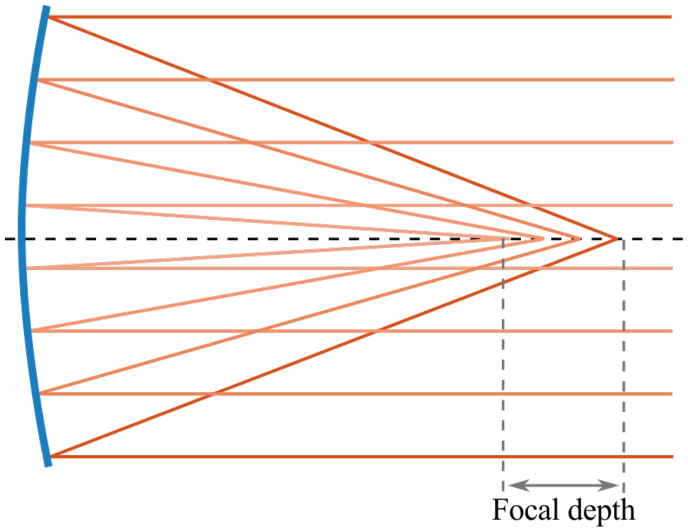
A New Optics for All-Optical Guiding: Axiparabola

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

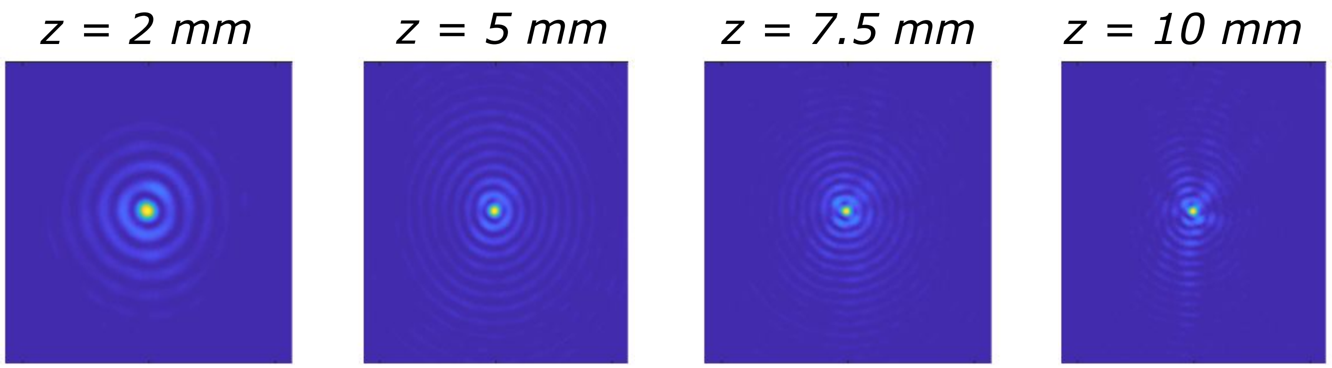
$$f(r) = f_0 + \delta(r)$$

Top hat beam and constant intensity line :

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



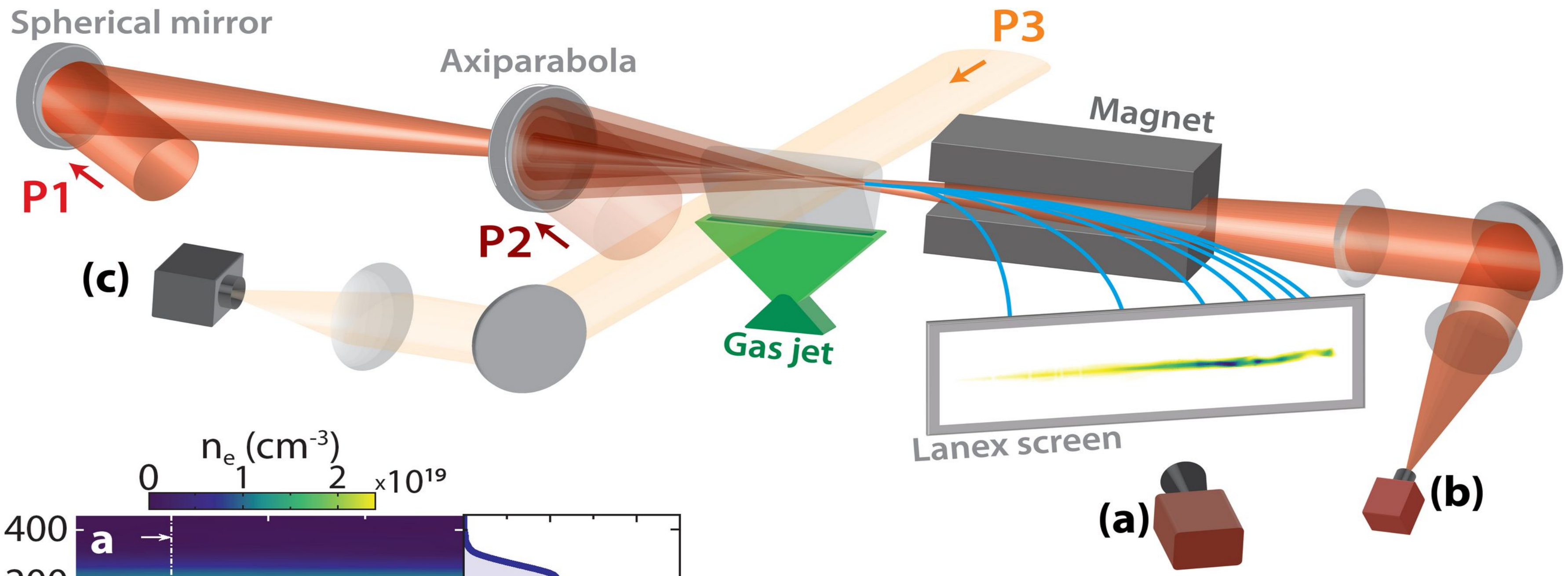
Laser focal spot along the line

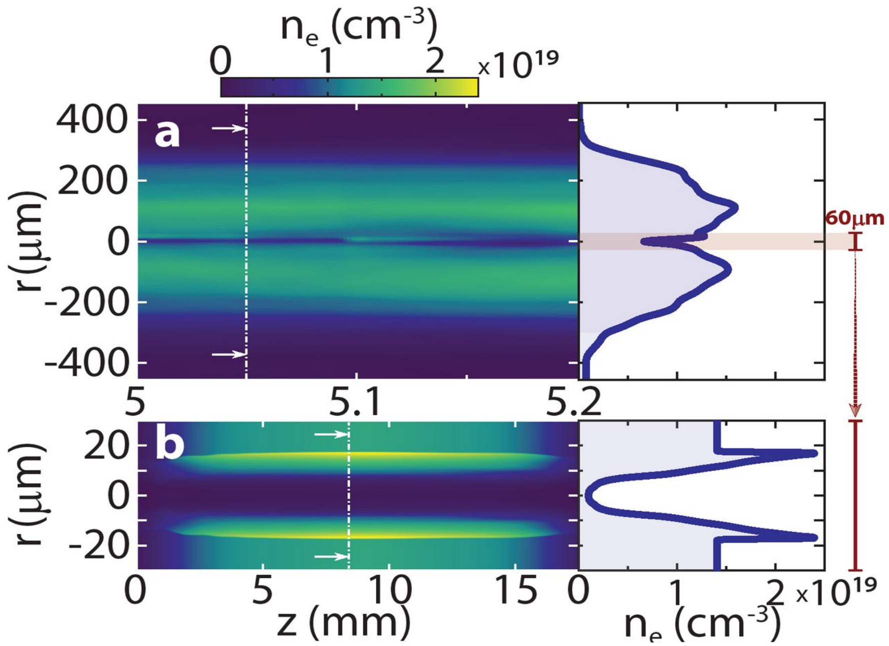


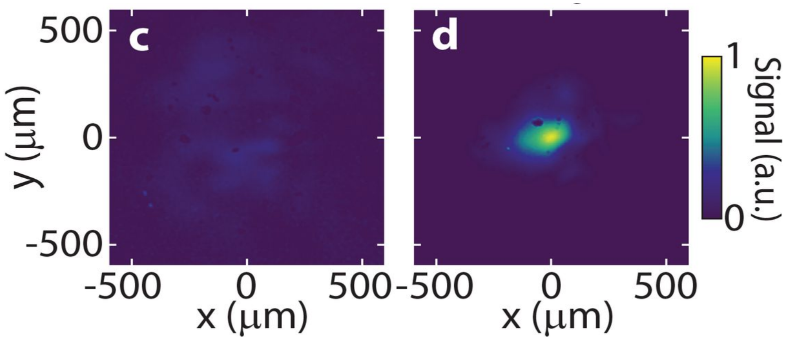
The surface can be shaped to get non-monotonic intensity profiles, curved lines...

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

Acceleration in a Laser-Generated Waveguide

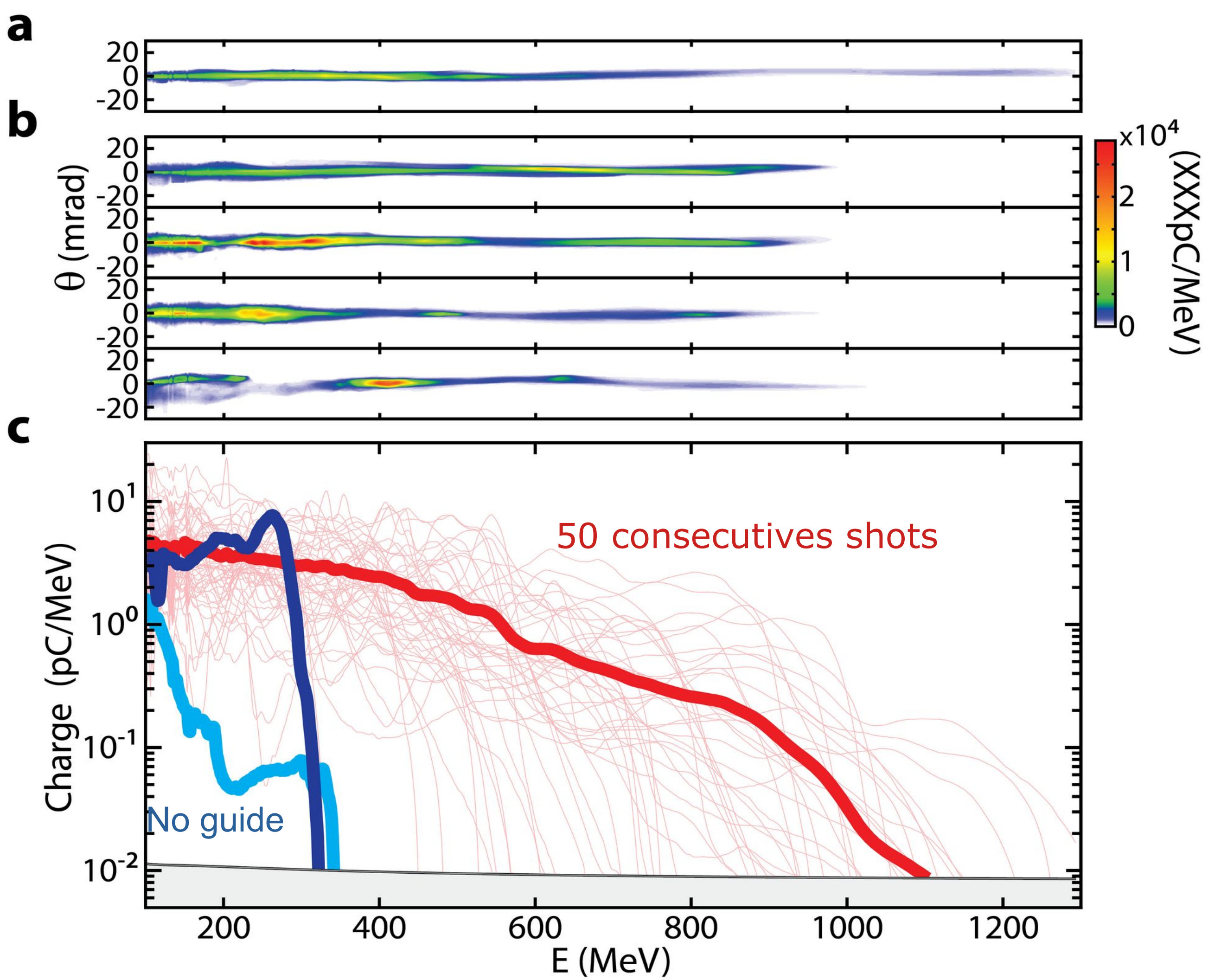






Acceleration in a Laser-Generated Waveguide

Ionization injection (gas= Hydrogen + 1% Nitrogen)

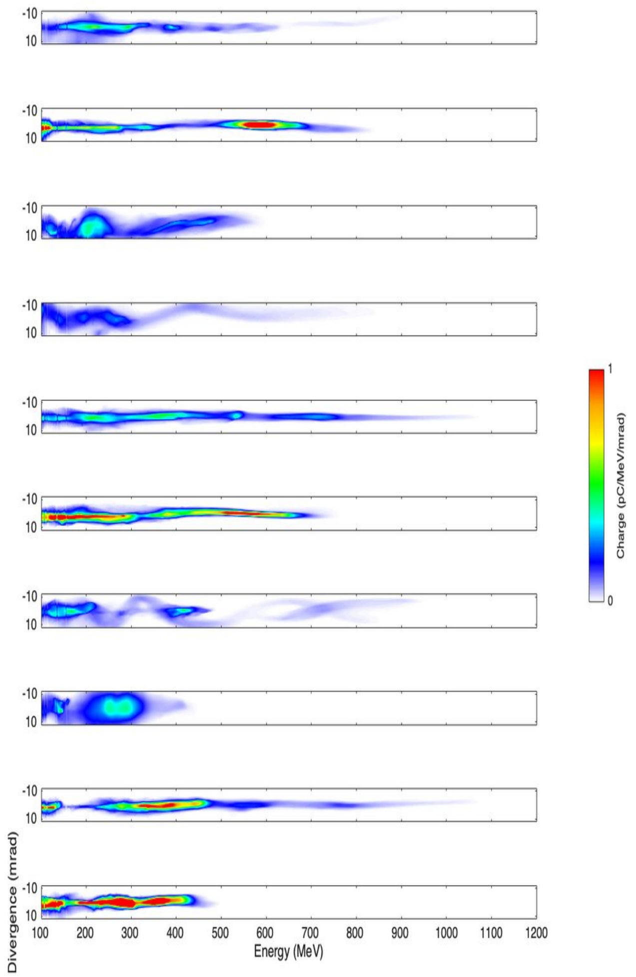


- 1.7 J – 30 fs laser for aceleration
- 15 mm gas jet
- 5 mJ for generating the waveguide
- Up to ~1.1 GeV electron energy

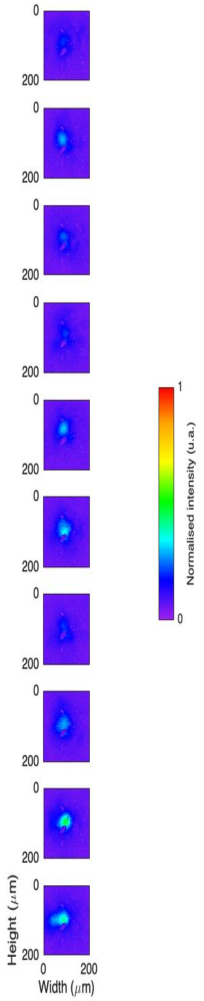
- 70% of shots with guiding and electron energy > 600 MeV
- 50 pC above 350 MeV (2% conversion efficiency)

Laser Pointing and Beam Stability

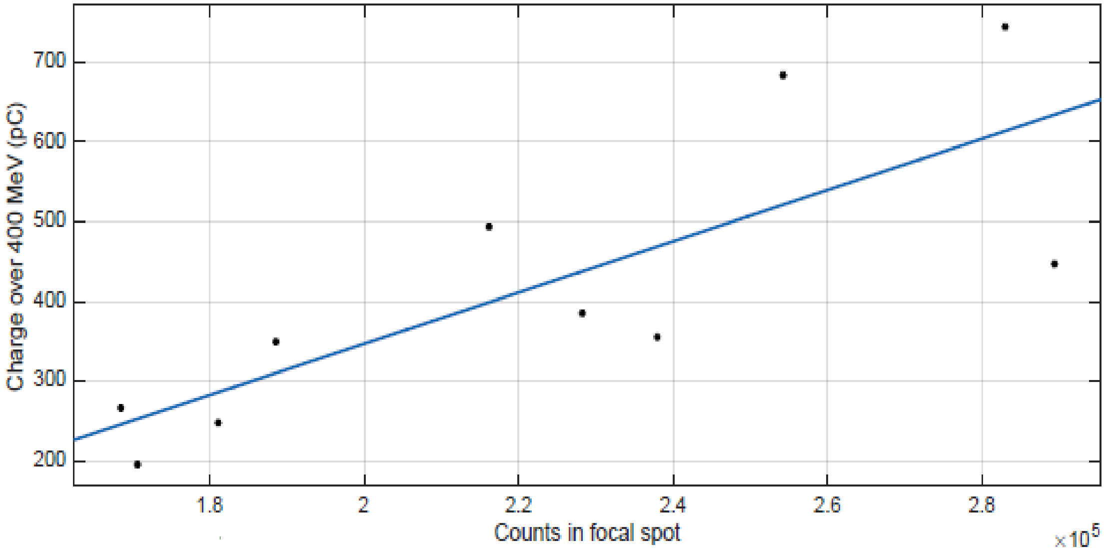
Consecutive electron spectra



Focal spots



Correlation between guiding quality and injected charge

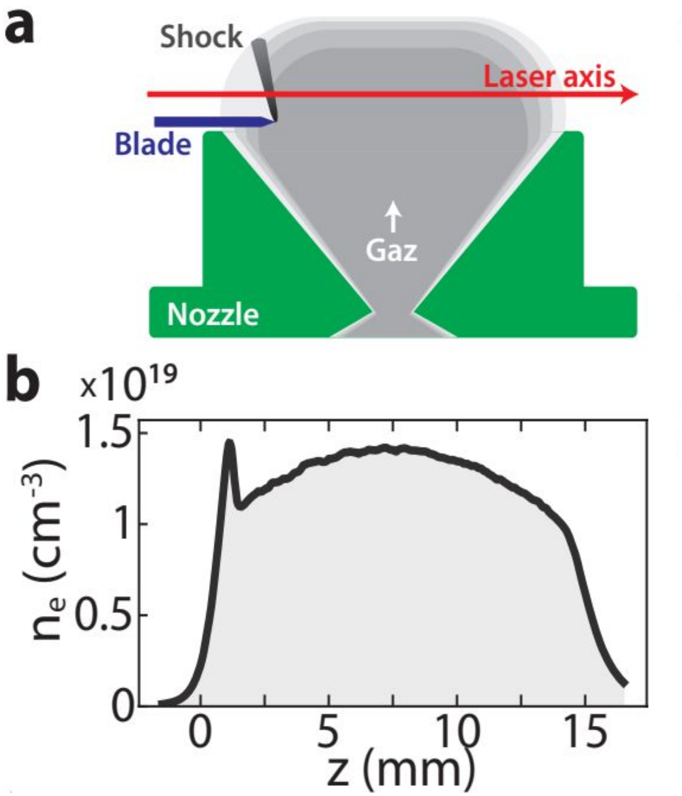


Laser pointing has to be controlled to stabilize the accelerated charge.

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

Controlled Injection in a Laser-Generated Waveguide

Density transition injection



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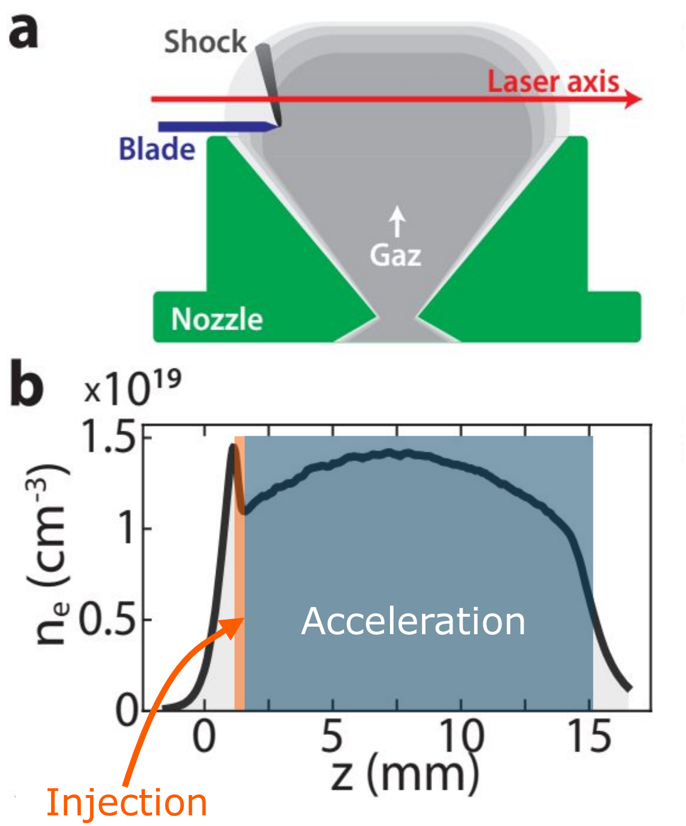
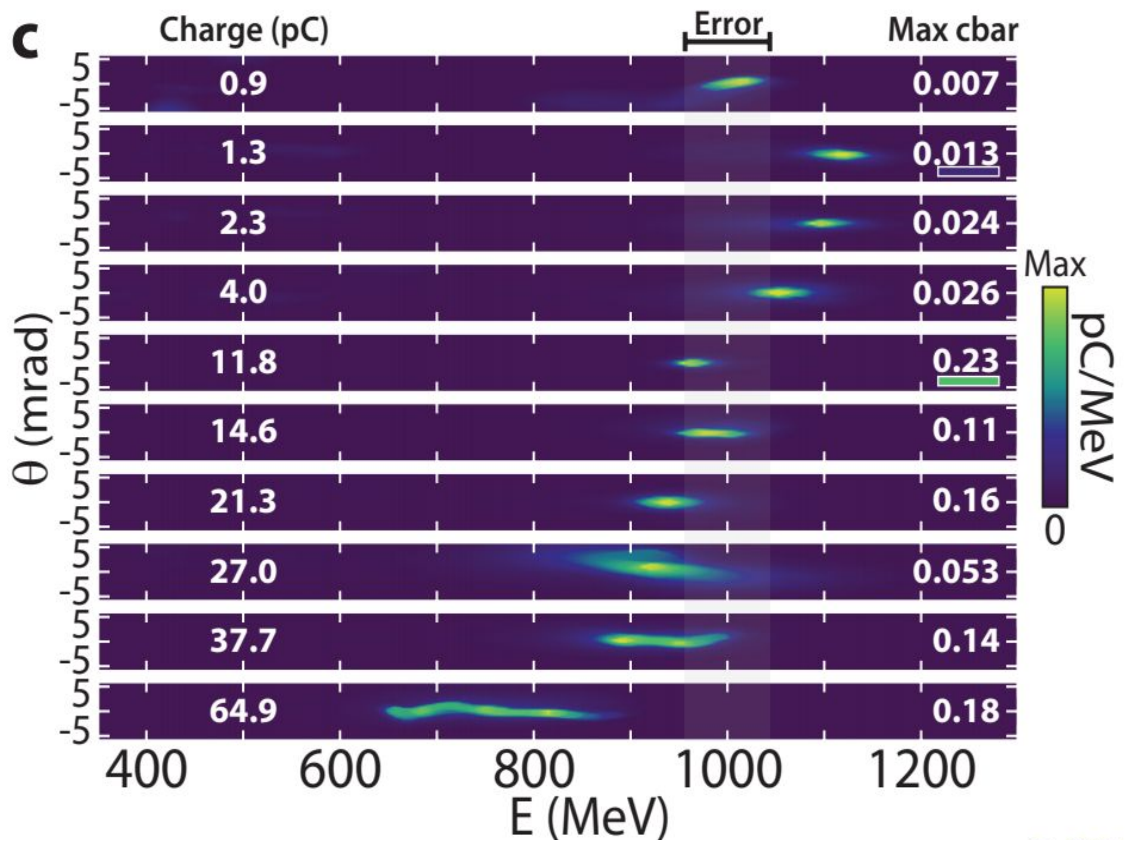


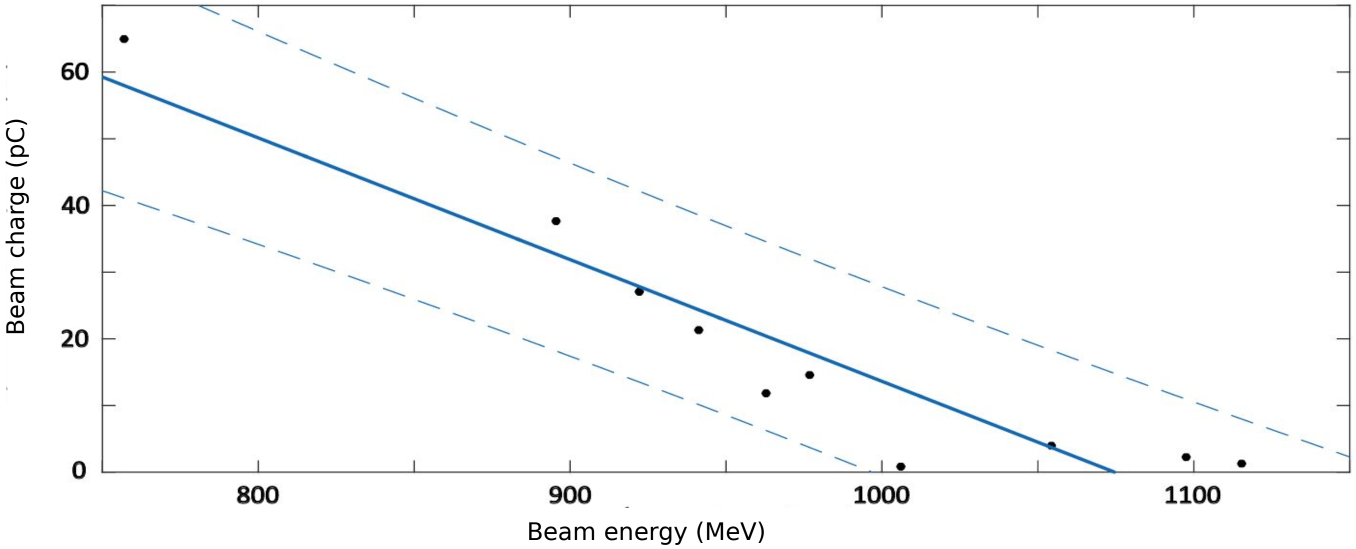
10 shots selected from a series of 14 sorted by charge

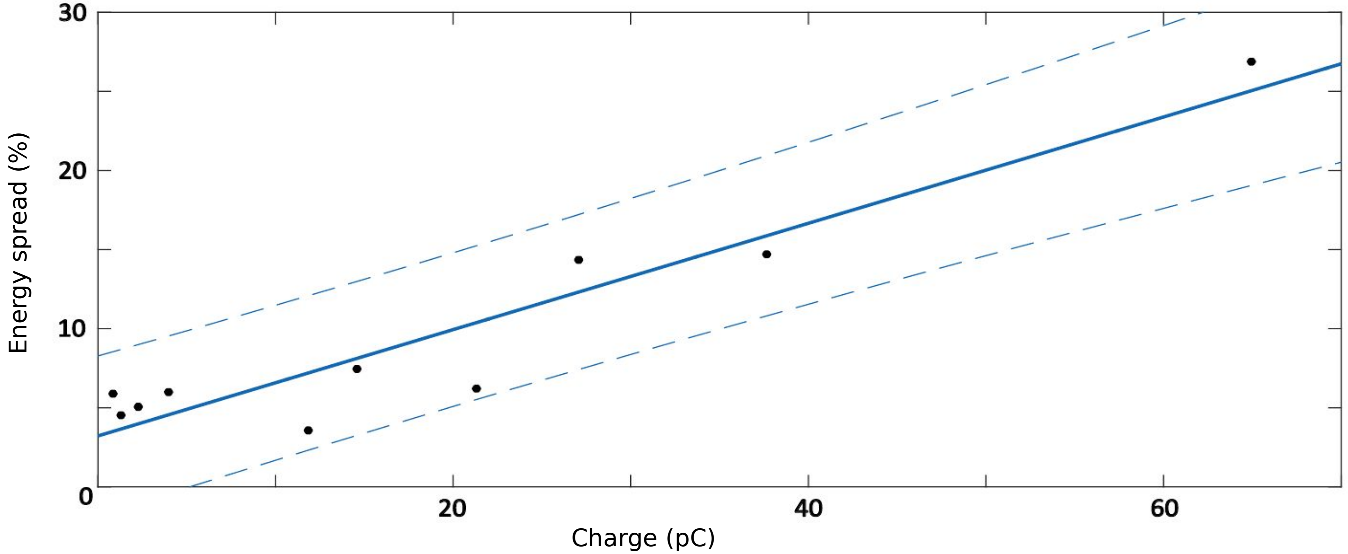


Guided laser ➡ peaked spectra > 600 MeV

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)

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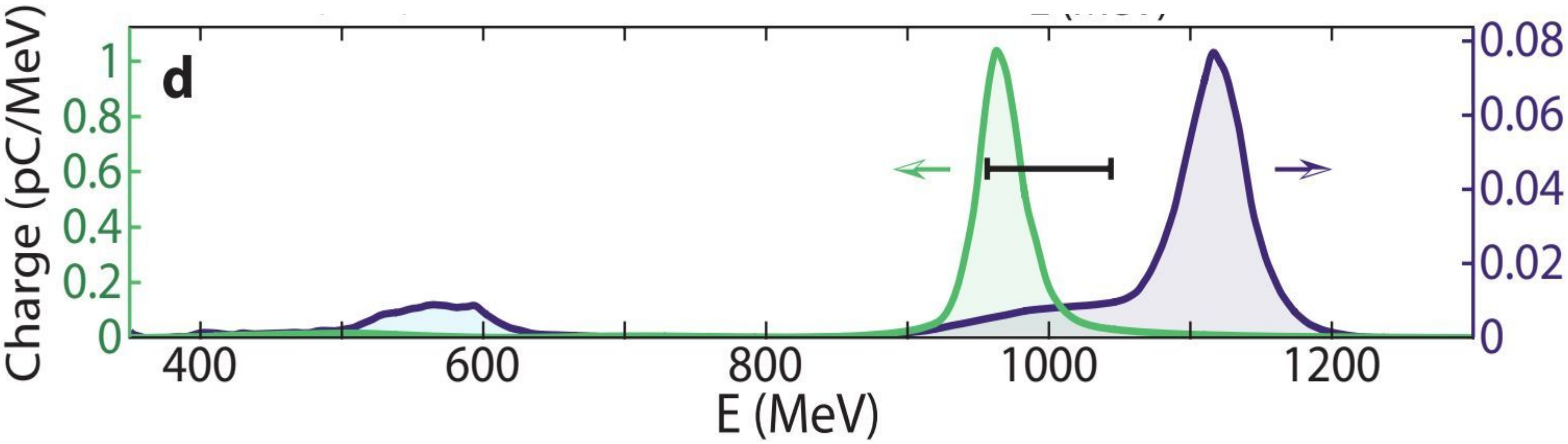


◆ Down to 2% energy spread (3.6% without divergence deconvolution)

◆ 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)

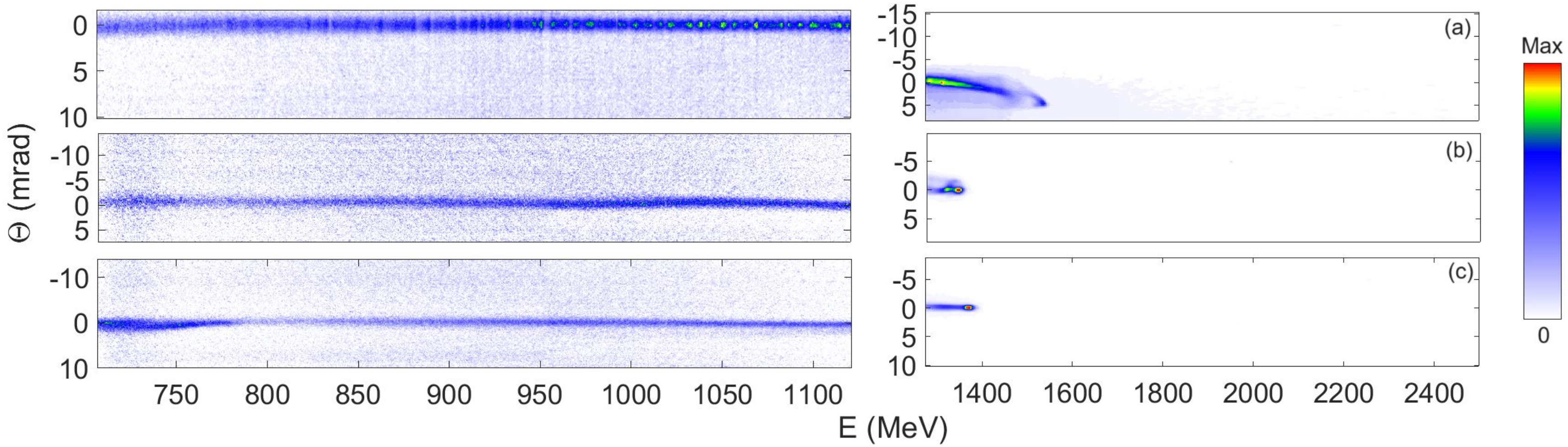
Increasing the Laser Energy with a PW-class Laser

View of the experiment

Target (6 cm long nozzle + blade)

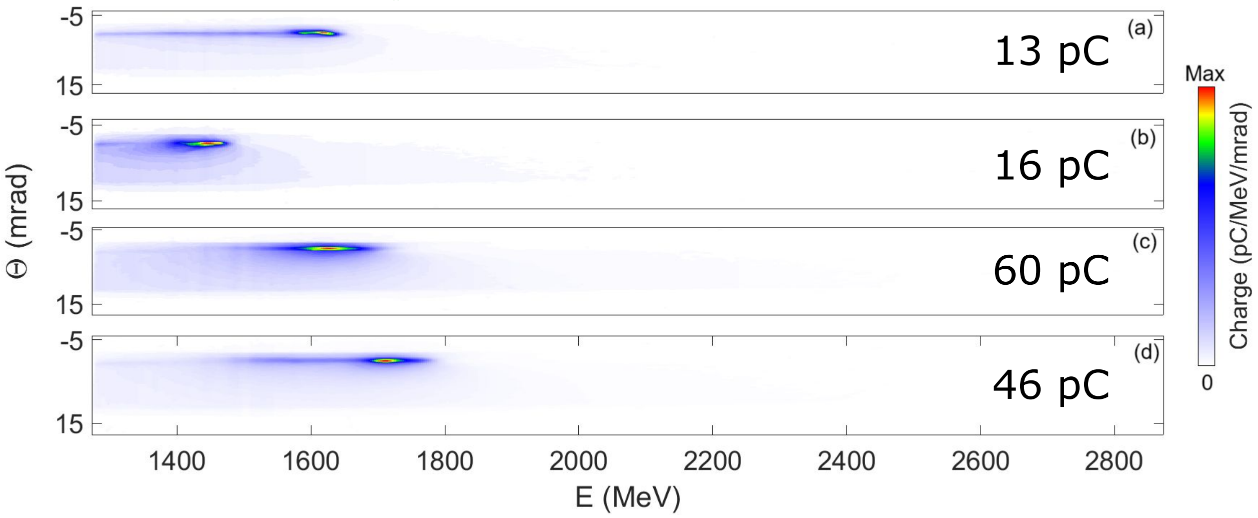
Apollon laser ~ 10 J on target, 25 fs
Helium gas

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



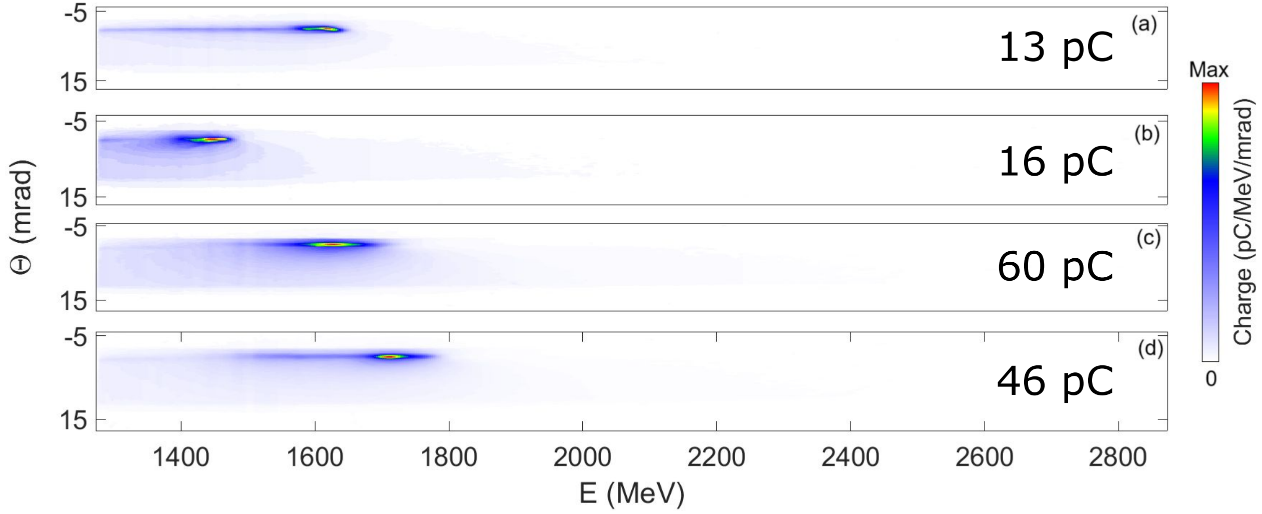
Increasing the Laser Energy with a PW-class Laser

Blade

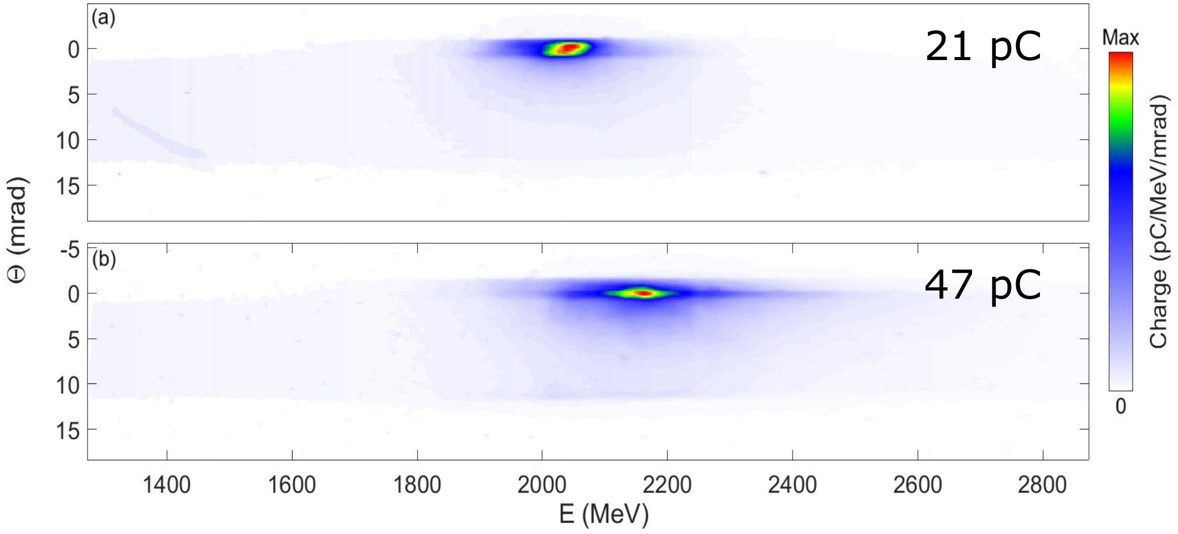


Increasing the Laser Energy with a PW-class Laser

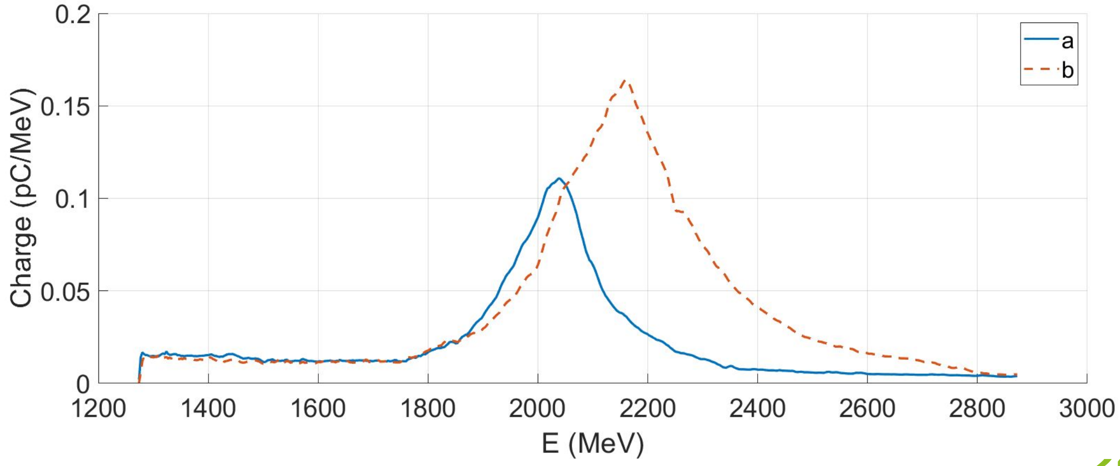
Blade



Blade + guiding



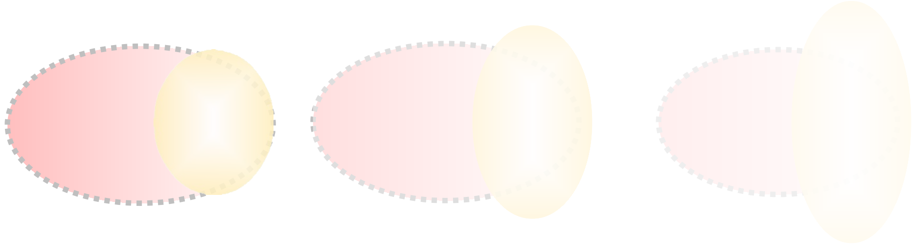
- 2.2 GeV
- 1% conversion efficiency
- 10% energy spread



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

Energy Limits in Laser Wakefield Accelerators

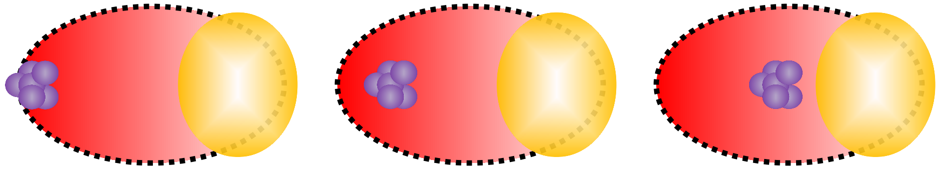
Diffraction



Laser intensity decreases because the laser diverge.

⇒ high plasma density (self-focusing)

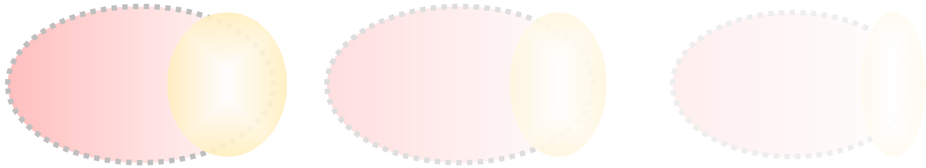
Dephasing



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

⇒ low plasma density

Depletion

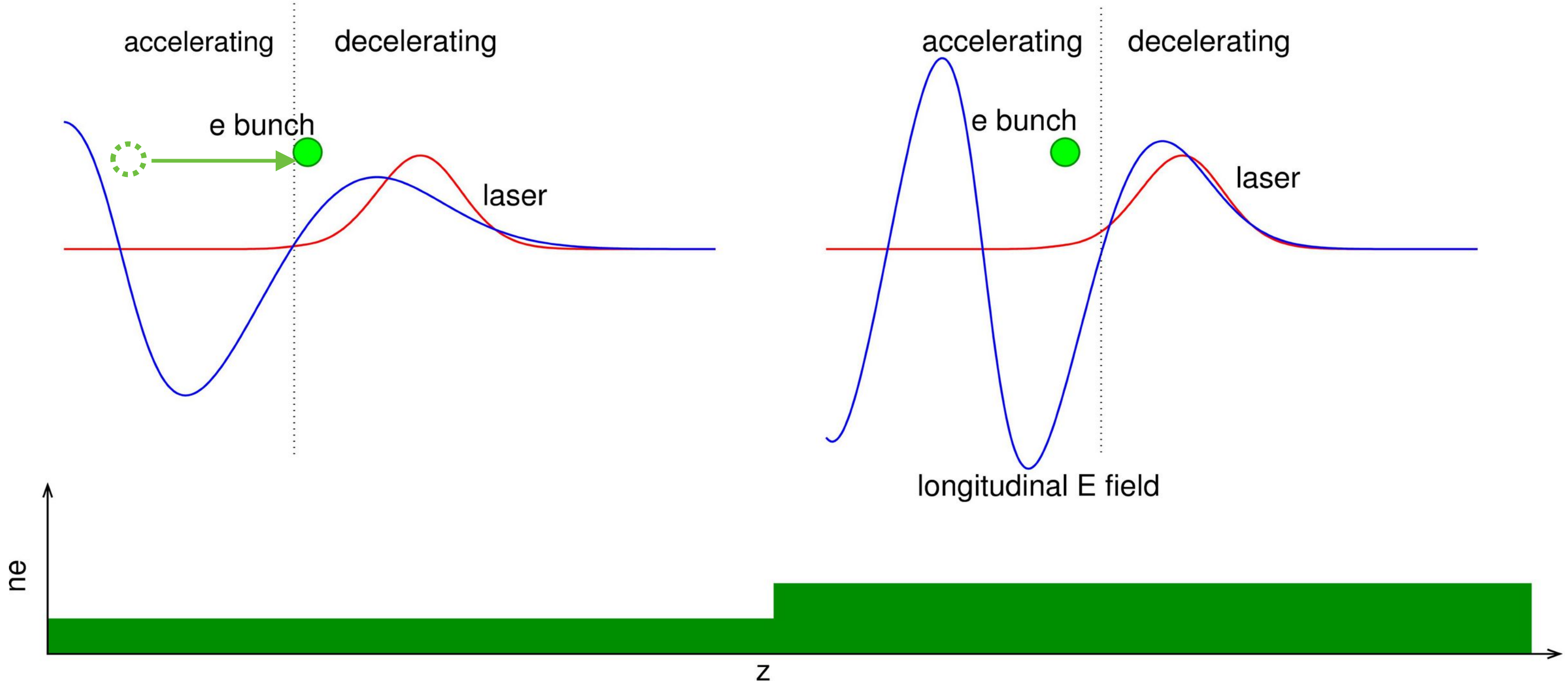


Laser intensity decreases as the laser gives its energy to the plasma.

⇒ low plasma density

The Rephasing Technique

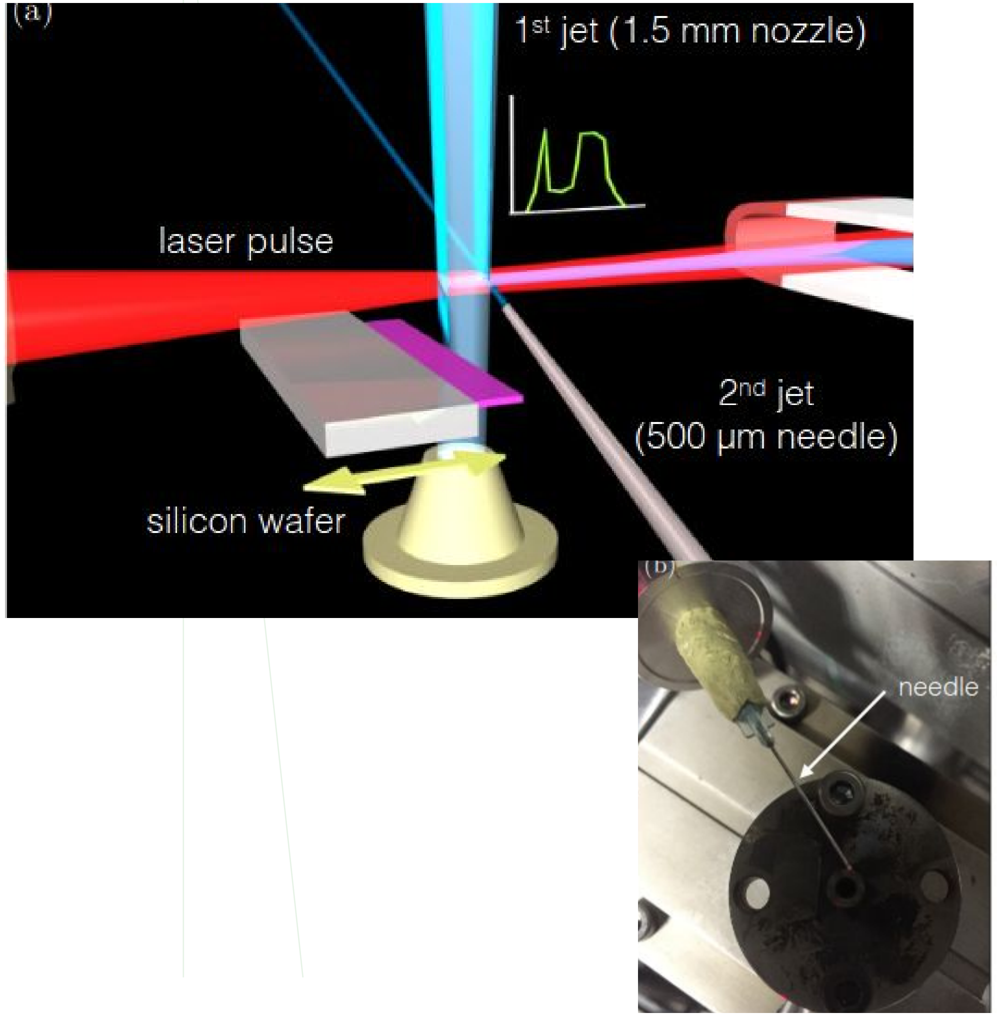
Idea: use plasma shaping to counter dephasing



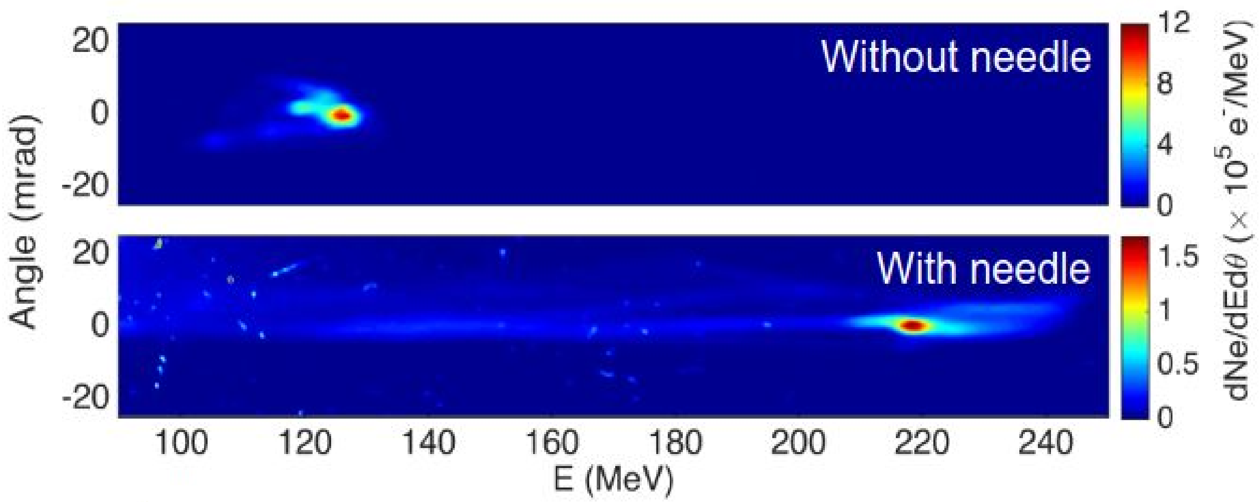
A density step is used to rephase the electron bunch

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

The Rephasing Technique



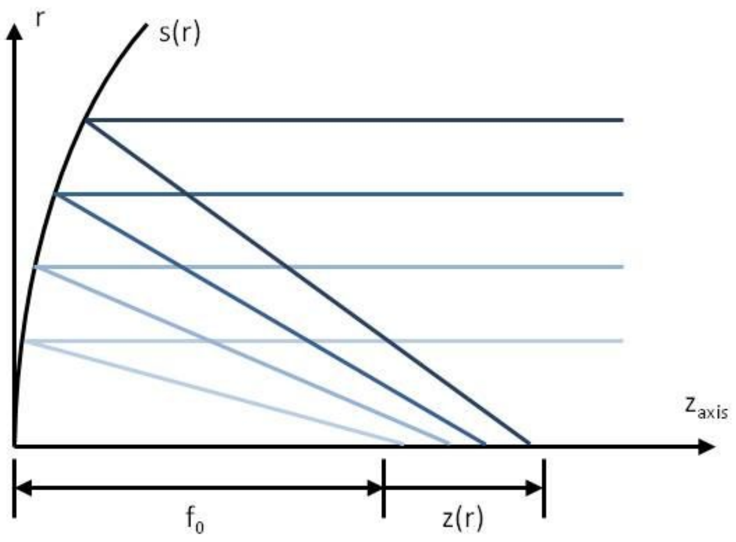
60% energy gain



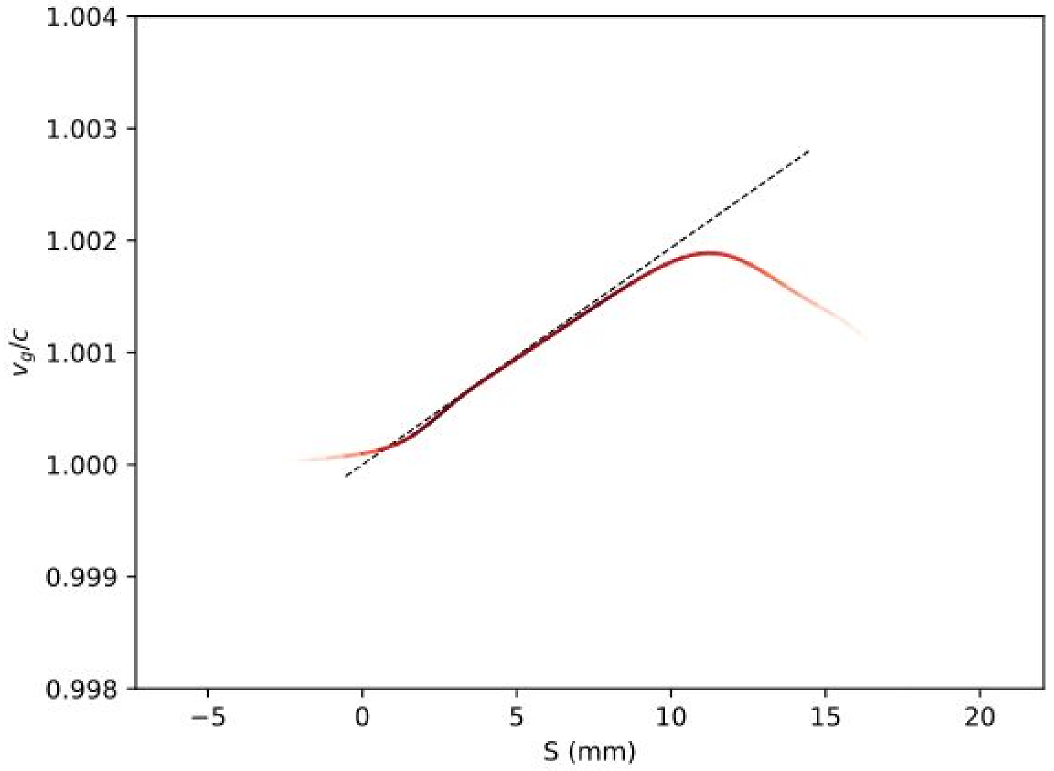
➡ to be tested with guiding

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

Axiparabola: Control of the Velocity - Theory



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

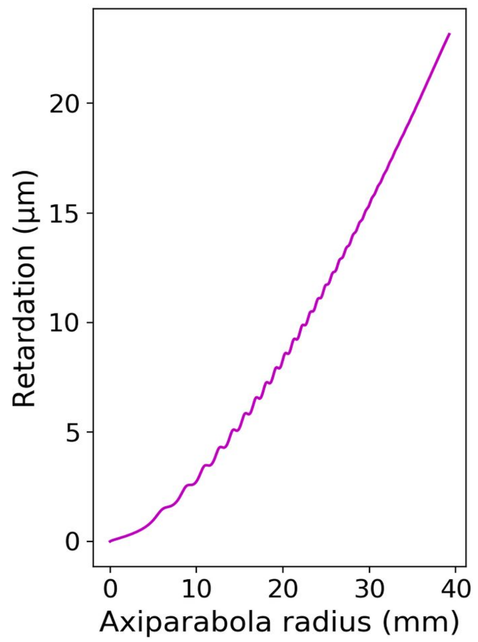


Intensity peak goes faster than c along the optical axis

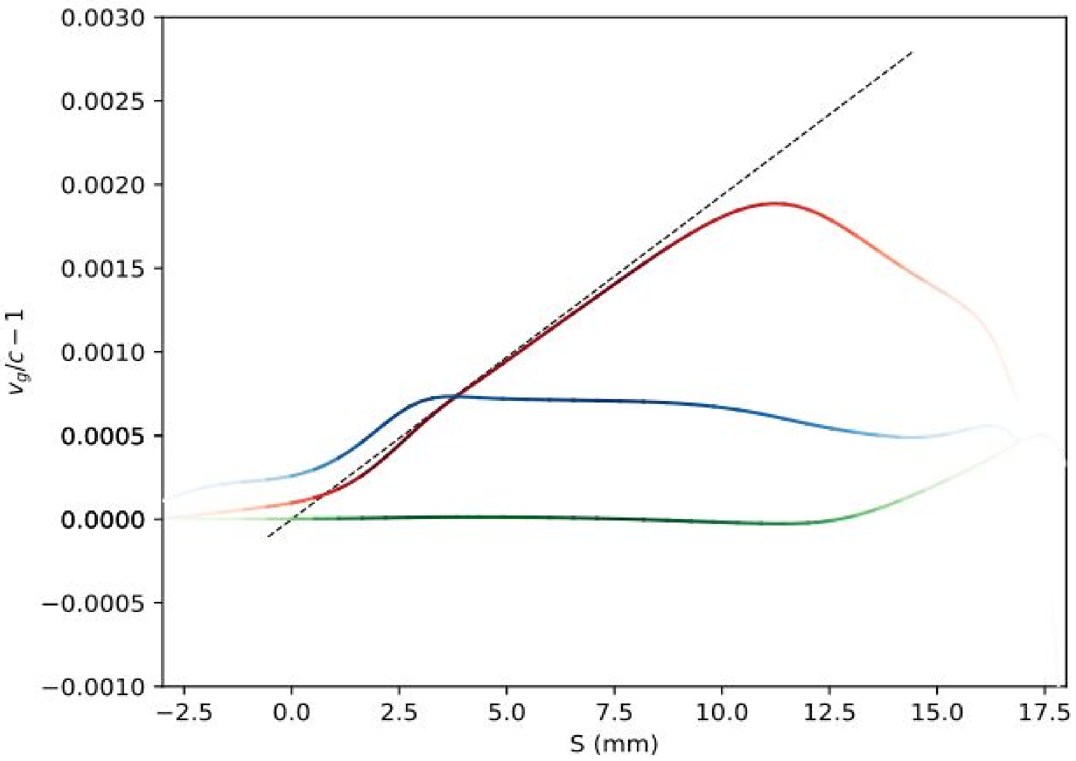
Oubrerie et al.J. Opt. 24 045503 (2022)

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.



Velocity along the focal line



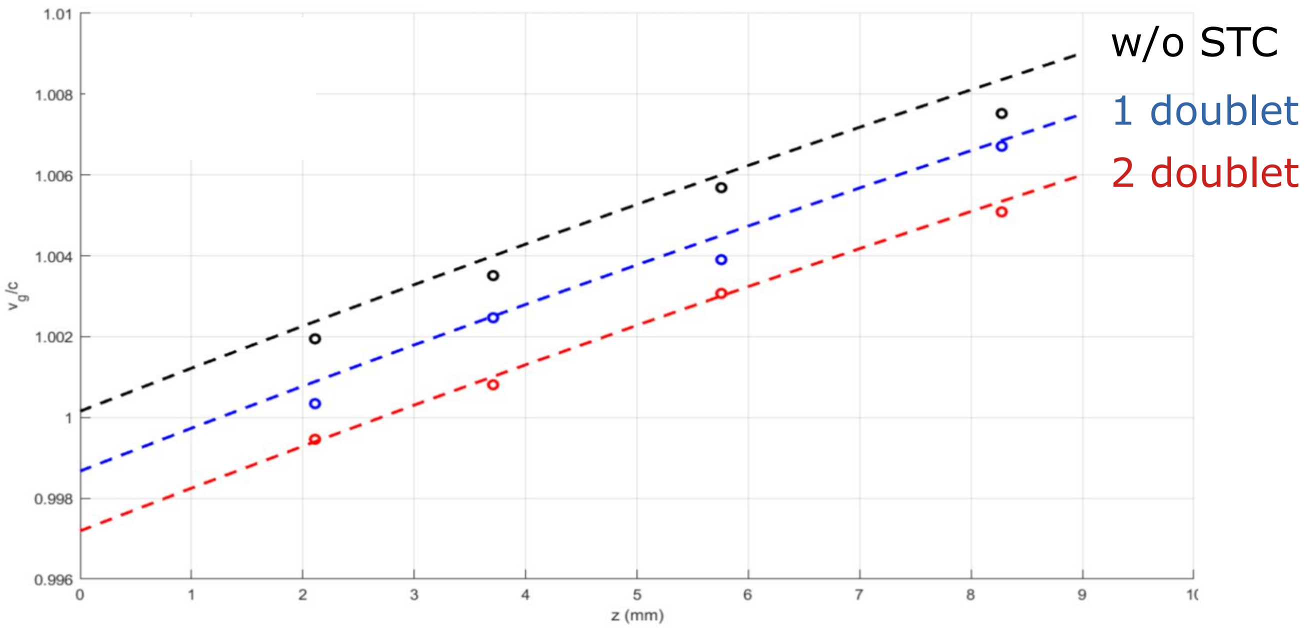
$$c\tau \simeq \frac{P_0}{\lambda_z R^2}\left(-\frac{v_0}{c}r^2 + \frac{1}{2f^2}\left(\frac{v_0}{c}+\frac{1}{2}\right)r^4\right) + o(r^5)$$

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

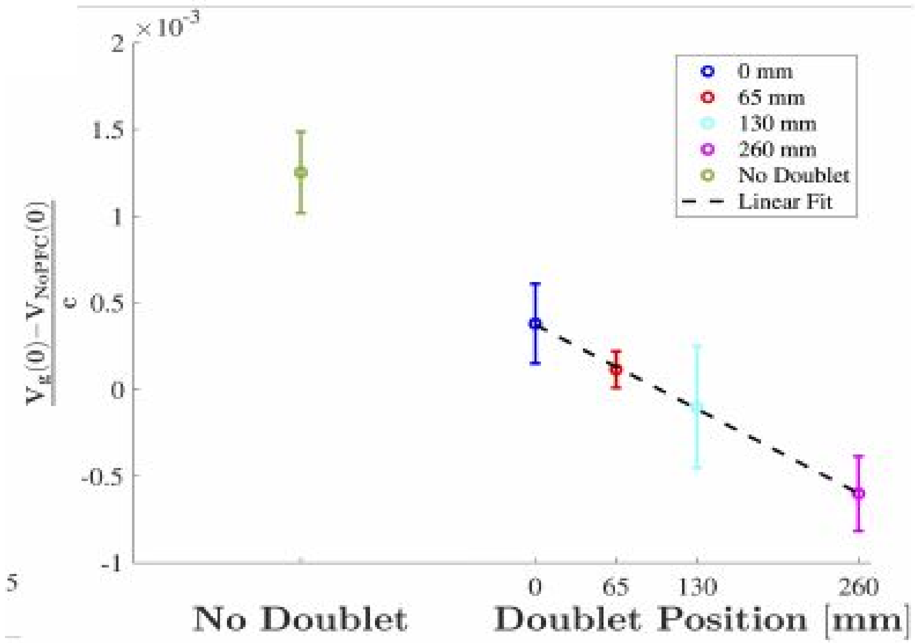
Axiparabola: Control of the Velocity - Experiment

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

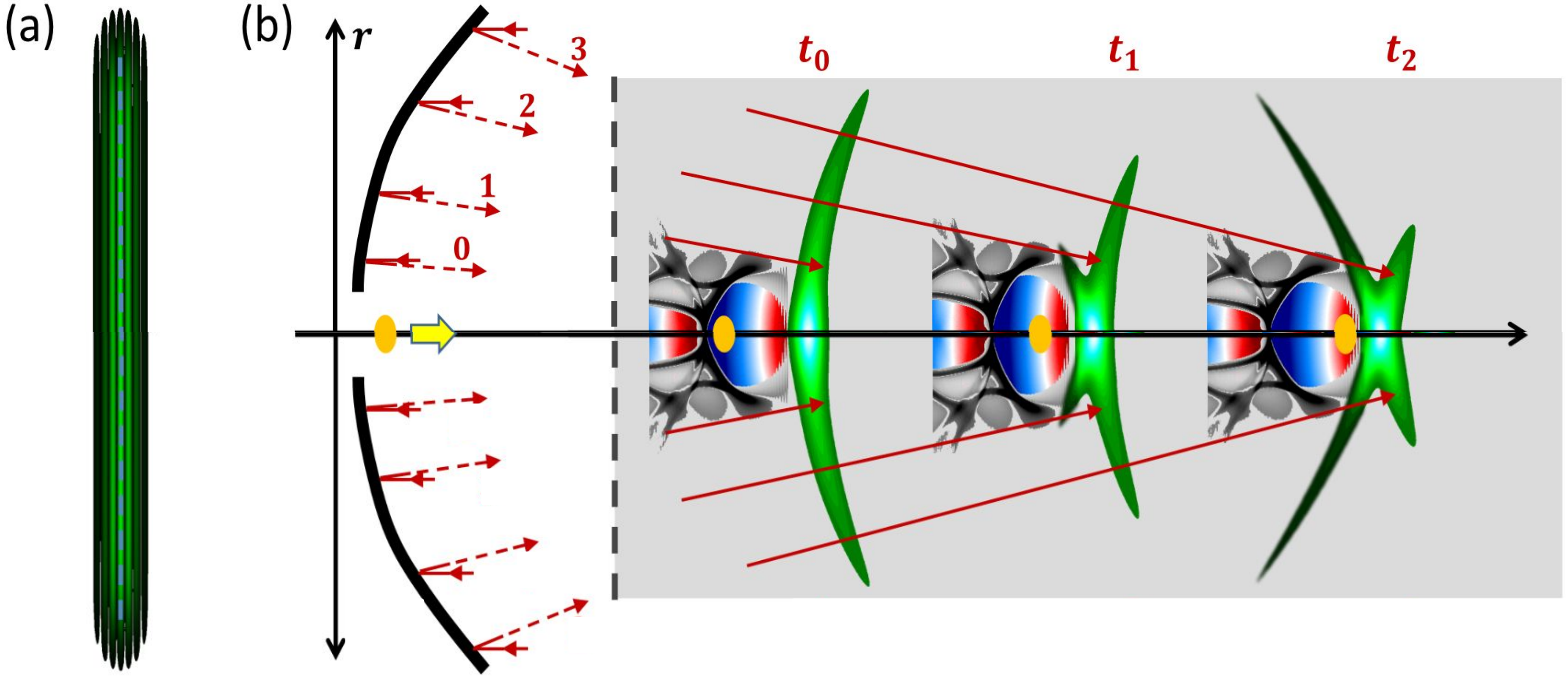


A. Kabacinski et al J.. Opt. 23 06LT01 (2021), A. Liberman et al *arXiv:2306.14327* (2023)

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

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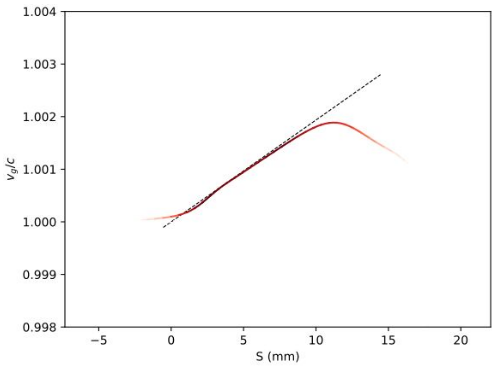
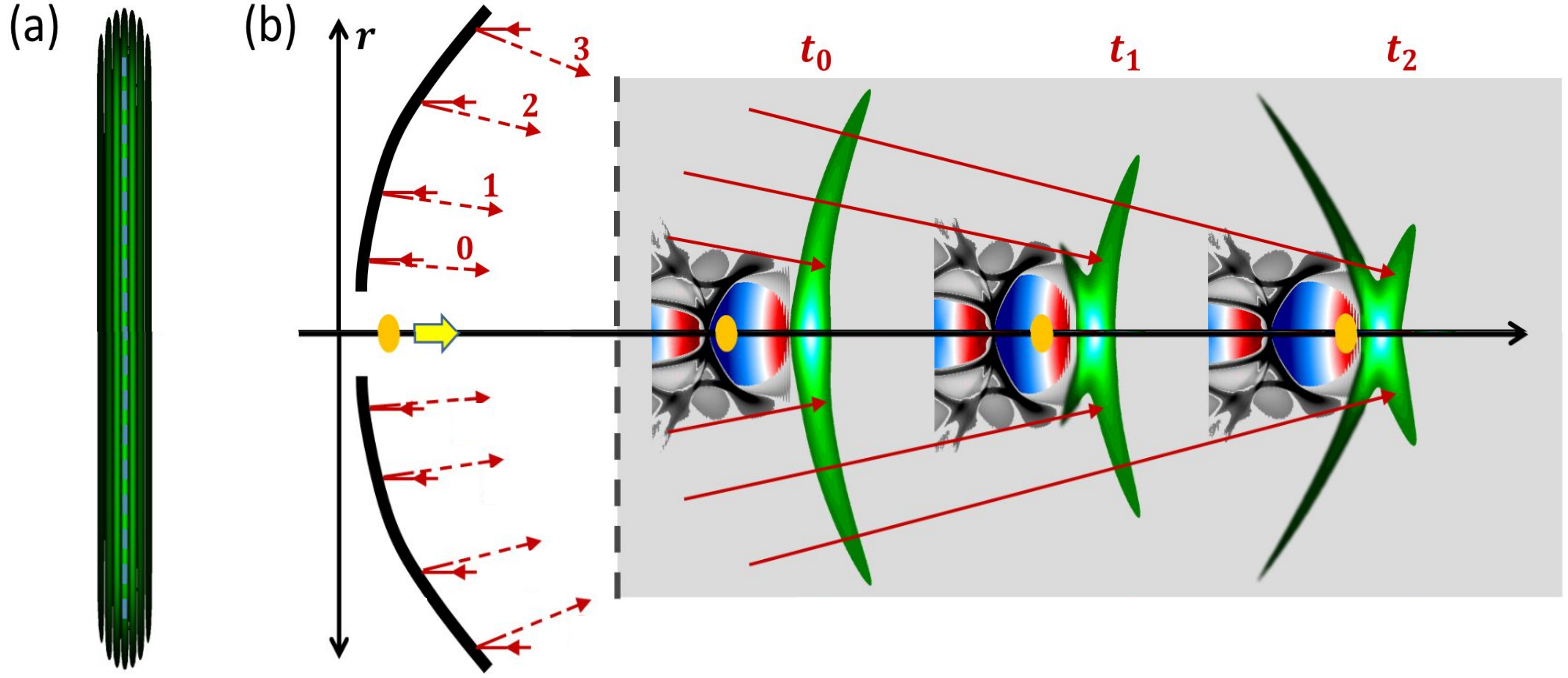




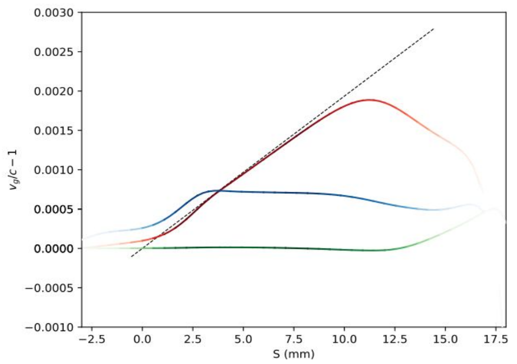
w/o STC
laser velocity
≠ electron beam velocity

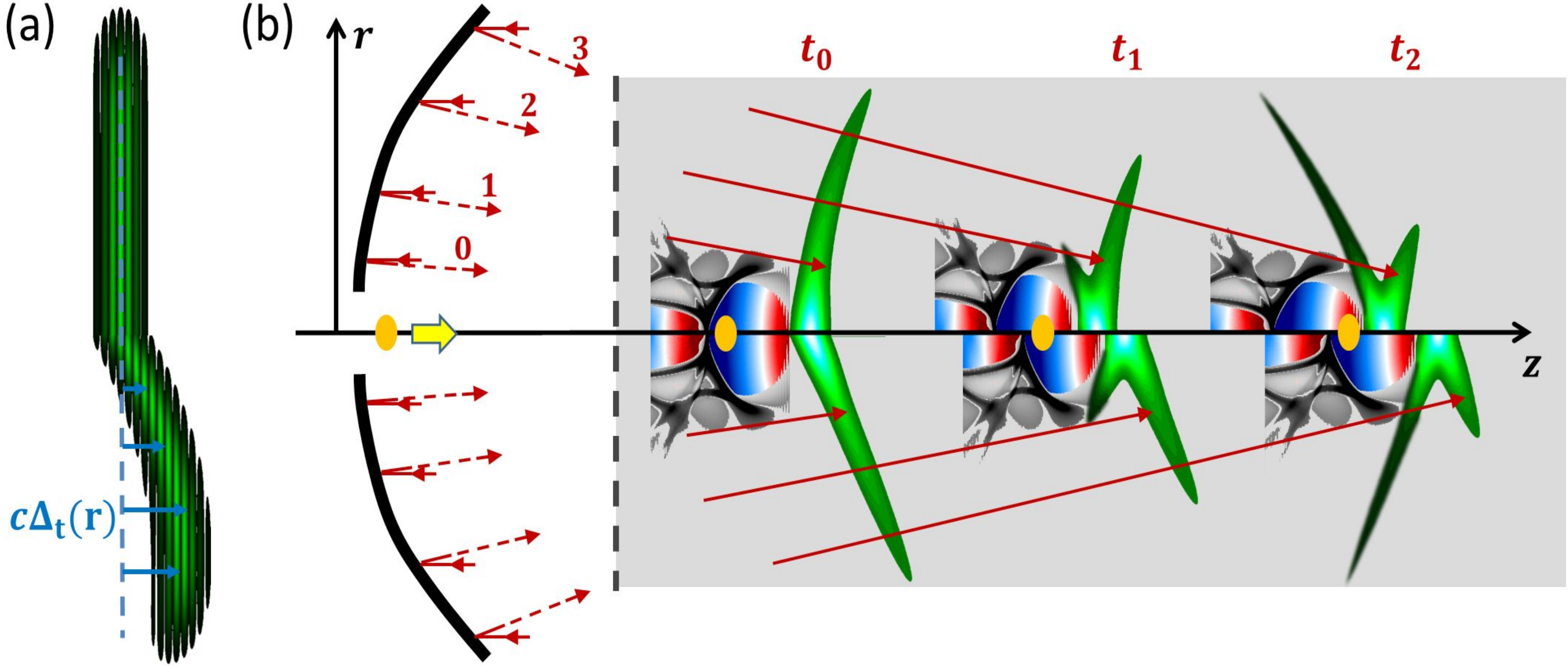
J.P. Palastro, Phys. Rev. Lett. 130, 159902 (2020)

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

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

Superluminal Acceleration - Principle

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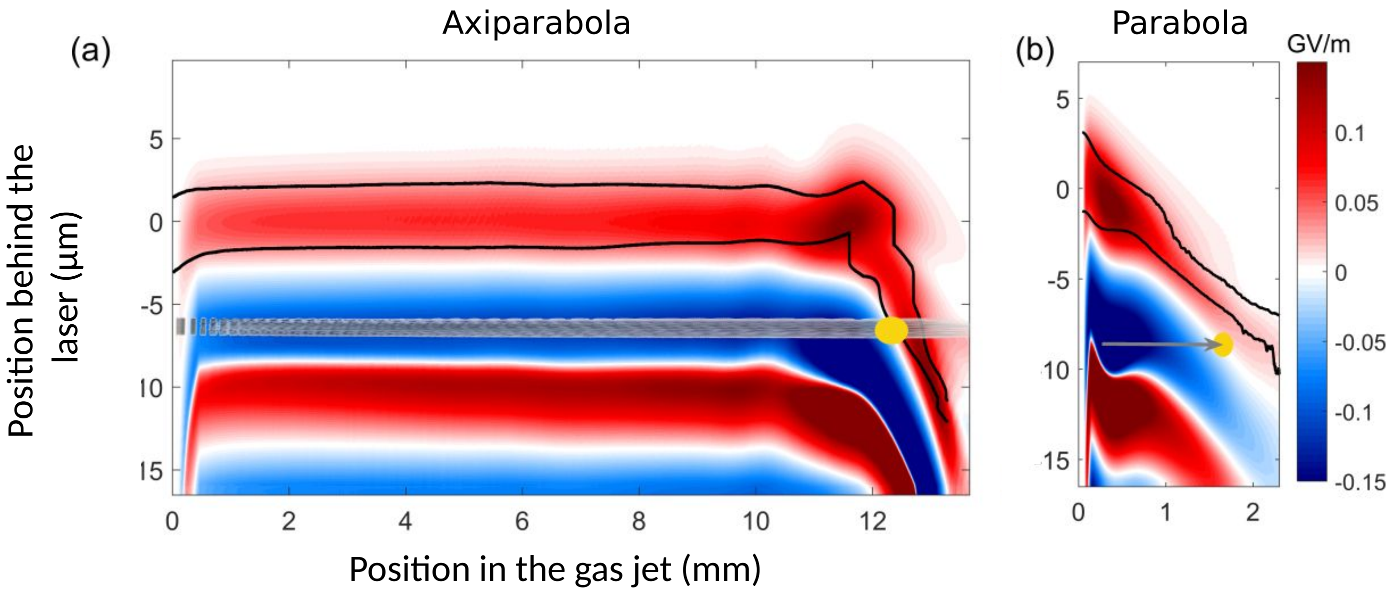
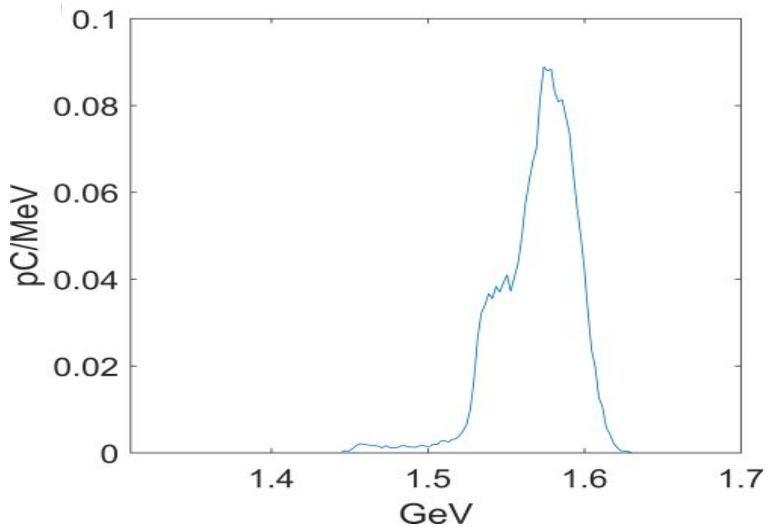
- Overcoming diffraction, dephasing and depletion.

Accelerating fields





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

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

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

Superluminal Acceleration - Principle

- Acceleration with a diffraction-free superluminal laser beam.
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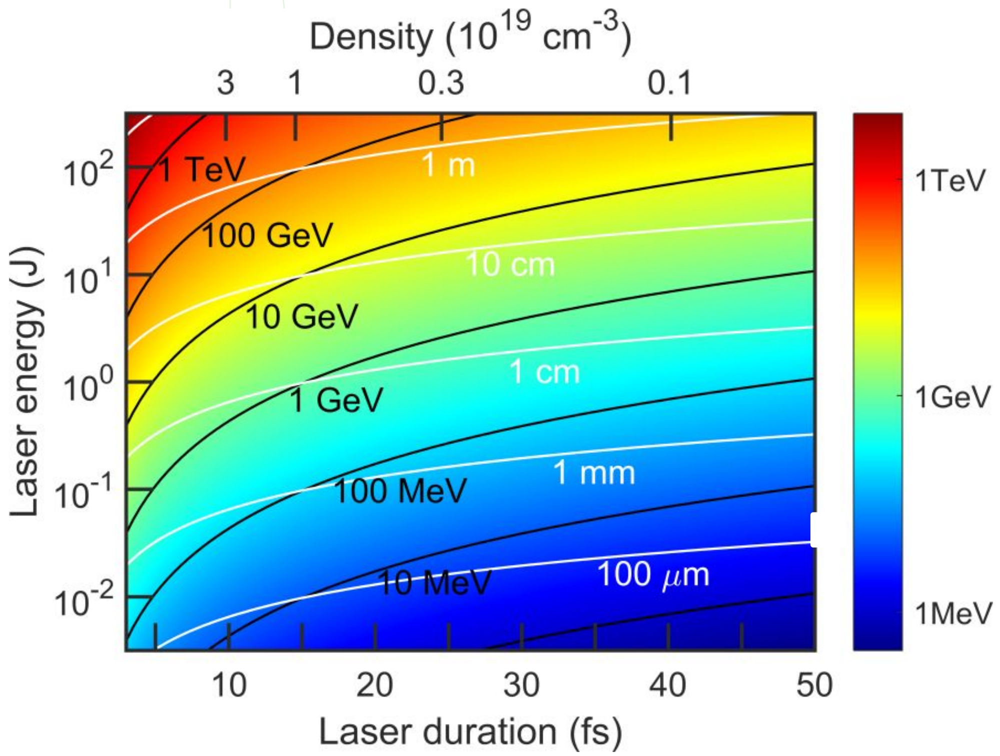
Beam energy according to Lu's model



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

$\gamma \propto E_L$

➡ **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

- 70% of successful shots (laser pointing stability has to be improved)
- Waveguiding + density transition injection
  → good quality beams up to 2.5 GeV
- Up to 6% conversion efficiency
- Down to 2% energy spread at 1 GeV
- **Next:** longer targets, rephasing

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:**
  - Numerical demonstration of injection of plasma electrons
  - Management of the dispersion of few-cycle laser pulses
  - Proof of principle experiment

Thank you for your attention

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