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Femtosecond relativistic electron microscopy of the laser-plasma wakefield

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https://www.weizmann.ac.il/complex/malka/

Outline

- Motivation, Principle, and highlights
- fs electrons microscopy of relativistic interaction
  - ⇒ The first observation of relativistic wave breaking
  - ⇒ The electron bunch from plasma to exit
  - ⇒ The entire transition from LWFA to PWFA
- Societal applications
- Conclusion & Perspectives

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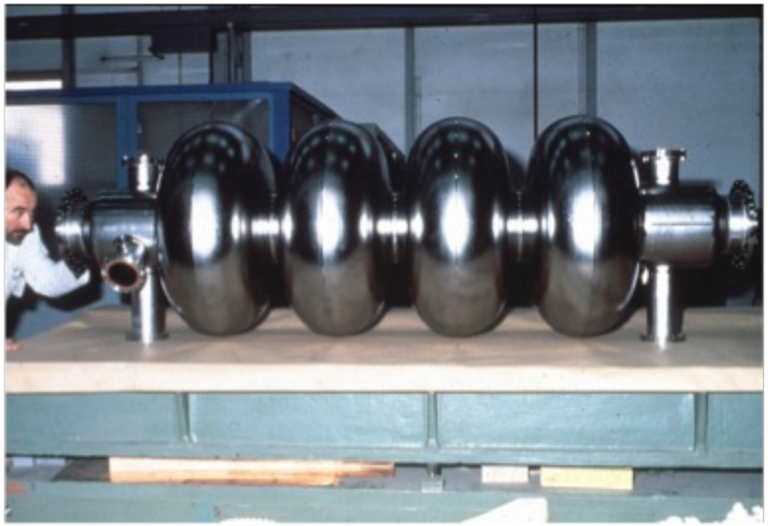
Compactness of Laser Plasma Accelerators

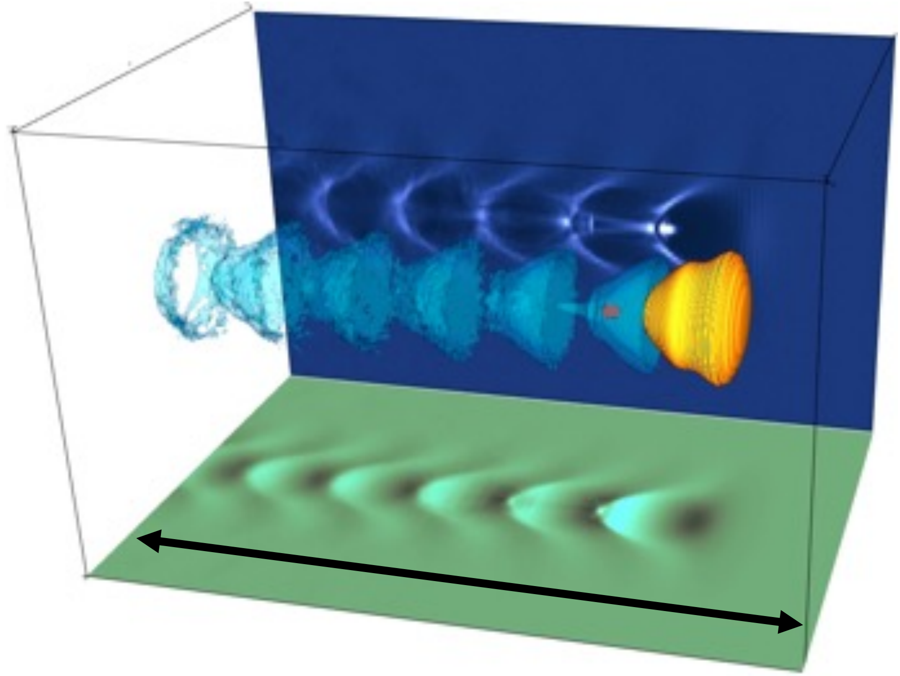
RF Cavity



1 m => 50 MeV Gain

Electric field < 100 MV/m

Plasma Cavity

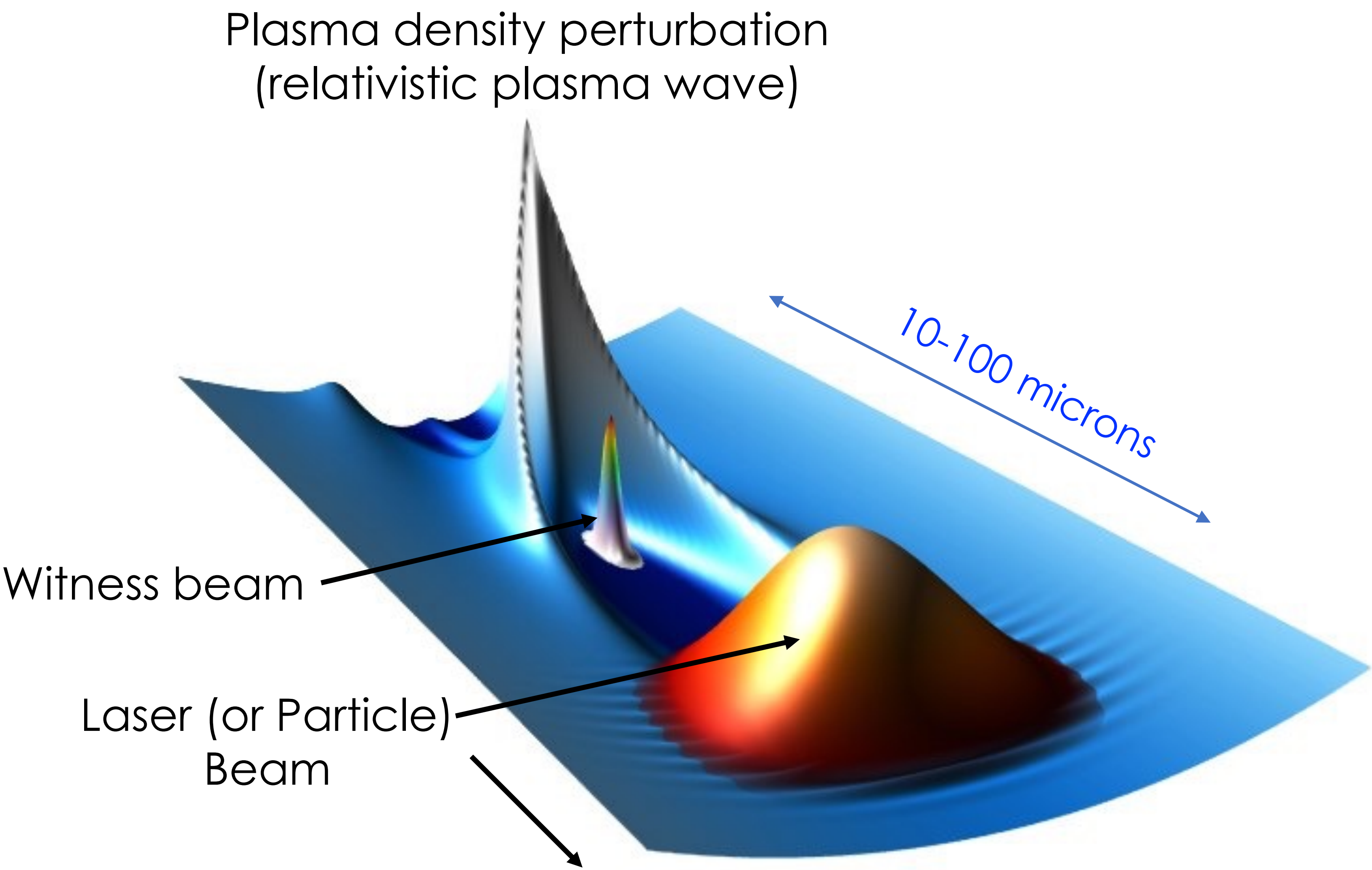


1mm => 100 MeV

Electric field > 100 GV/m

V. Malka *et al.*, Science **298**, 1596 (2002)

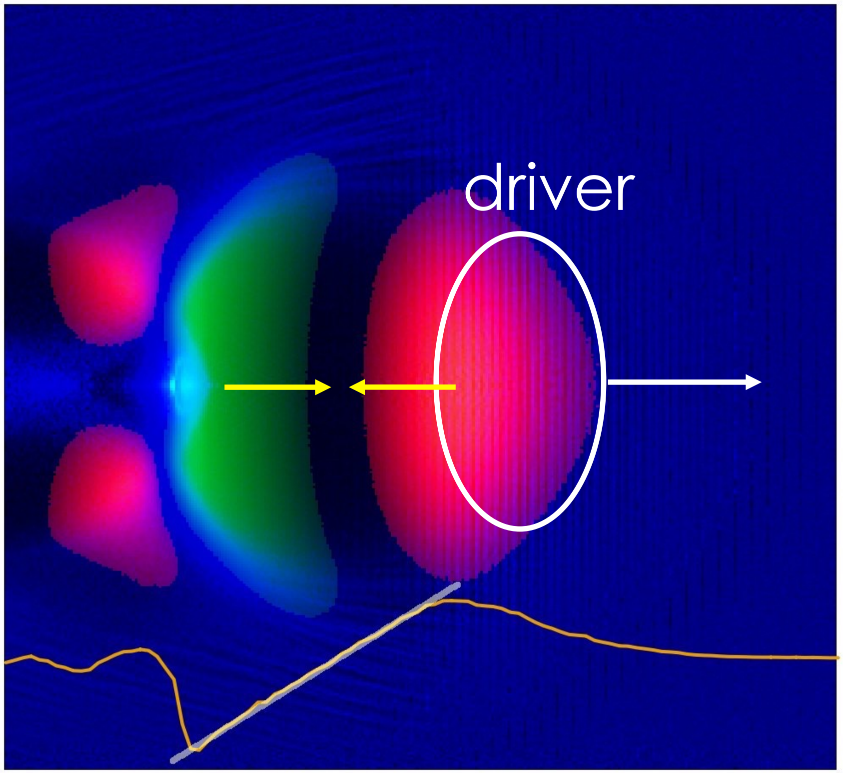
How do plasma accelerators work ?



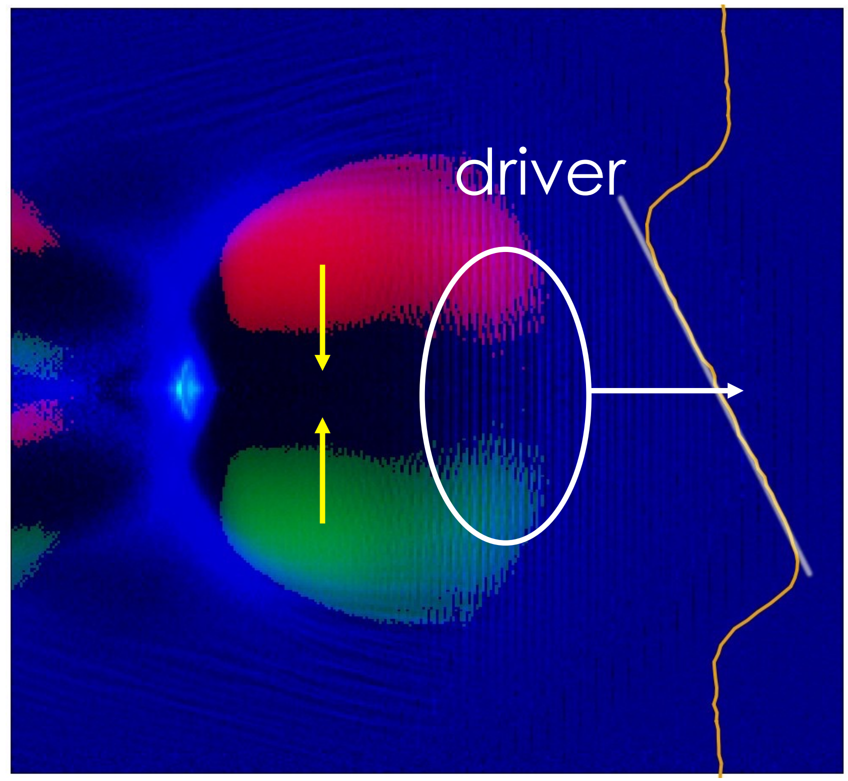
Courtesy of J. Vieira

What about measuring relativistic fields ?

100's GV/m e-field components: Longitudinal and Transverse



Linear accelerating gradient



Linear focusing gradient

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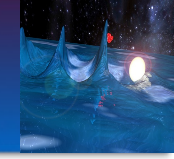
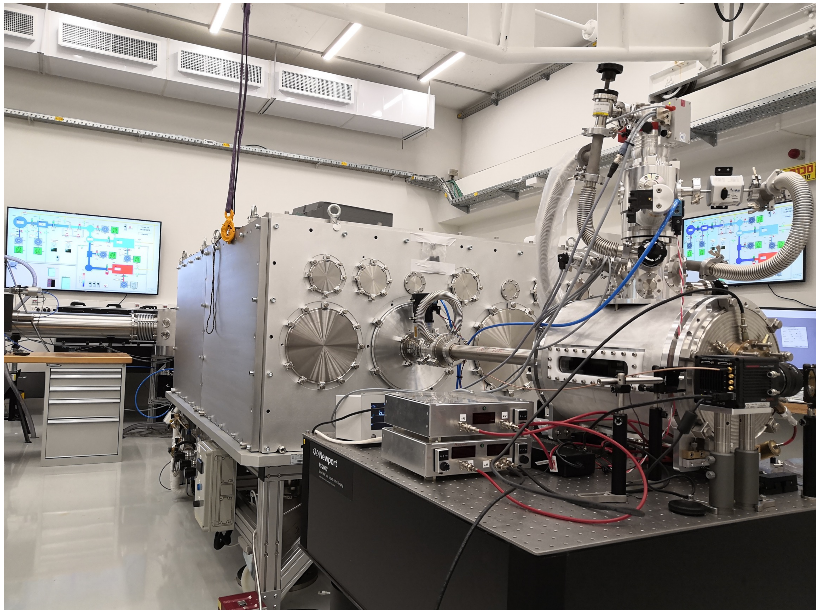
WIS Laser Sciences Center : the lab





WIS Laser Sciences Centre : the Team

The team (1 permanent staff, 1 technician, 2 Post-Docs, 5 PhDs, 2 MScs)

Eyal Kroupp, Permanent staff, experiments

Eitan Levine, PhD(Y4) Electron beams improvement

Omri Sleeman, PhD(Y4) Near critical plasma

Arujash Mohanty, (Y2), Betatron and targetry

Aaron Liberman, PhD (Y1), axicon, superluminal

Heychal Davidovich, MSc, Laser and/to beam driven WF

Salome Bencassa, Msc, LPI with STP beams

Sheroy Tata, Post Doc (Y4+) laser and experiments

Ruben Piloposian, technician support for experiments

Previously:

Yang Wan, Permanent staff, experiments and simulations

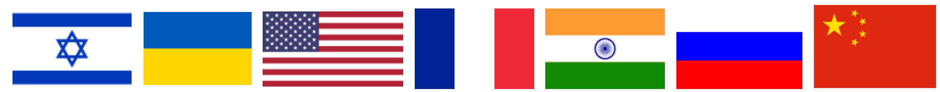
Celine Hue, Post Doc(Y1), Simulation injection LPA

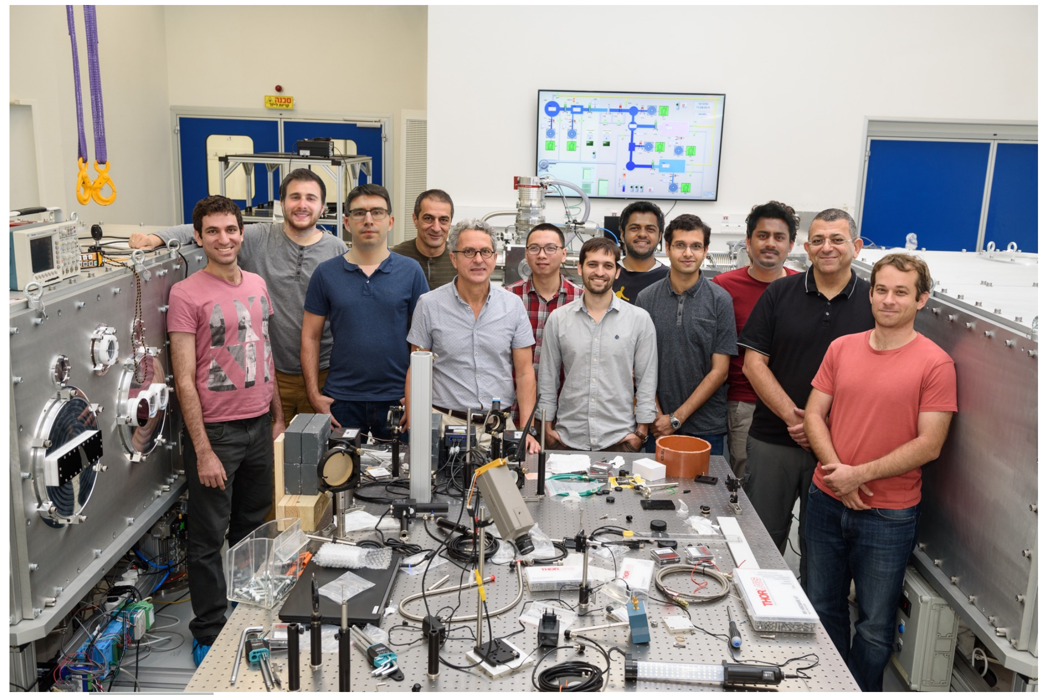
Atoul Sengar, Post Doc(Y2), Simulation dose/transport

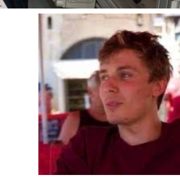
Dan Levy, PhD(Y5+) on Ion acceleration gas/solid target

Slava Smartsev, PhD(Y5) guiding & Superluminal wave

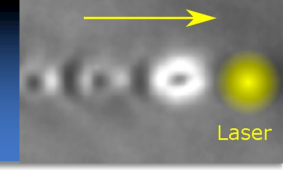
Daria Raspopova, MSc, Shock injection





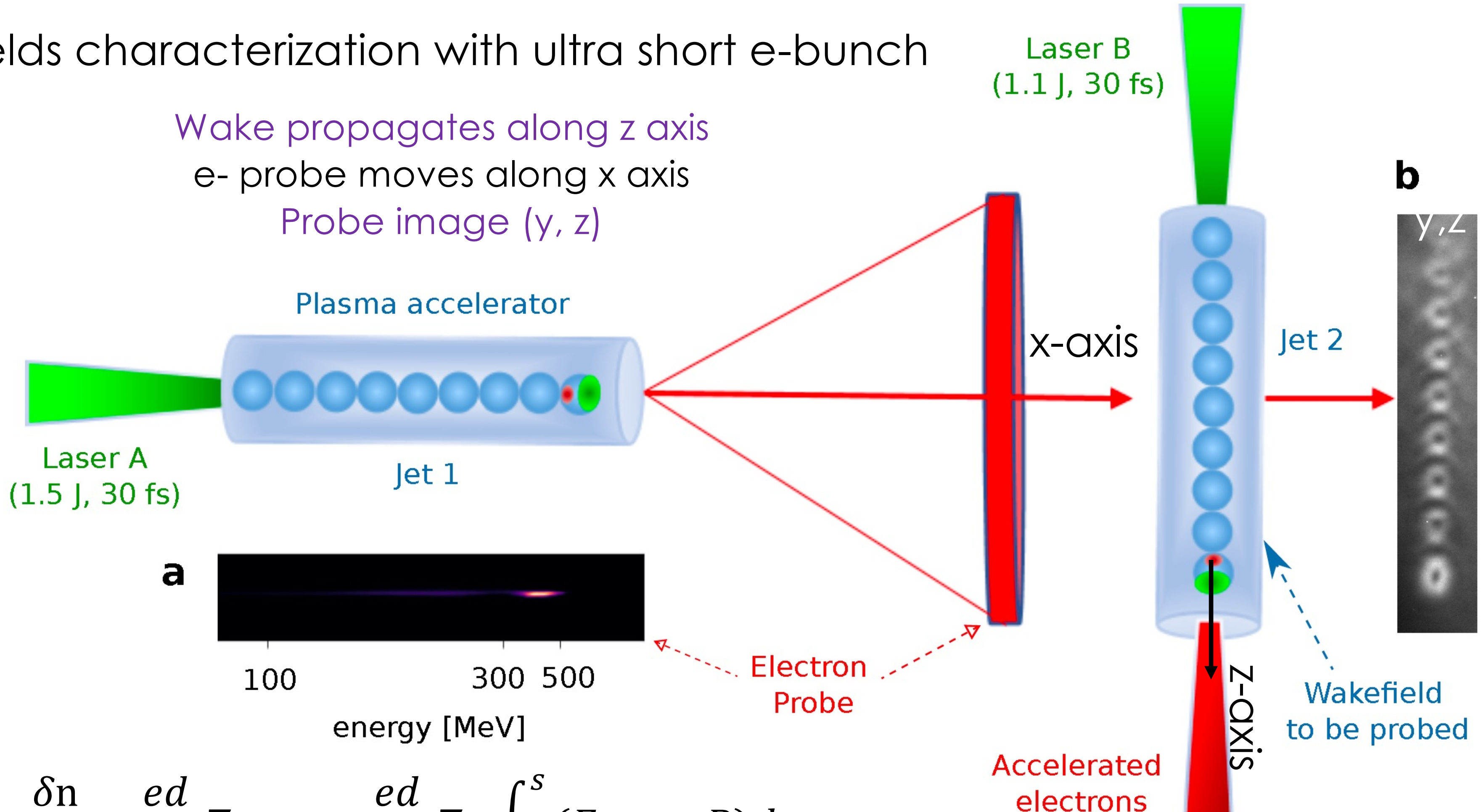


An insight of Non-Linear Laser Wakefield



E-fields characterization with ultra short e-bunch

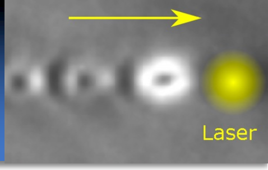
Wake propagates along z axis
e- probe moves along x axis
Probe image (y, z)



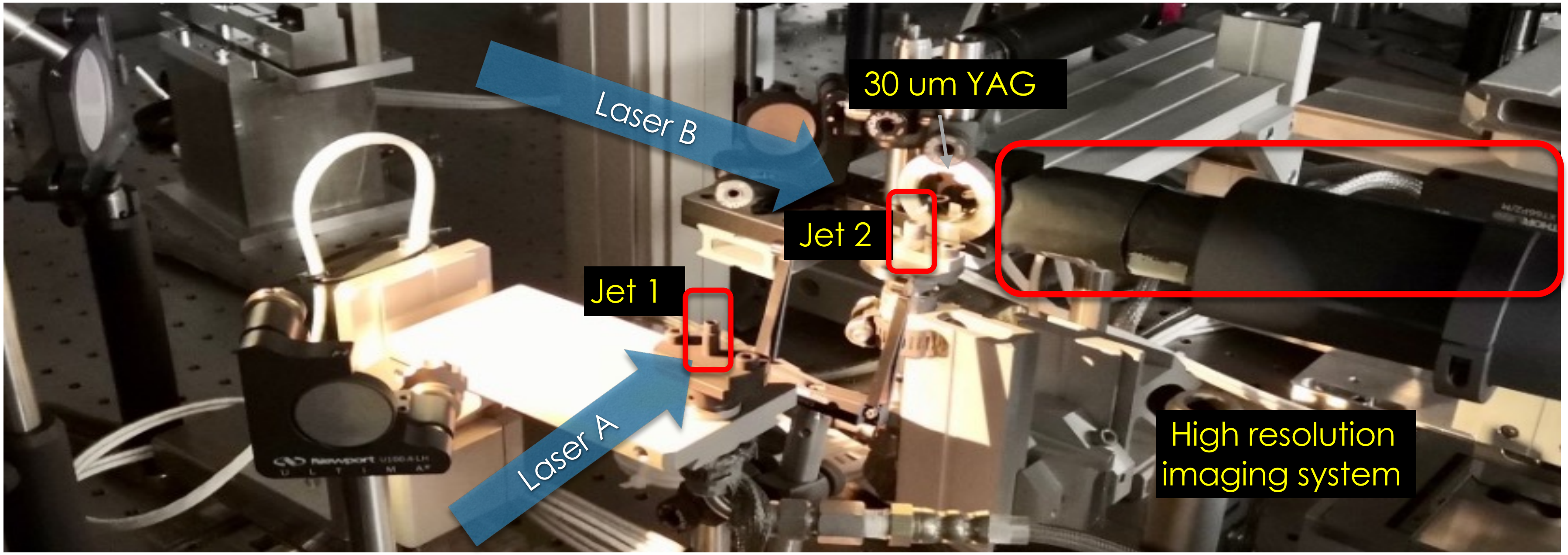
$$\frac{\delta \mathrm{n}}{n} = \frac{ed}{cp_0} \nabla \cdot p_{\perp} = \frac{ed}{cp_0} \nabla \cdot \int_{-s}^{s} (E + v \times B) dx$$

C. J. Zhang et al., Sci Reports 2016

Experimental Setup



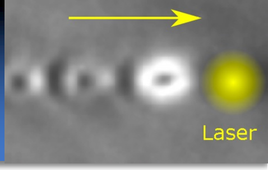
E-fields characterization with ultra short e-bunch



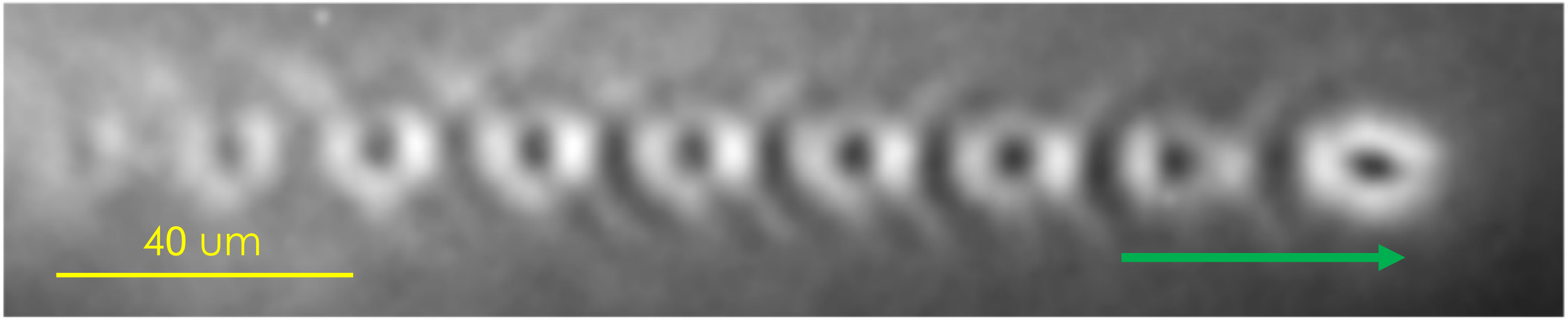
Jet 1 and Jet 2 distance: 10cm

YAG screen to Jet 2: 3 mm

First nonlinear wakefield raw image



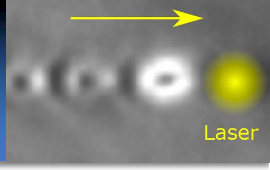
Raw Data

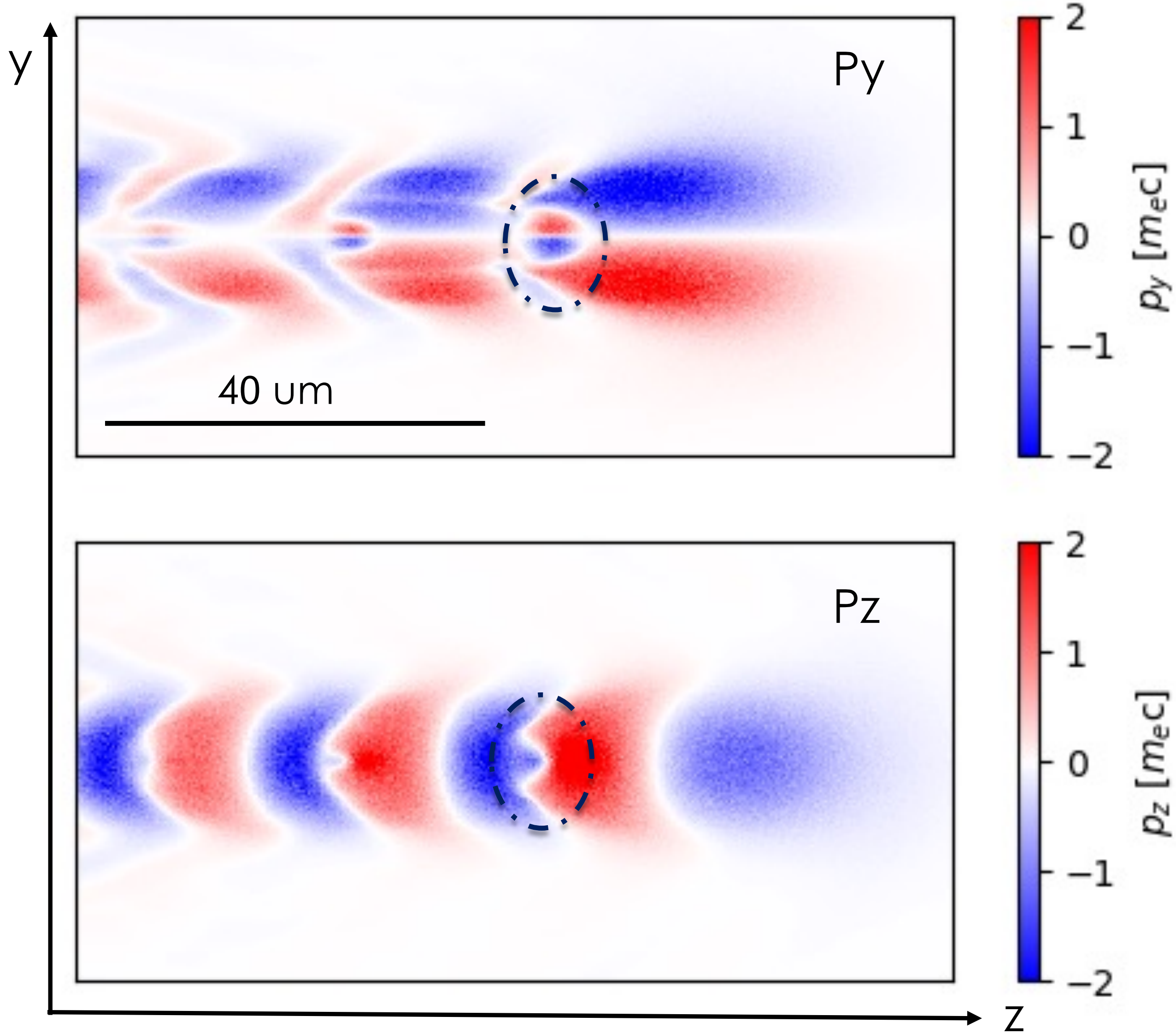


Jet 2: pure He, plasma density $4x10^{18}$ cm^{-3}

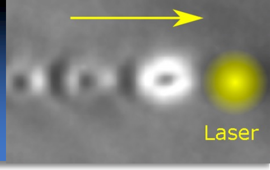
Laser B: ~1J on target, w_0=24um, 30 fs

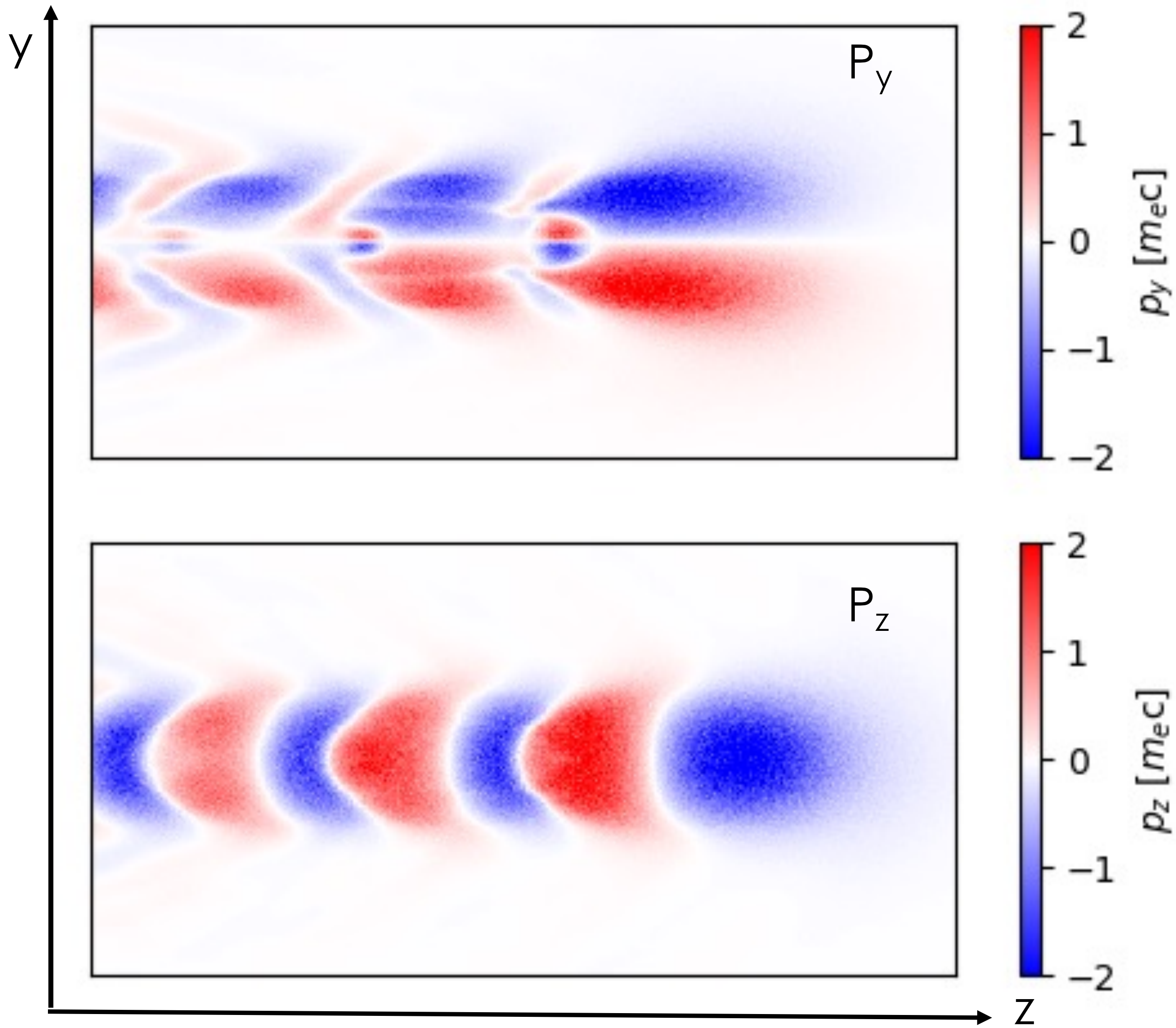
Momenta of electron probe after LWF



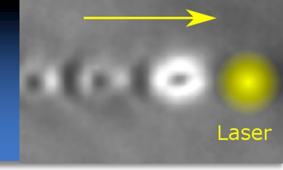


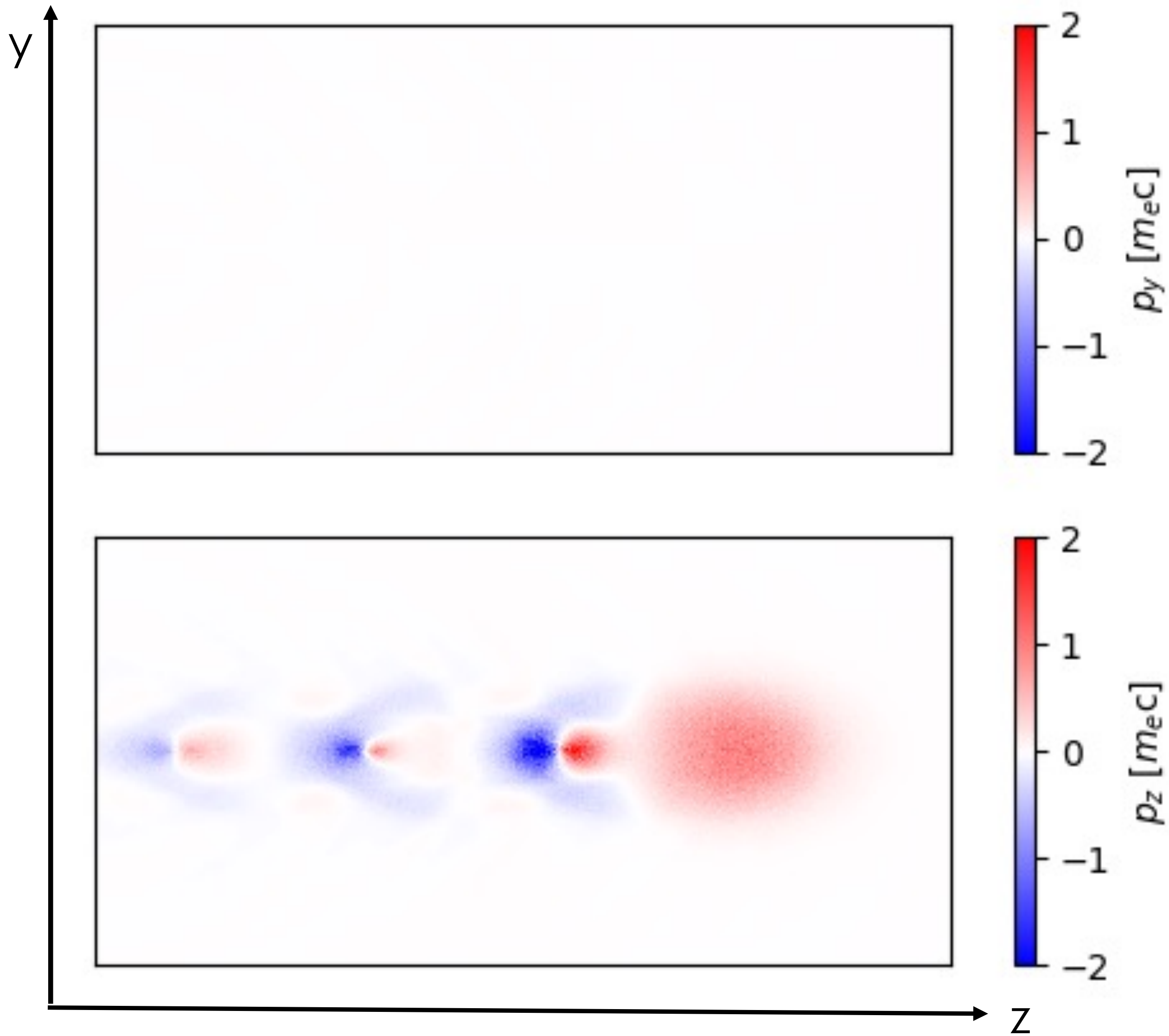
E Field Contributions



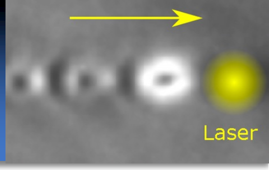


B Field Contributions





Conclusions of Field Contributions

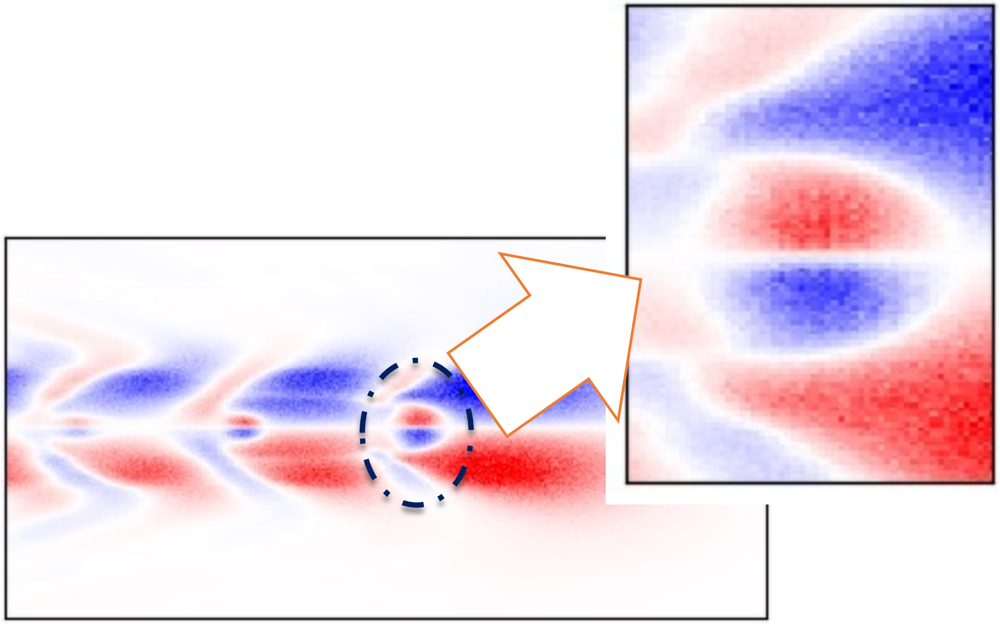


Hollow vertical width is related to E_y field

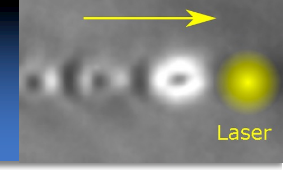
Hollow horizontal width is related to B_y field

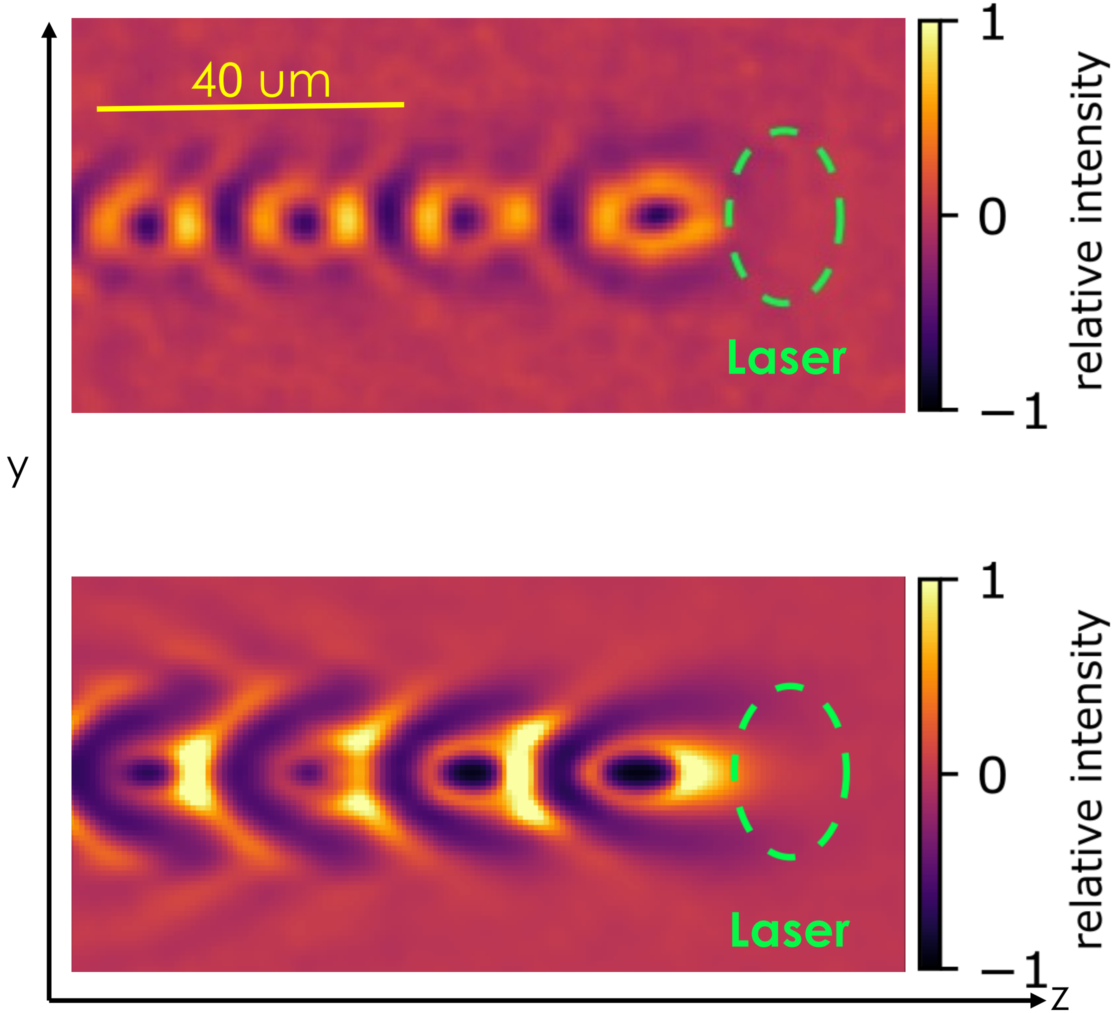
$$p_y = -\int_{-s}^{s} eE_y dx$$

$$p_z = \int_{-s}^{s} ecB_y dx$$



Comparison with 3D PIC simulation

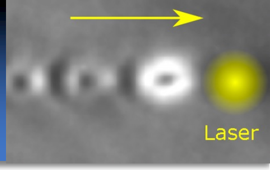




Experimental image after subtracting background

High resolution quasi-3D simulation (FBPIC) with homemade tracking code

The dependence on driver strength



drive laser energy

0.55 J

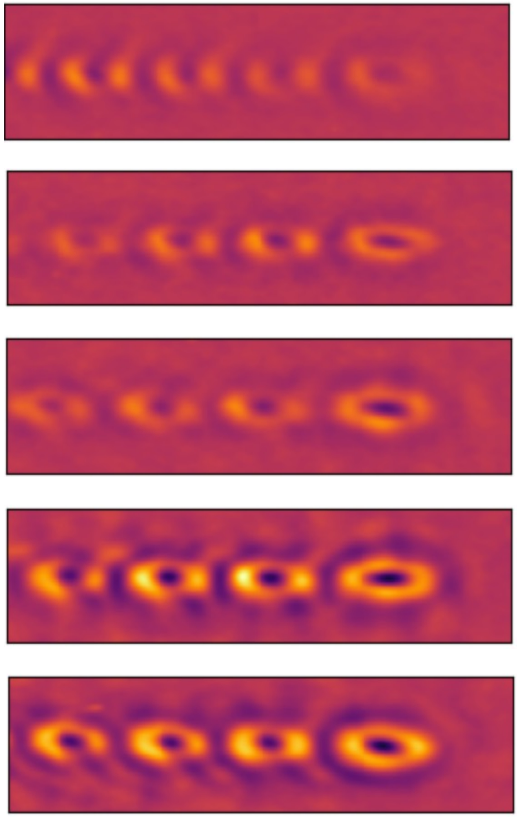
0.71 J

0.82 J

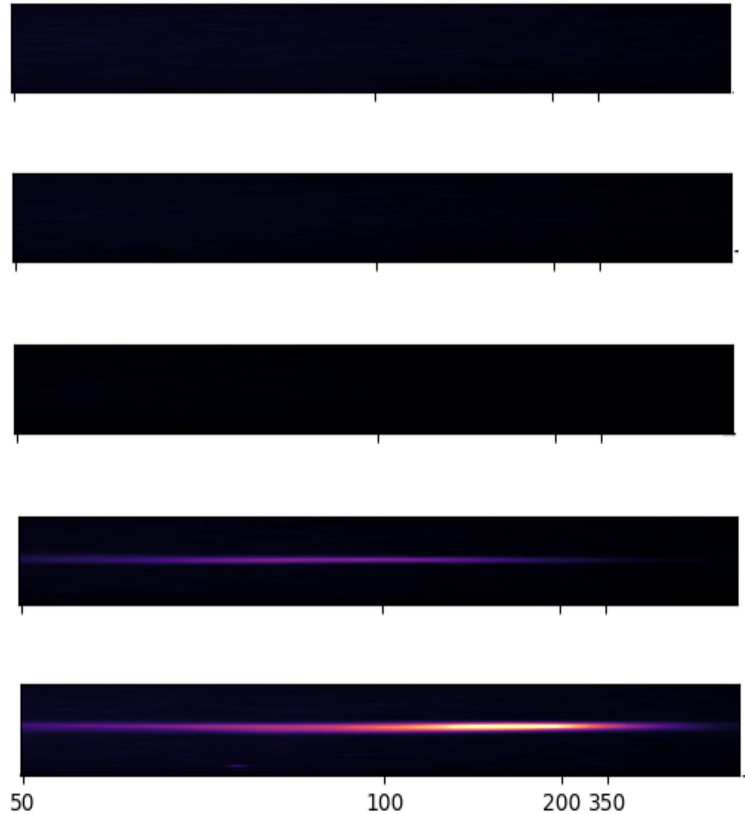
0.94 J

1.1 J

Probe density modulation



Accelerated electrons from the probed wakefield



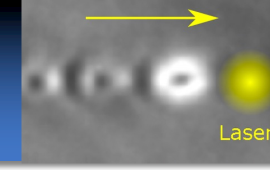
3.5 ± 1.3pC

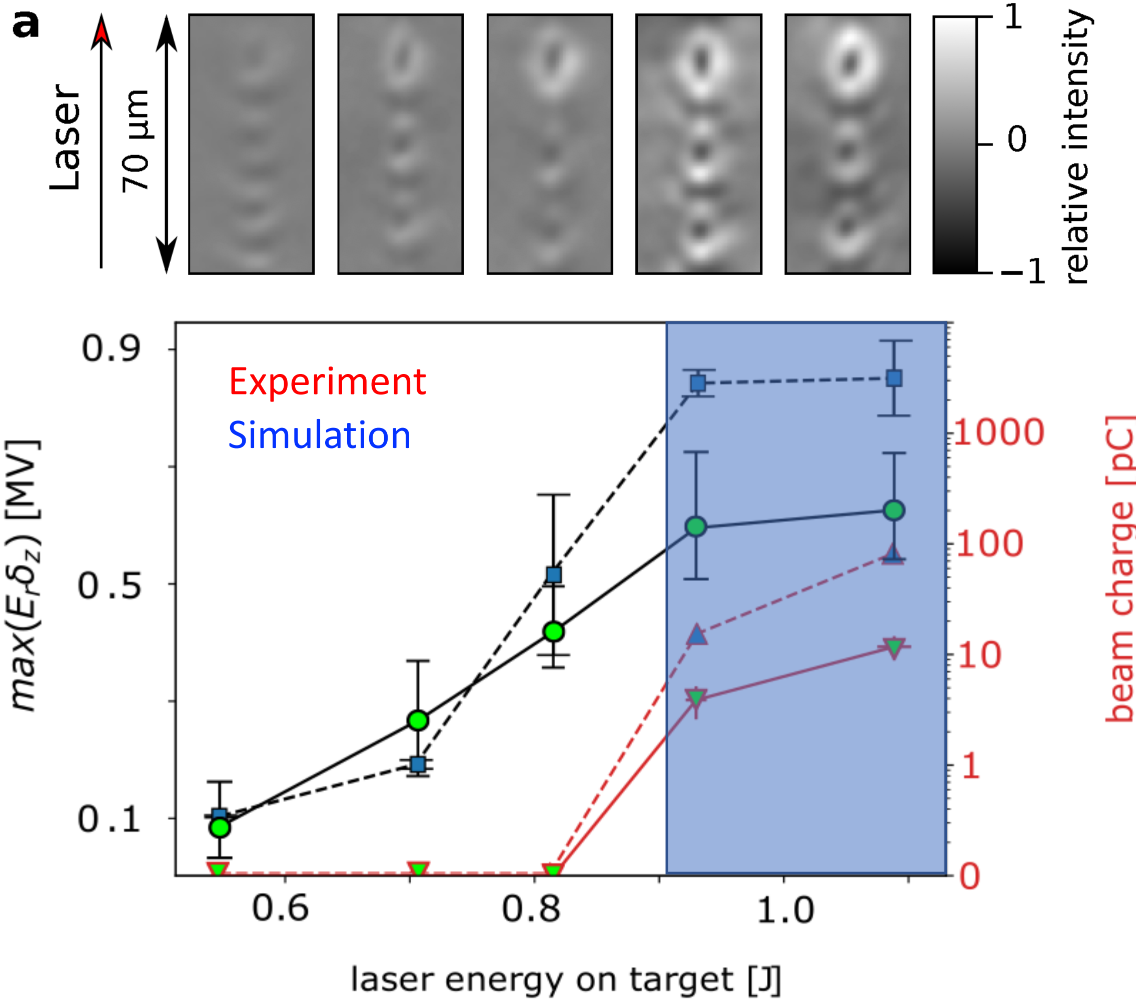
12.7 ± 2.9pC

electron energy [MeV]

Y. Wan *et al.*, Nature Physics (2022)

Relativistic broken waves : saturation of field amplitude & occurrence of relativistic electrons





The reaching of relativistic wave-breaking by increasing input laser energy for 0.55, 0.71, 0.82, 0.94, and 1.1 J

The measured spike field integral $E_r(z)$ (green circles) and beam charge (red up-triangles) and corresponding simulated values for the first wakefield bucket

Y. Wan *et al.*, Nature Physics (2022)

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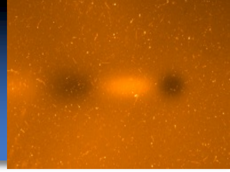
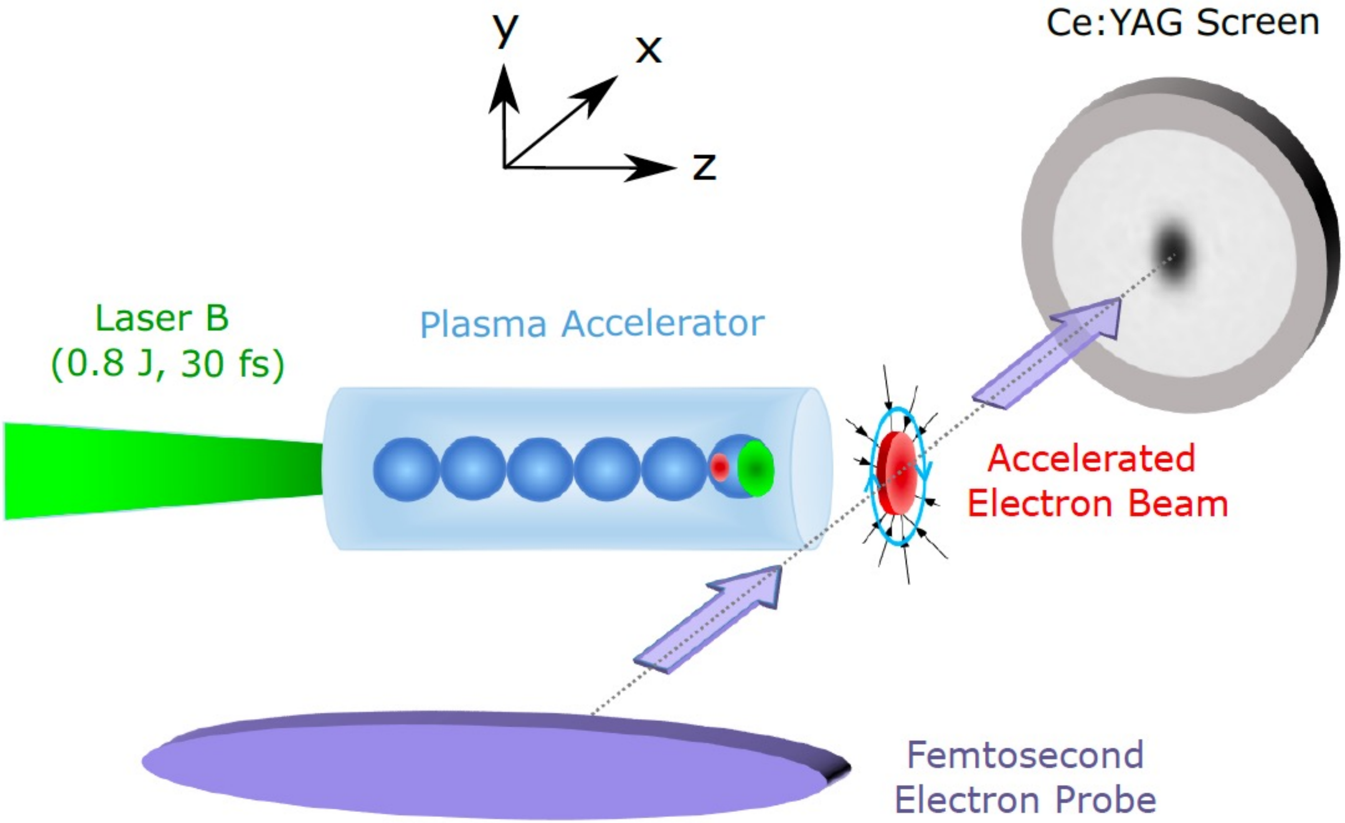
Probing "e- bunch" with "e- bunch"

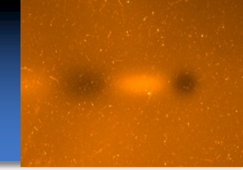




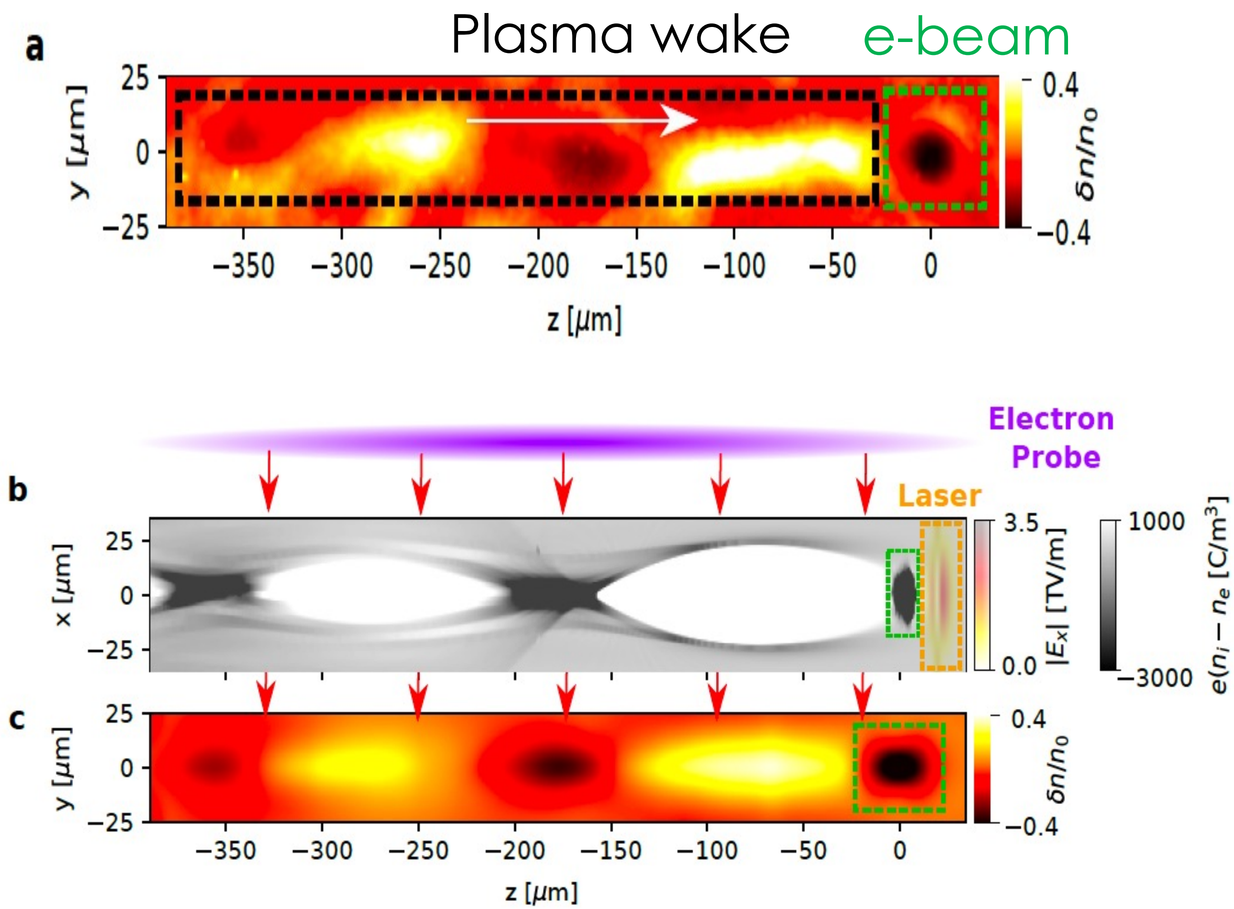
The space-charge force of the "electron beam" can deflect the "probe electrons"

Encode its spatial structure on the probe image

First fs electron microscopy of relativistic e-bunch



Jet 2: He (1% N_2), plasma density $4x10^{18}$ cm^{-3}
Laser B: on-target energy ~ 0.8J, linearly polarized (horizontal)



Exp. Probe image

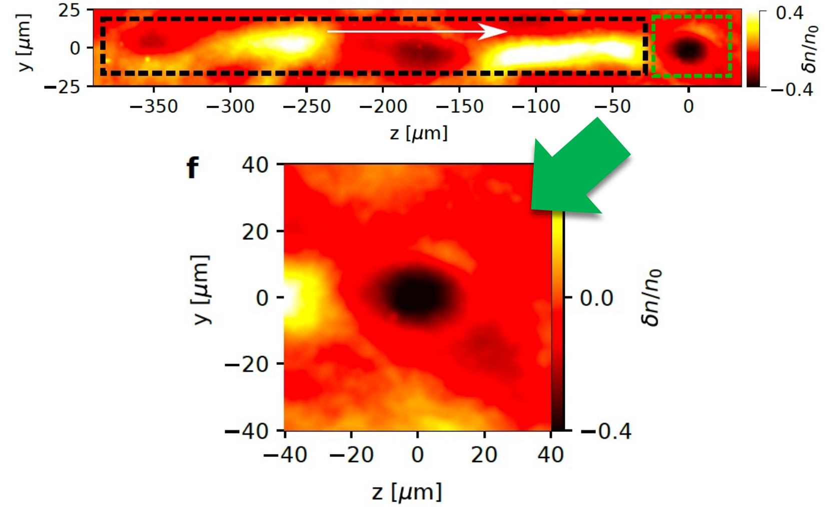
Sim. E beam and plasma wake

Sim. Probe image

Measure of the e beam lateral property

Probe density modulation → $$\frac{\delta n}{n_0} \simeq -\frac{eL}{Mcp_0\epsilon_0}\sigma_b,$$ ← e beam surface charge density

Experimental data



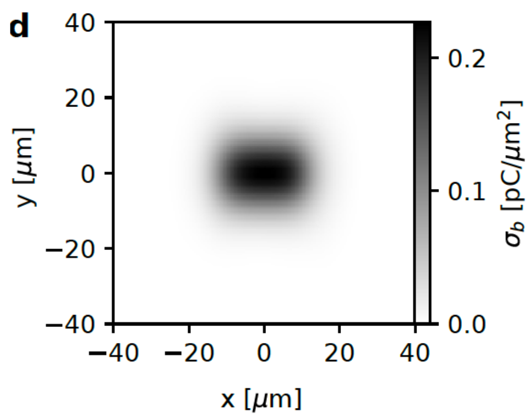
$$\sigma_{b0} = 0.14 \pm 0.03 \text{ pC}/\mu\text{m}^2$$

$$\Delta_y = 7.2 \pm 0.5\ \mu\text{m (vertical)}$$

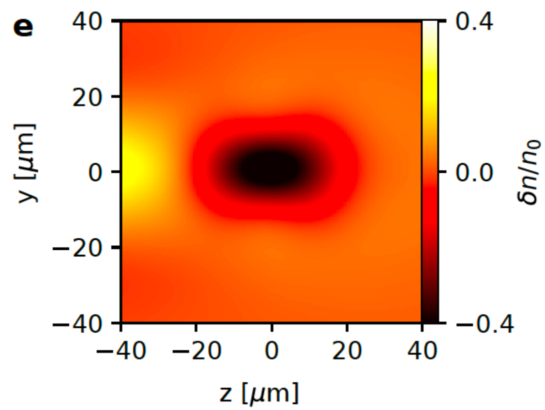
$$\Delta_x = 12.5 \pm 1.4\ \mu\text{m (horizontal)}$$

$$79 \pm 31 \text{ pC},$$

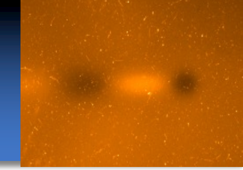
e beam lateral profile



Probe image



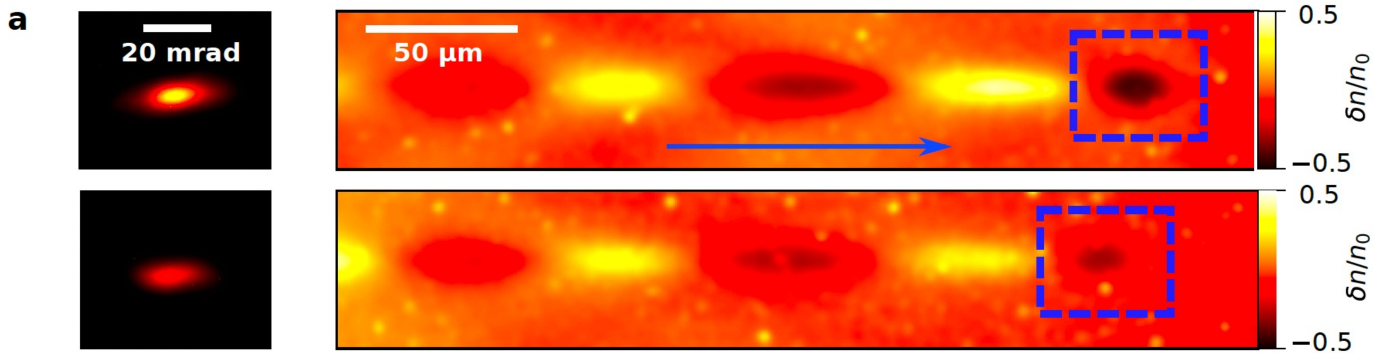
Simulation



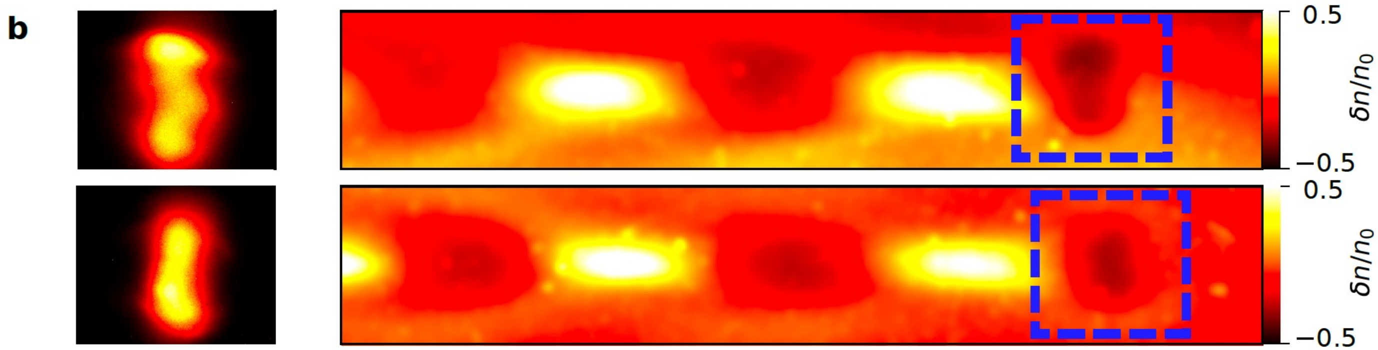
First fs electron microscopy of relativistic e-bunch

Transverse beam size changed due to laser beam polarization

Linear laser polarization

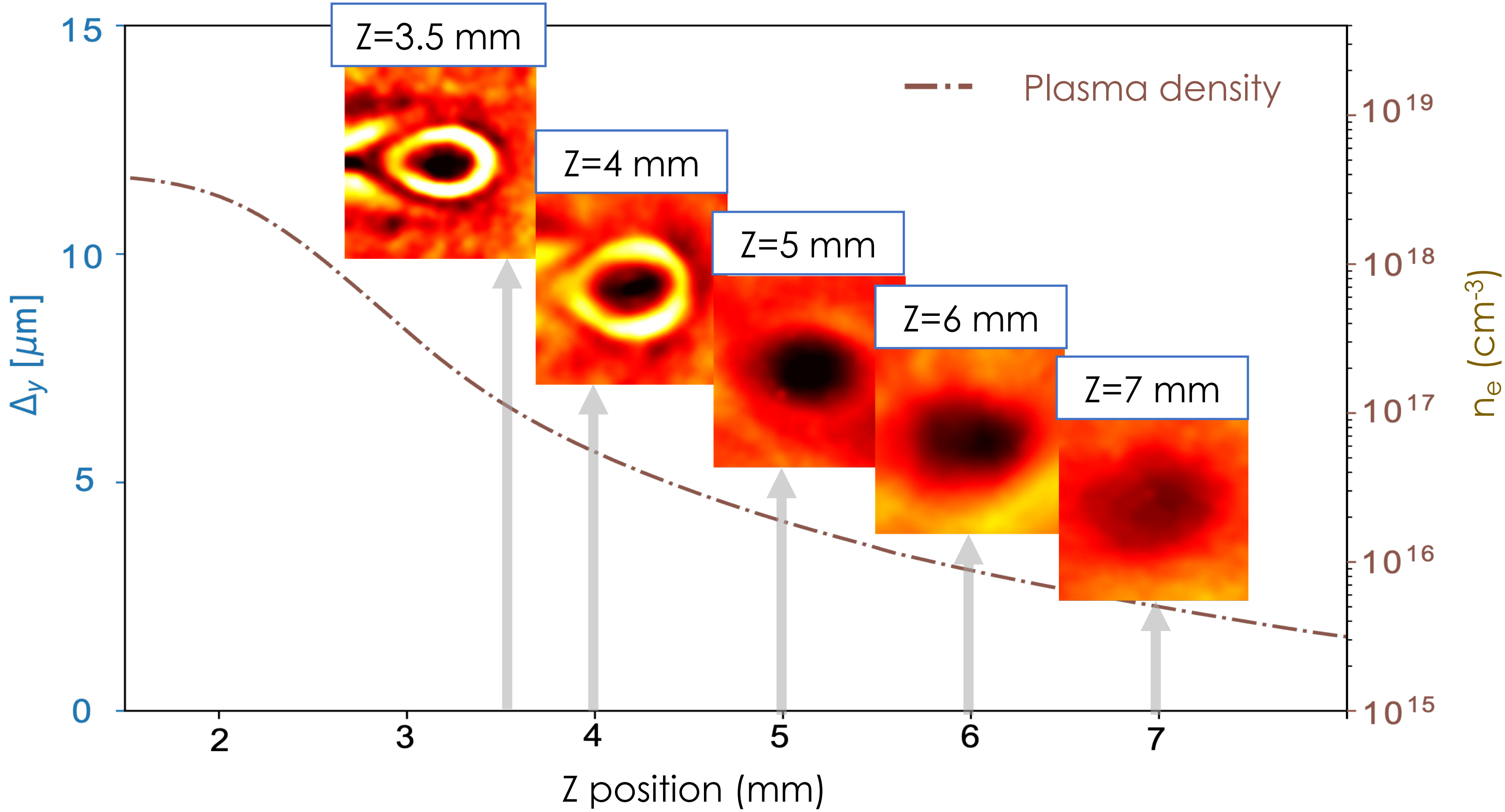


Circular/Elleptical laser polarization



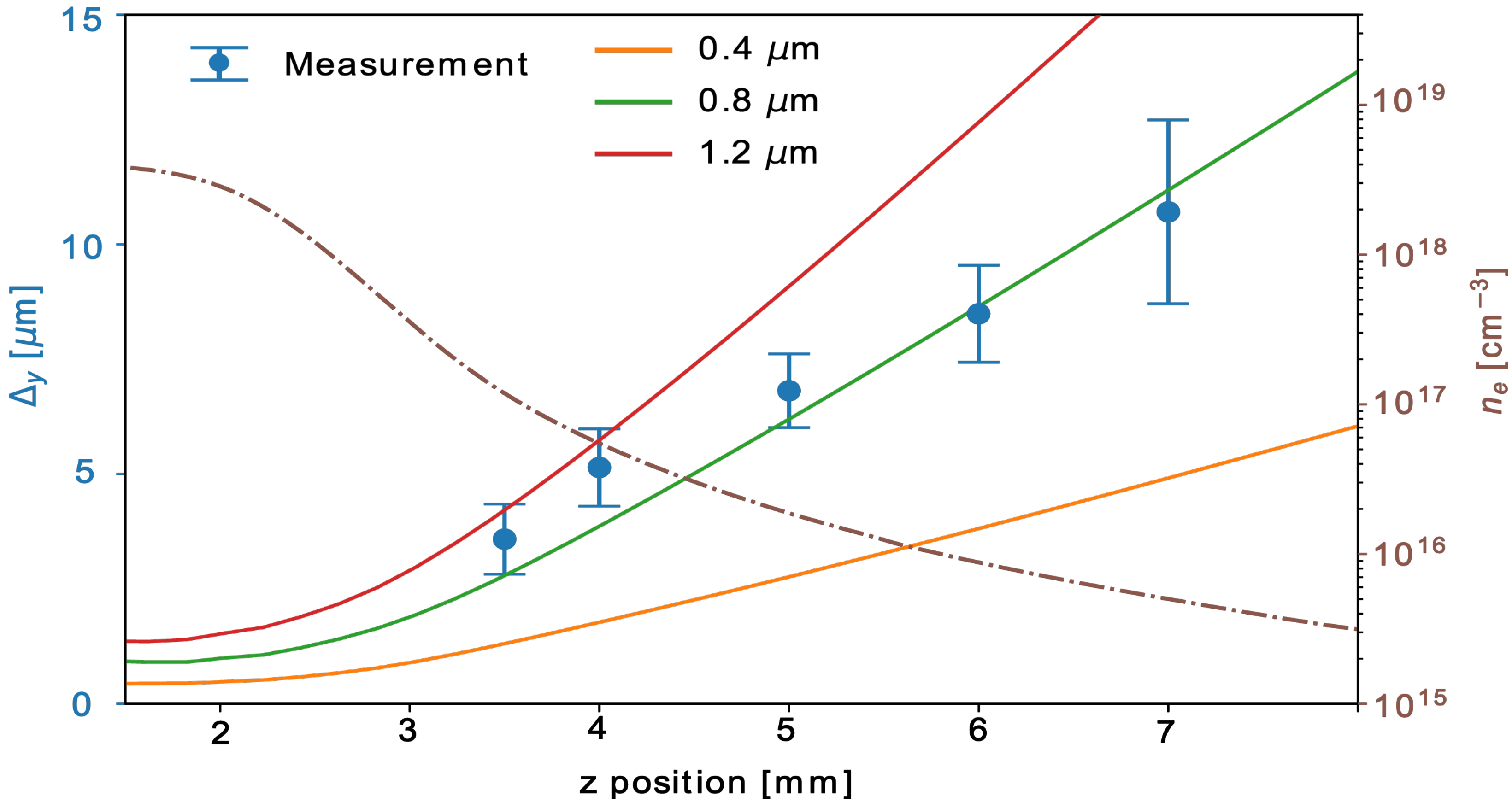
The experimental results of the probe images (right) and corresponding electron beam angular profiles (left) for linear (a) and circular (b) laser polarization.

E beam evolution at plasma exit



Y. Wan *et al.*, accepted in Light Sci. Appl.

Evolution of the electron beam envelope



Y. Wan *et al.*, Light: Science & Applications, May 2023

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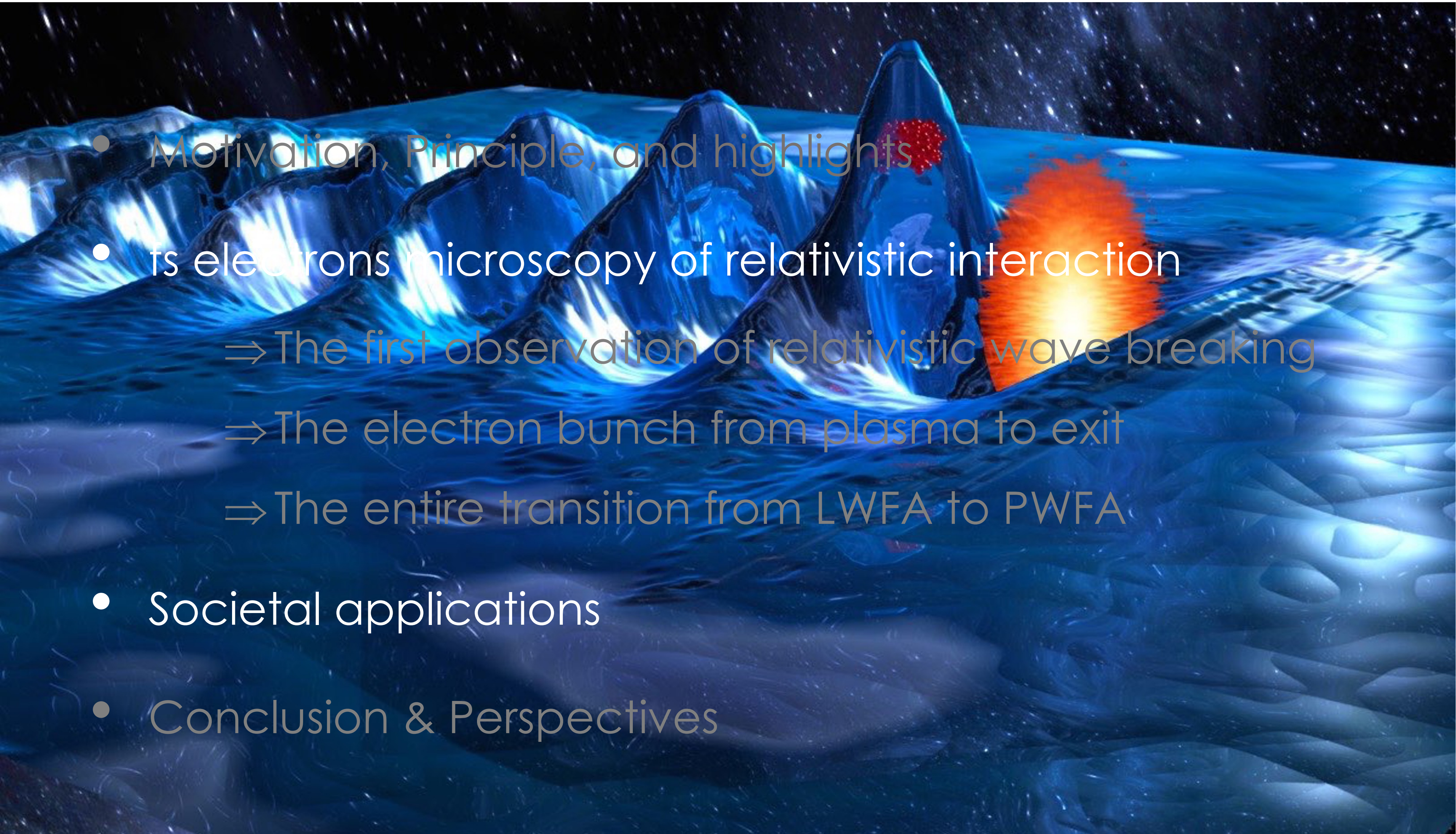

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A journey in the lab…

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Conclusion of the FREM

- ✓ The FREM (Fs Relativistic Electron Microscopy) allows us to directly observe that
  - The nonlinear plasma waves (rear spikes)
  - The electron bunch from plasma to exit
  - The entire transition from LWFA to PWFA

- ✓ Complementary and/or together to optical diagnostics, its open new perspectives for better understanding of LPA and Laser Matter Interaction

Acknowlegments

[1]**Yang Wang**, [1]Sheroy Tata, [1]Omri Seemann, [1]Eitan Y. Levine, [1]Eyal Kroupp, [1,2]Slava Smartsev, and [1,2]Igor Andriyash

[1]Weizmann Institute of Science
[2]Laboratoire d'Optique Appliquée

PhD, PostDoc and more positions are waiting for you

at WIS and ELI-NP

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To follow....and more,