Scalable laser-plasma acceleration

using Traveling-Wave Electron Acceleration (TWEAC)

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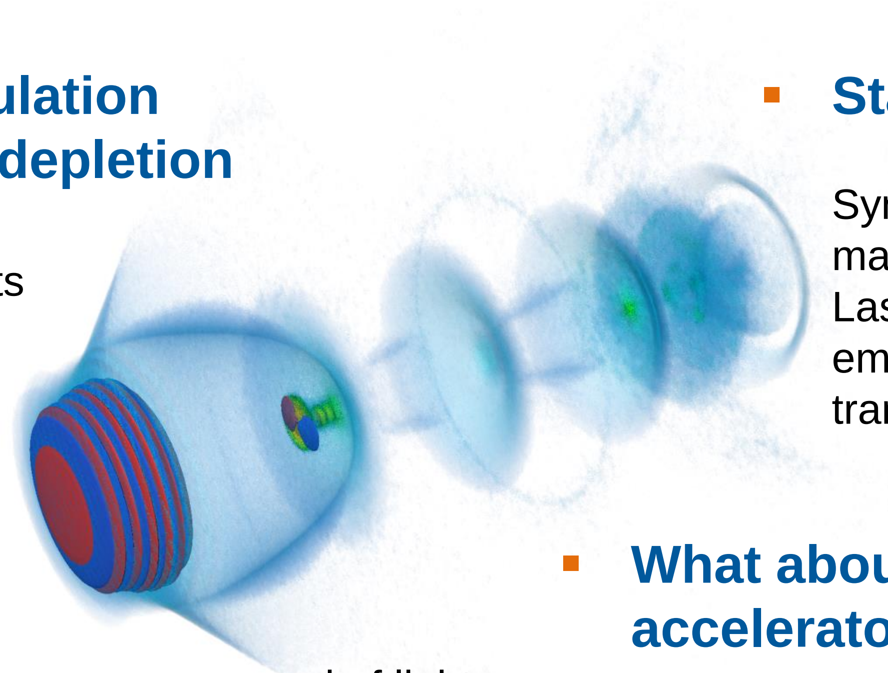
Challenges in Laser-wakefield acceleration for reaching electron energies beyond 10 GeV

- **Self-phase modulation and laser pump depletion**

  Drive laser transfers its energy to the plasma.

- **Staging is hard!**

  Synchronization, Beam size matching, charge loss, Laser in/outcoupling, emittance growth in beam transport, etc.



- **Dephasing limit**

  Laser propagates below vacuum speed of light, so accelerated electrons outrun wakefield

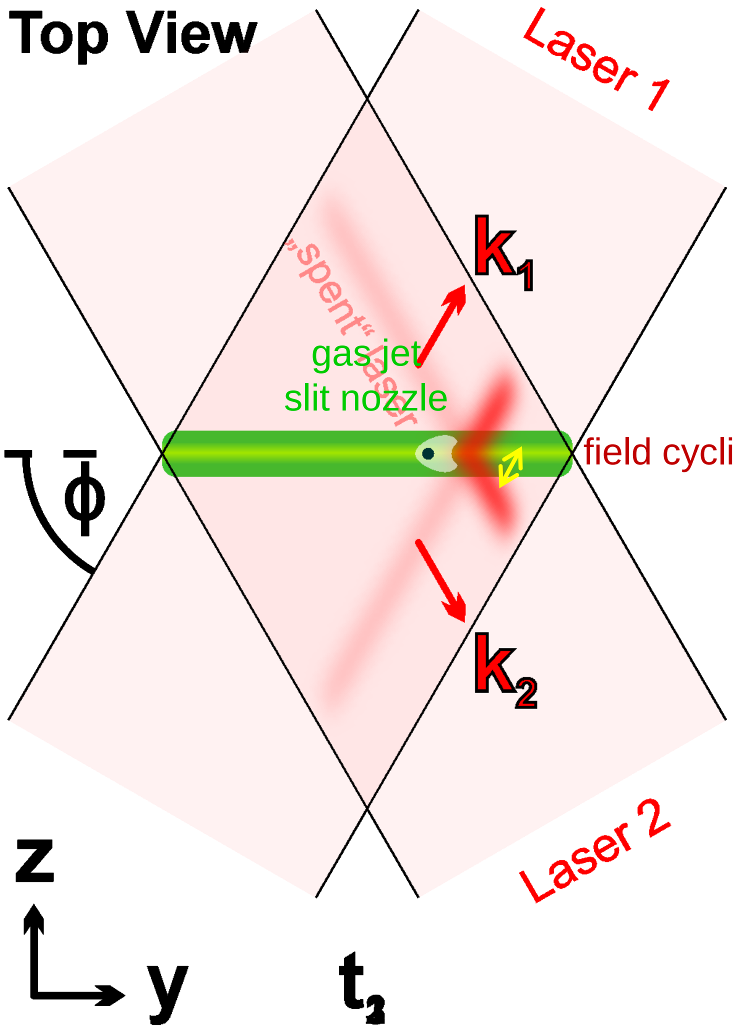
- **What about Plasma-wakefield accelerators?**

  Another accelerator required, energy gain limited by transformer ratio, beam-instabilities.

- **Laser pulse guiding**

  Guiding of high-power lasers over extended distances at low densities $<10^{17}$ cm^{-3}

Traveling-Wave Electron Acceleration (TWEAC)



- Pulse-front tilted laser enforces vacuum speed of light propagation of laser overlap in plasma.

$$\alpha = \Phi/2 \;\rightarrow\; v_{wake} \equiv c$$

- Oblique laser beam geometry continuously feeds a „fresh“ portion of the laser beams into an unperturbed plasma.

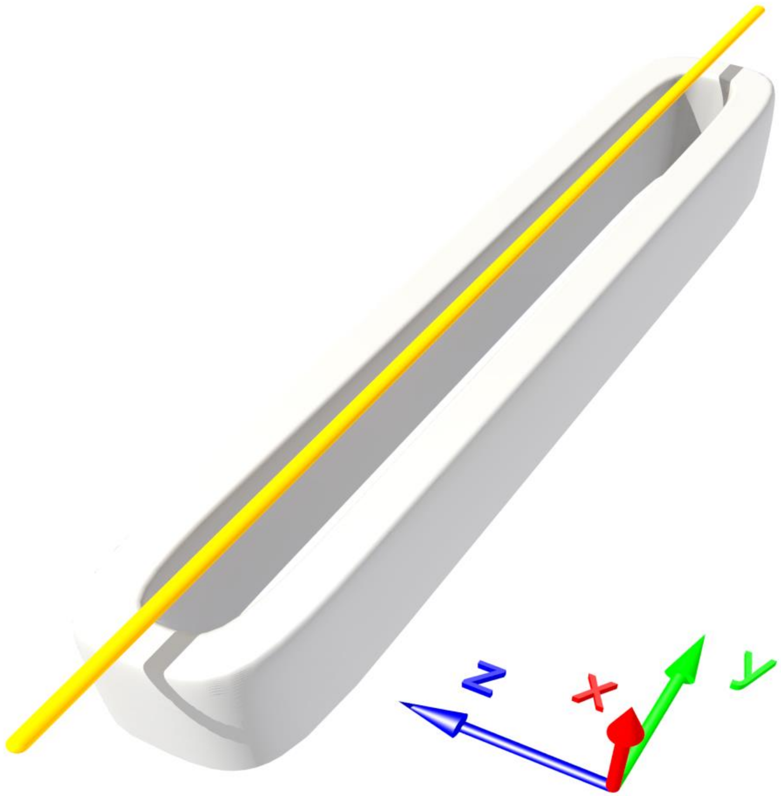
L(accelerator**) > L(**depletion length**)**

is fine, as long

L(field cycling length**) < L(**depletion length**)**

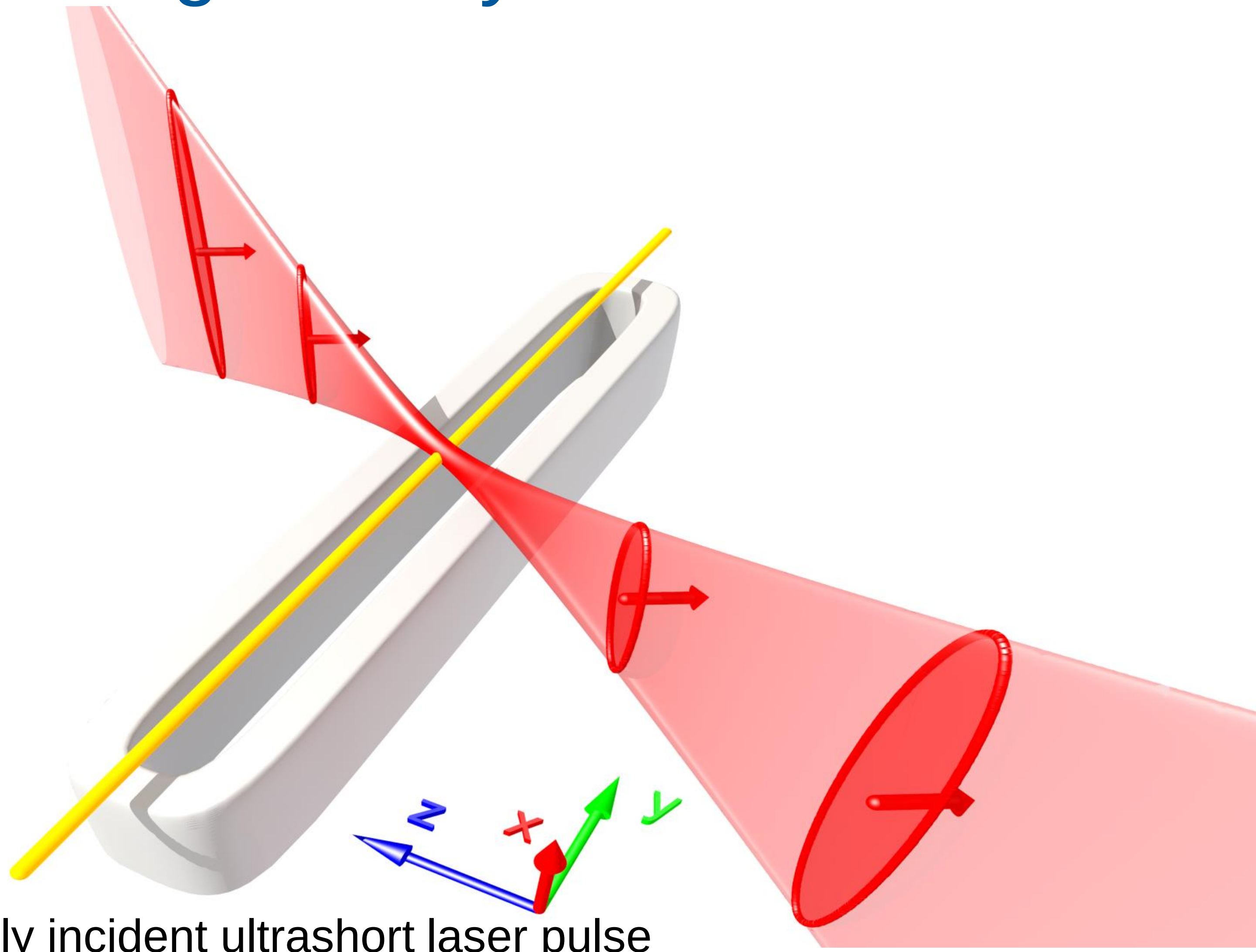
Debus *et al.*, Phys. Rev. X **9**, 031044 (2019), **DOI:** 10.1103/PhysRevX.9.031044

TWEAC geometry in a nutshell



1.) An extended gas jet slit nozzle defines a line focus axis for cylindrical optics.

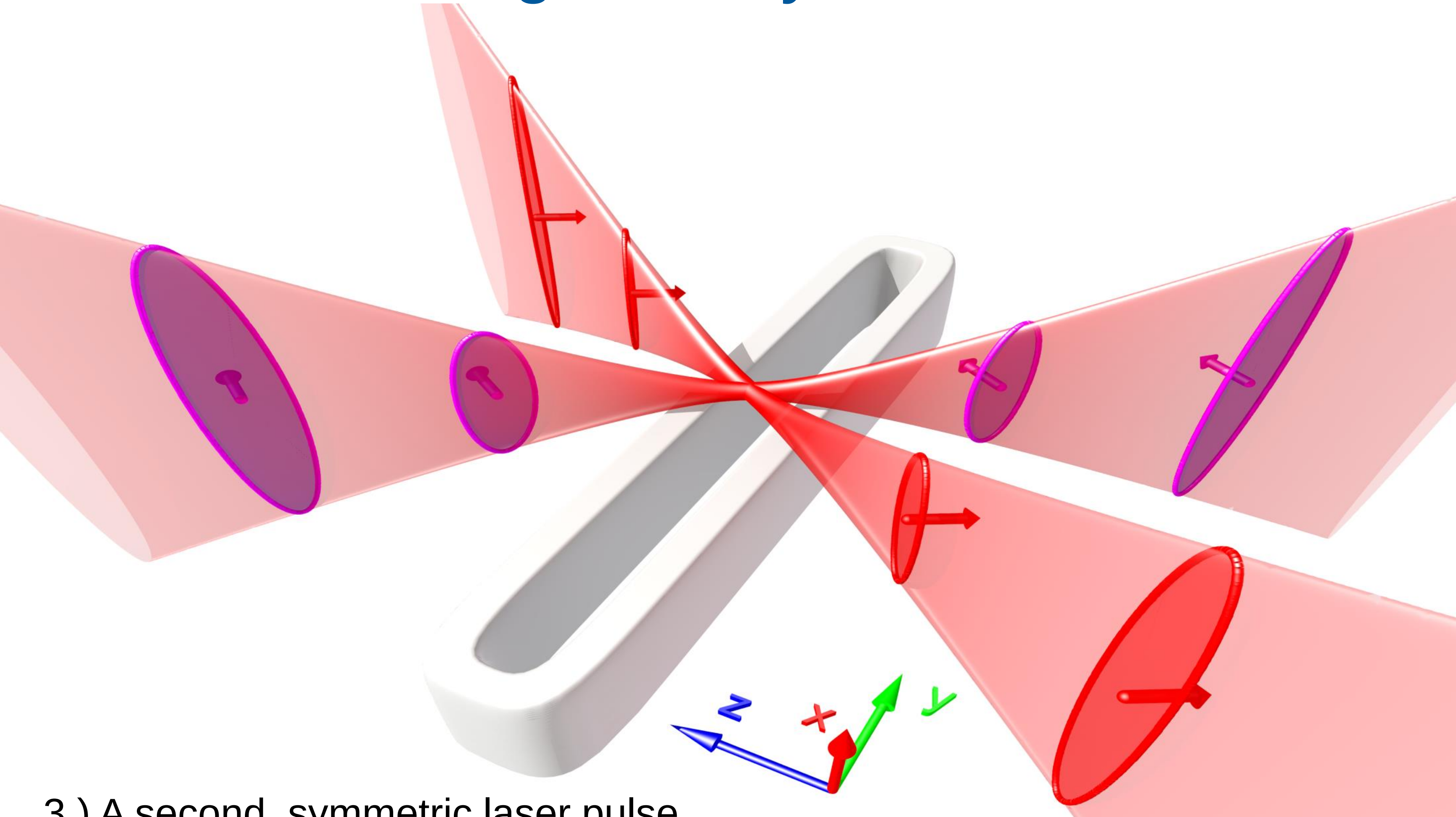
TWEAC geometry in a nutshell



2.) A first, obliquely incident ultrashort laser pulse
with a carefully tuned pulse-front tilt creates a comoving focus.

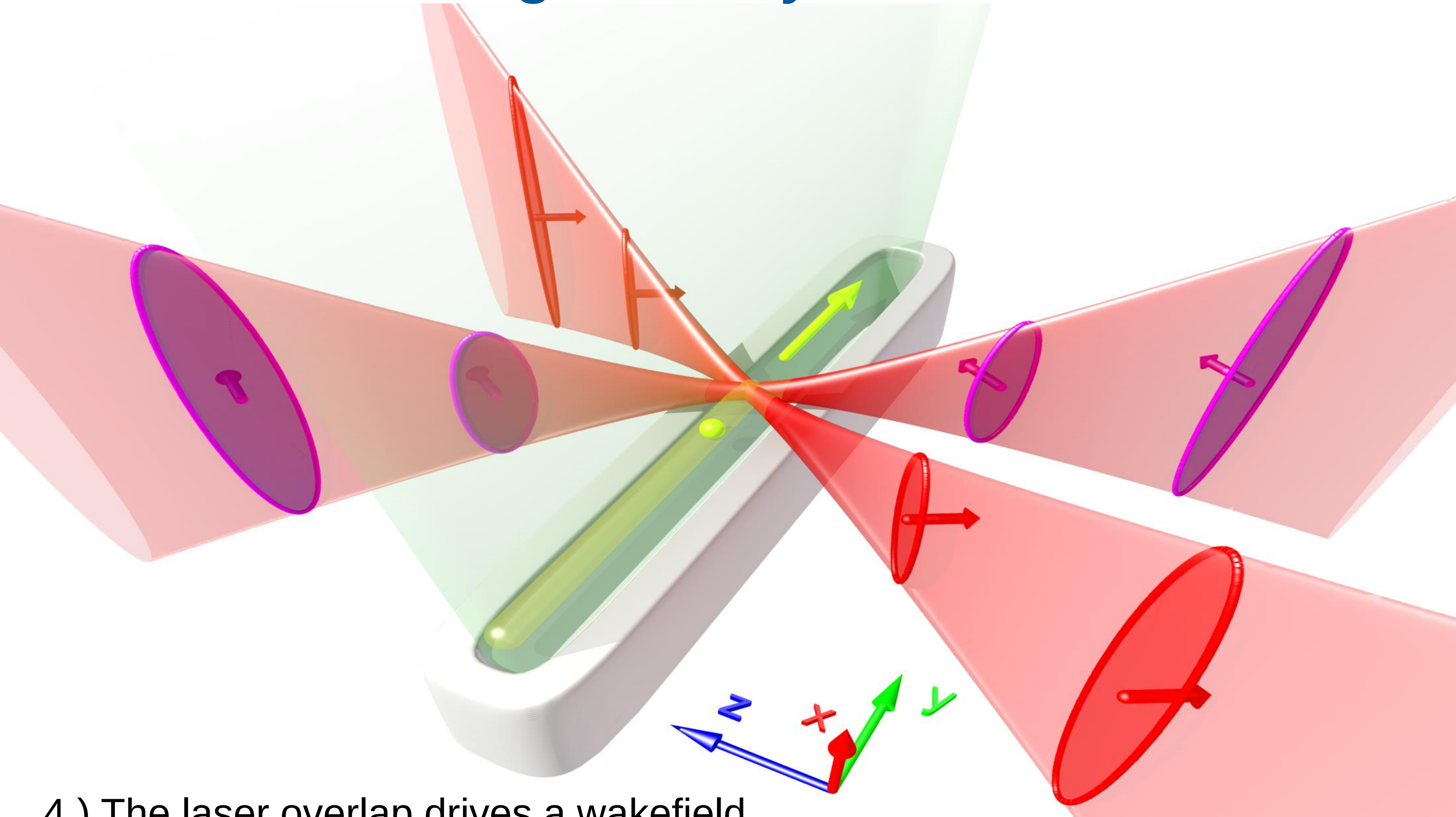
HZDR

TWEAC geometry in a nutshell



3.) A second, symmetric laser pulse overlaps with the first laser.

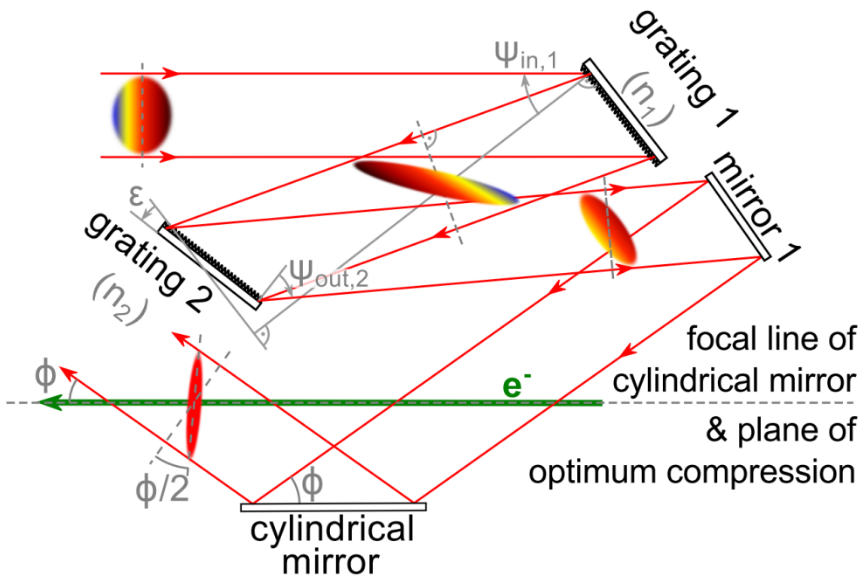
TWEAC geometry in a nutshell



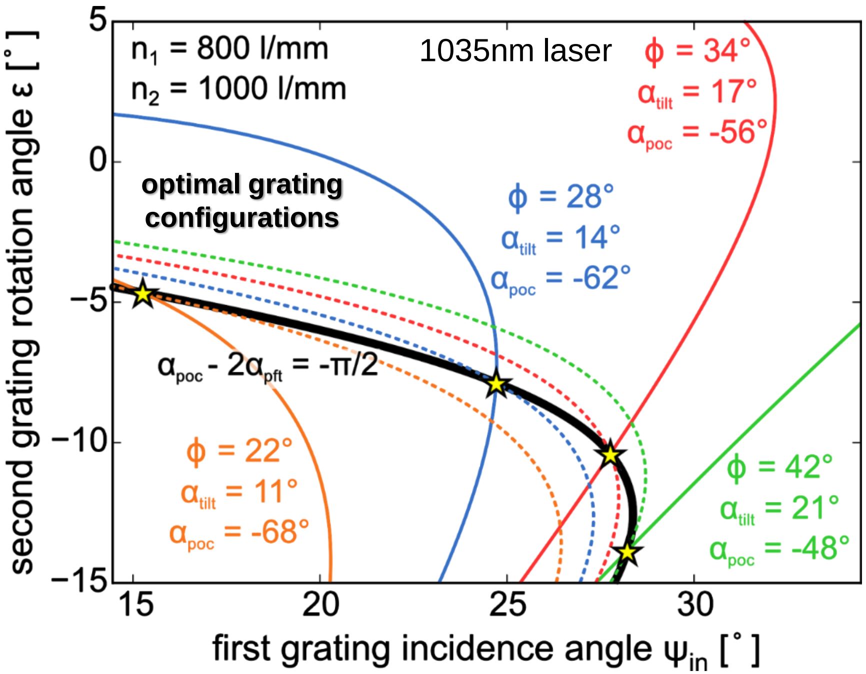
4.) The laser overlap drives a wakefield moving with the vacuum speed of light.

TWEAC type lasers are experimentally feasible using standard optics

Optical setups for TWEAC are similar to Traveling-Wave Thomson-Scattering



Pulse synthesis using two-grating setups provides tunability by varying pulse-front tilt.



Traveling-Wave Thomson-Scattering aims for

High photon yields per shot, low bandwidths, tunablitity and all-optical FELs

A. Debus *et al.*, *Appl. Phys. B* **100** (2010) 1, 61

K. Steiniger *et al.*, *J. Phys. B* **47** (2014) 23, 234011

K. Steiniger *et al.*, Front. Phys. 6 (2019),

“Building an Optical Free-Electron Laser in the Traveling-Wave Thomson-Scattering Geometry“.

$\alpha = \Phi/2 \rightarrow v_{wake} \equiv c$

PIConGPU

github.com/ComputationalRadiationPhysics/picongpu

picongpu.readthedocs.io

Challenges for simulating TWEAC

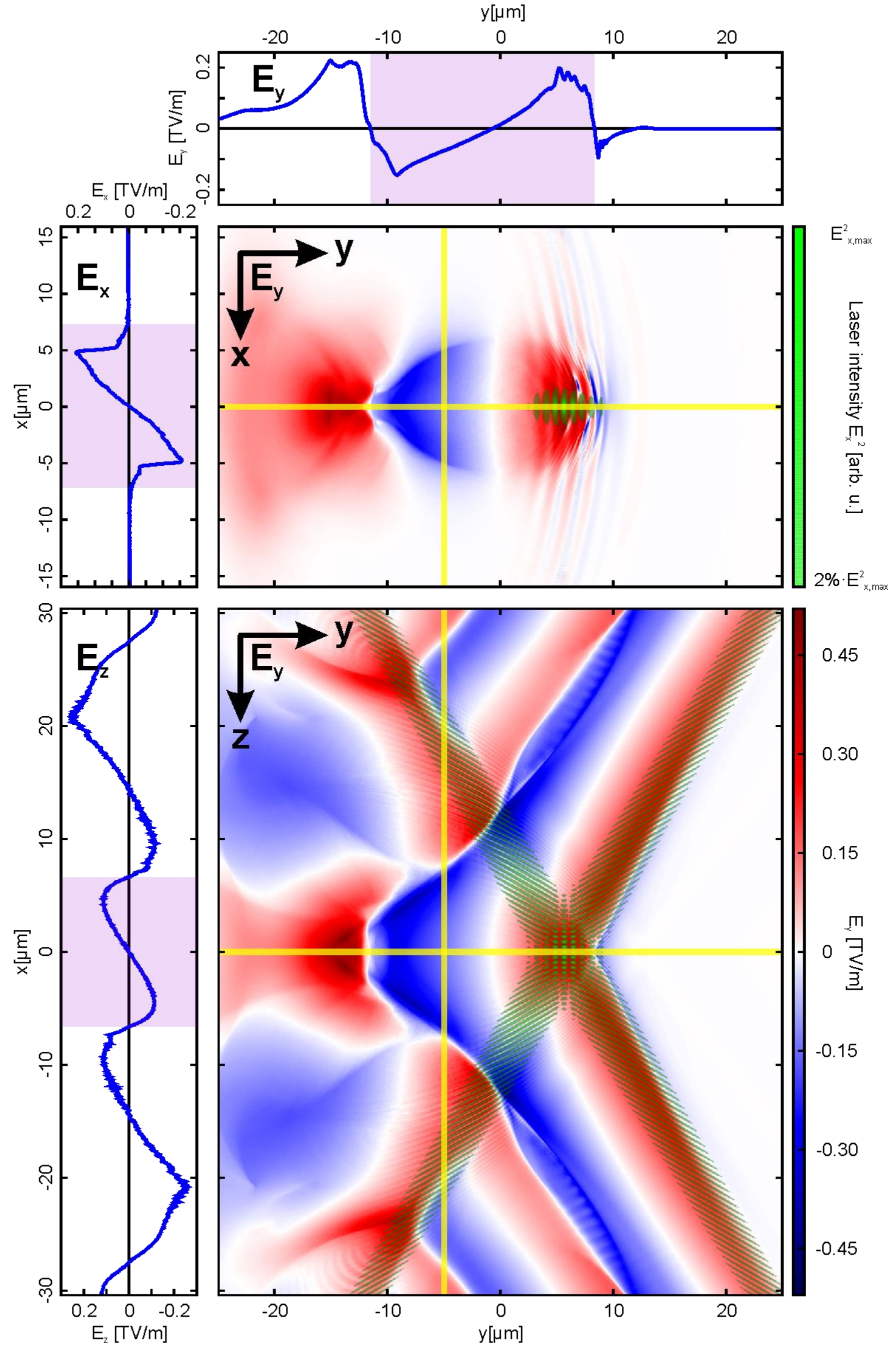
- Non-rotationally symmetric 3D geometry
- Long acceleration lengths beyond LWFA depletion and dephasing lengths
- Requires robust laser insertion, extraction and absorption techniques at simulation boundaries

→ **High requirements on performance, resolution, memory and boundary conditions**

Simulate TWEAC using PIConGPU

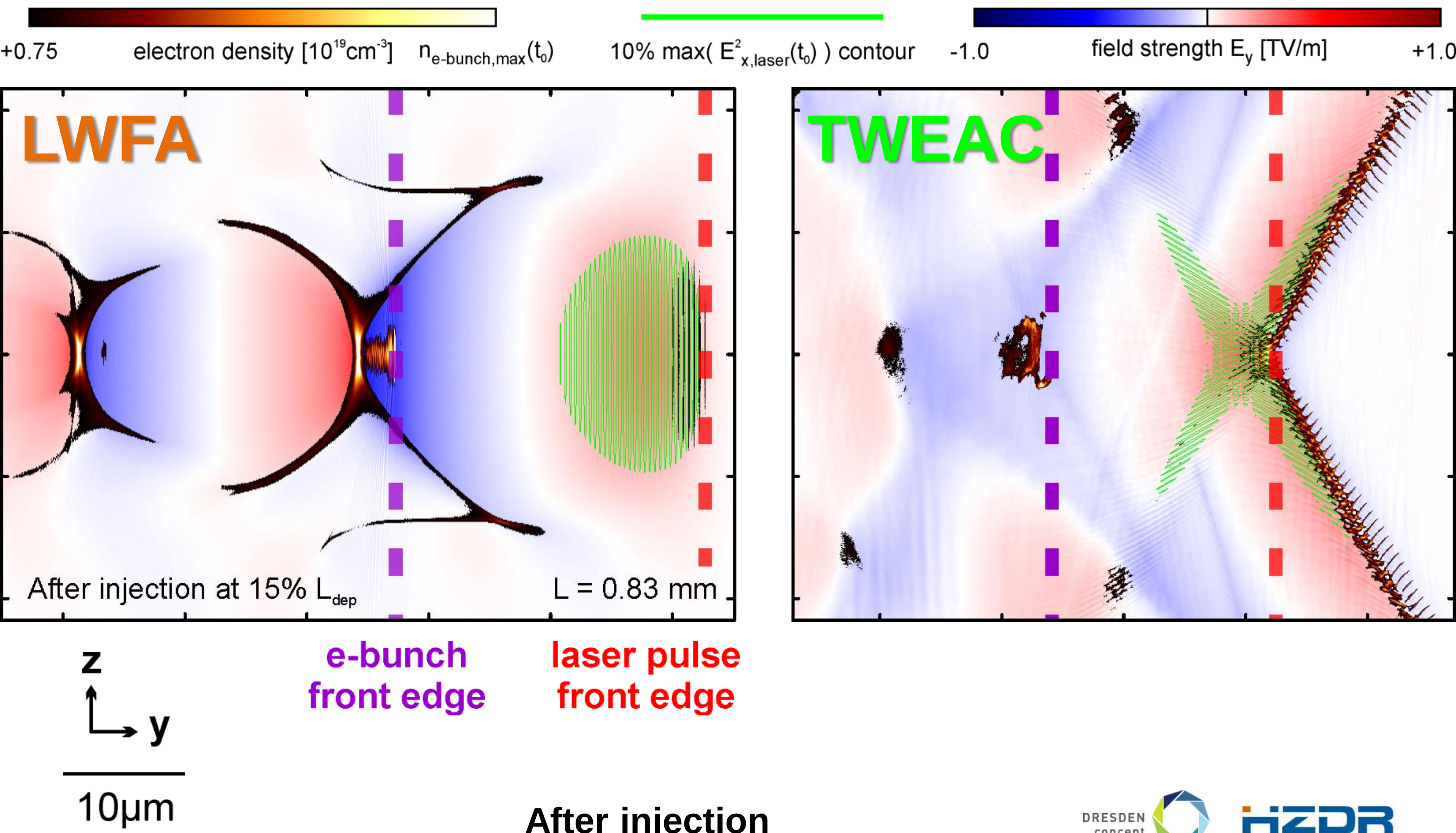
- Field strengths of plasma cavity and focusing fields are comparable to LWFA.
- V-shaped cavity profile in the plane of laser propagation.
- Existence of side cavities.
- At constant density self-injection is absent.

a_0=3.5 each arm ; a_0 = 7.0 in overlap
Φ=60°; n_e=6.4 · 10^{18} cm^{-3} ; τ=10fs (FWHM)



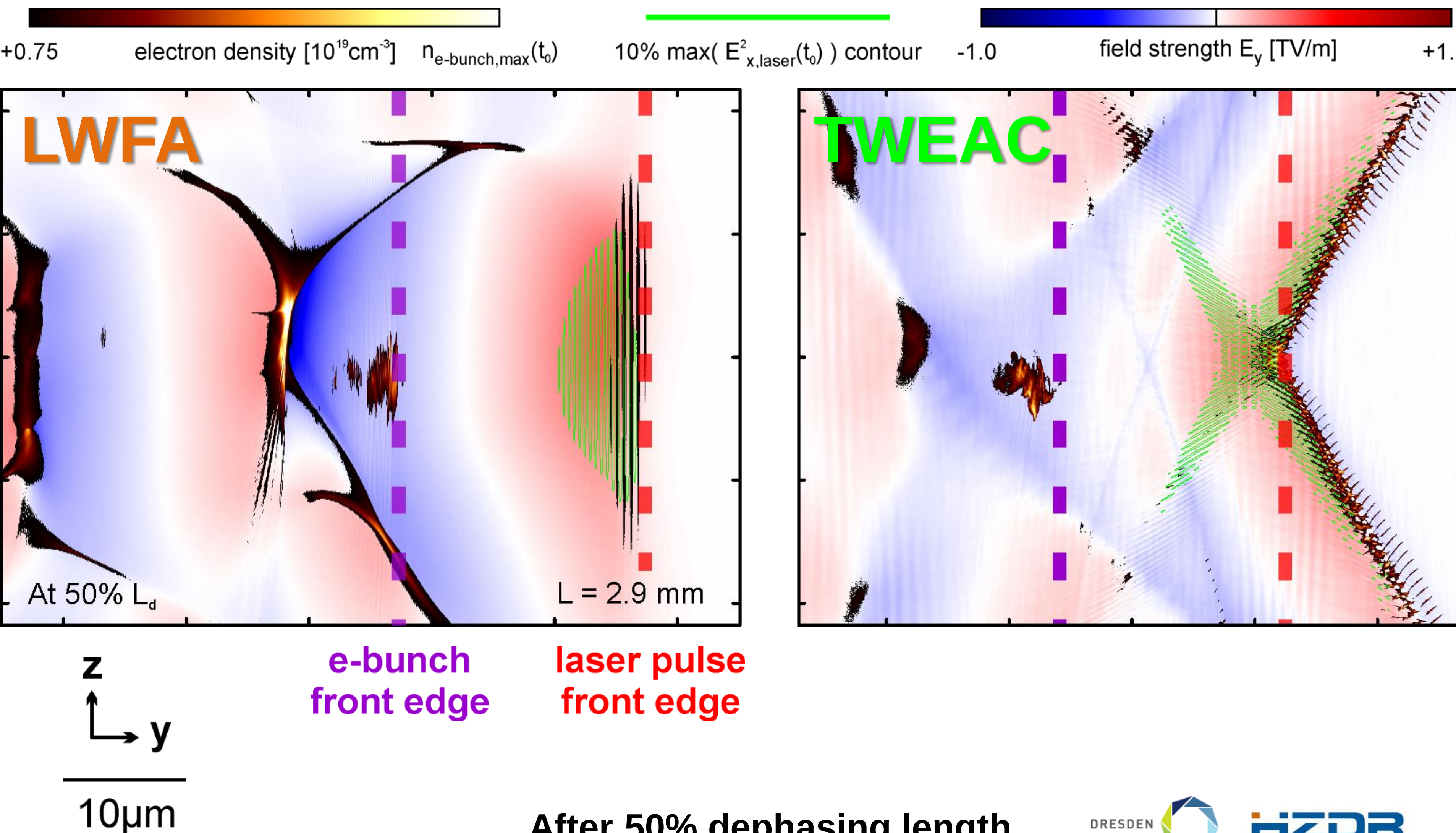
Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

TWEAC eliminates the dephasing and depletion limit.



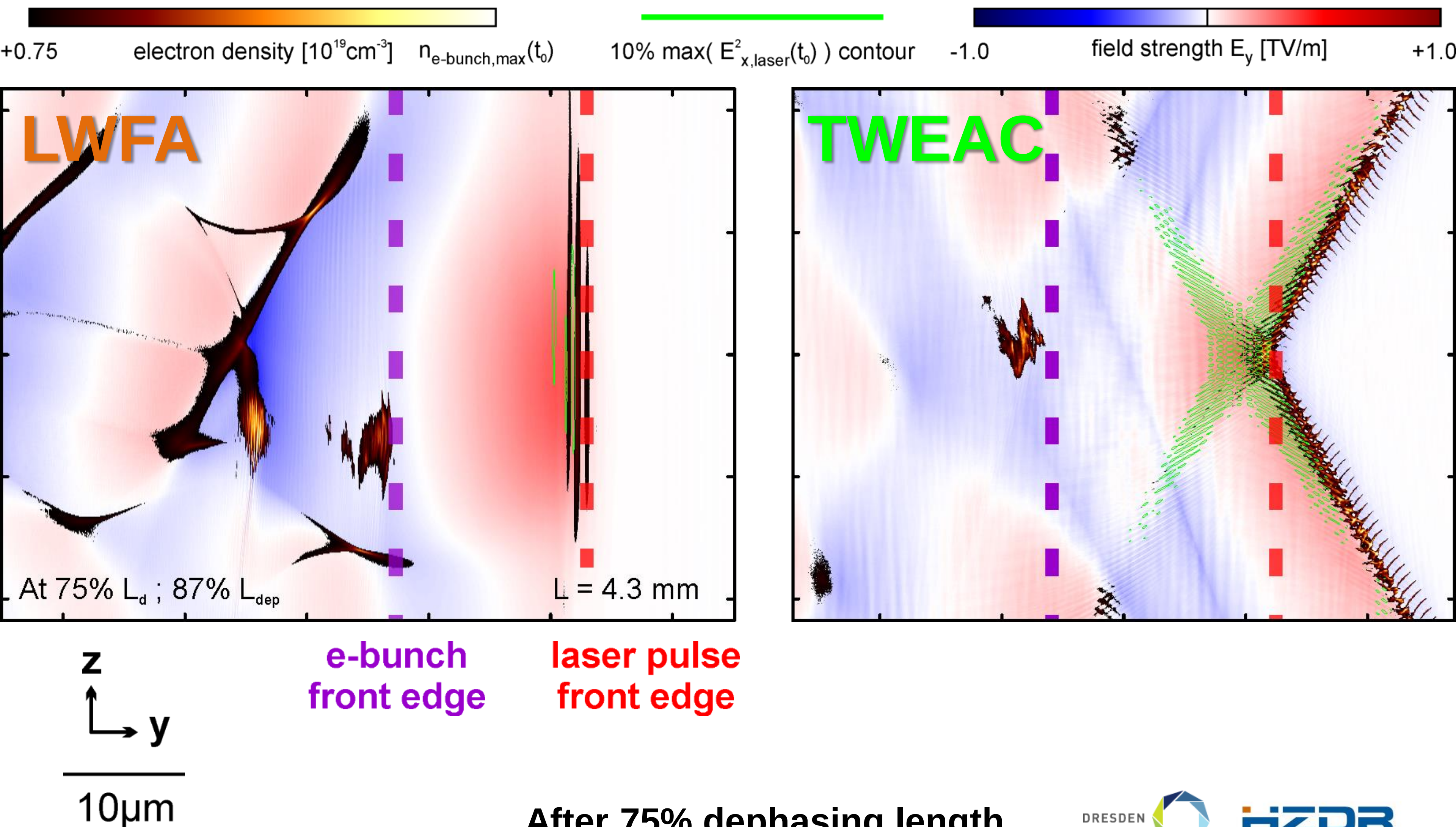
After injection

TWEAC eliminates the dephasing and depletion limit.



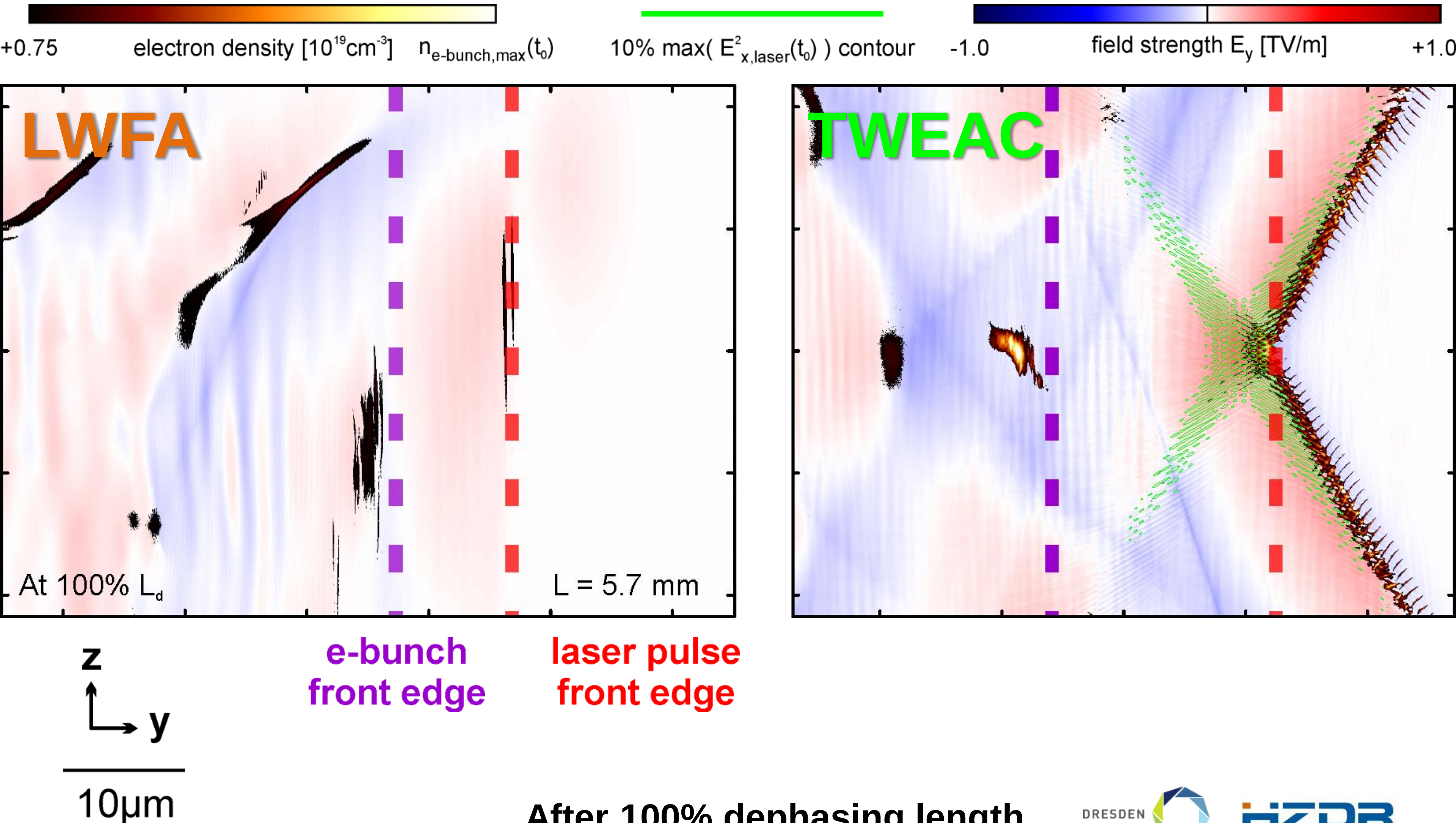
After 50% dephasing length

TWEAC eliminates the dephasing and depletion limit.



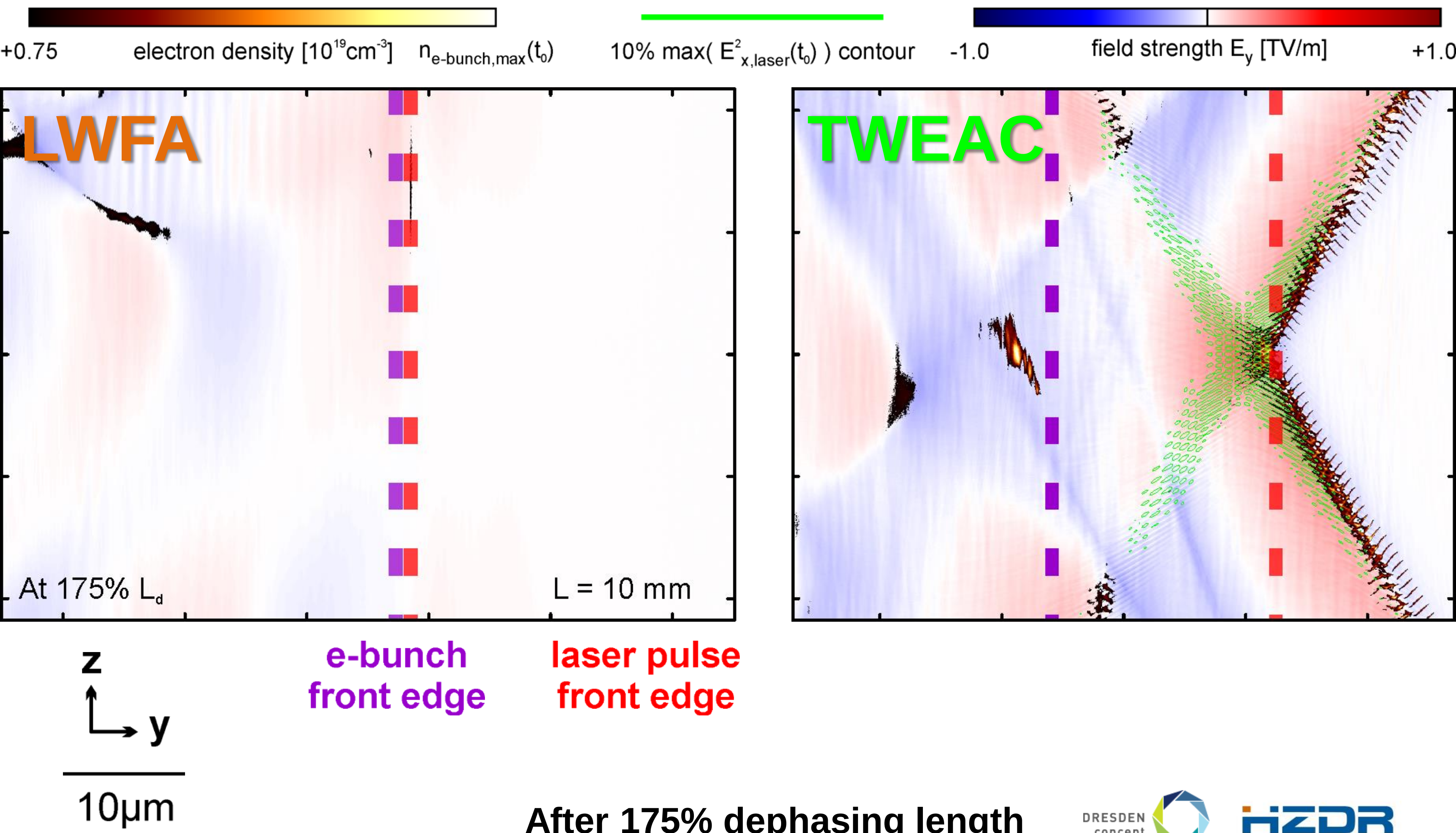
After 75% dephasing length

TWEAC eliminates the dephasing and depletion limit.



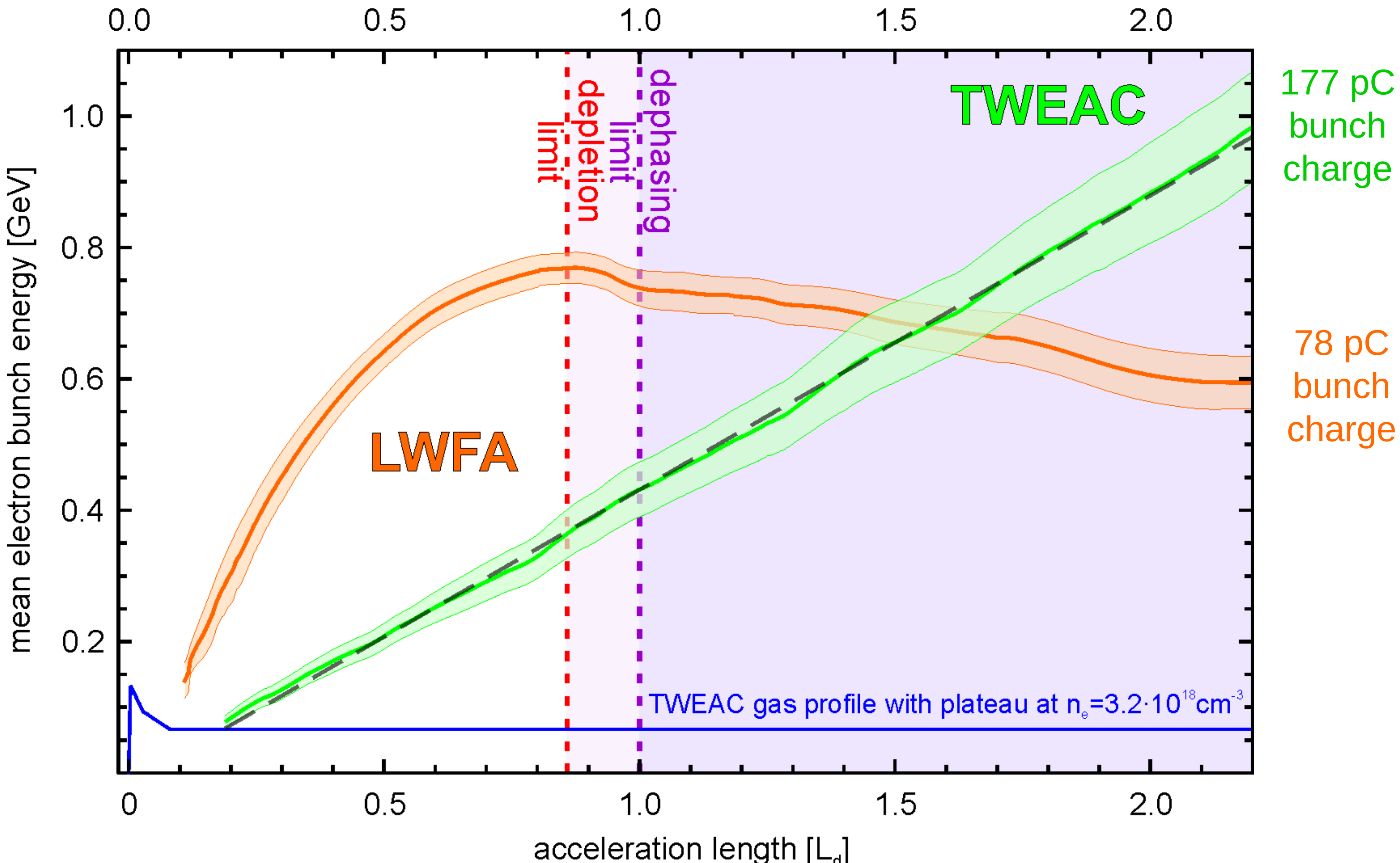
After 100% dephasing length

TWEAC eliminates the dephasing and depletion limit.



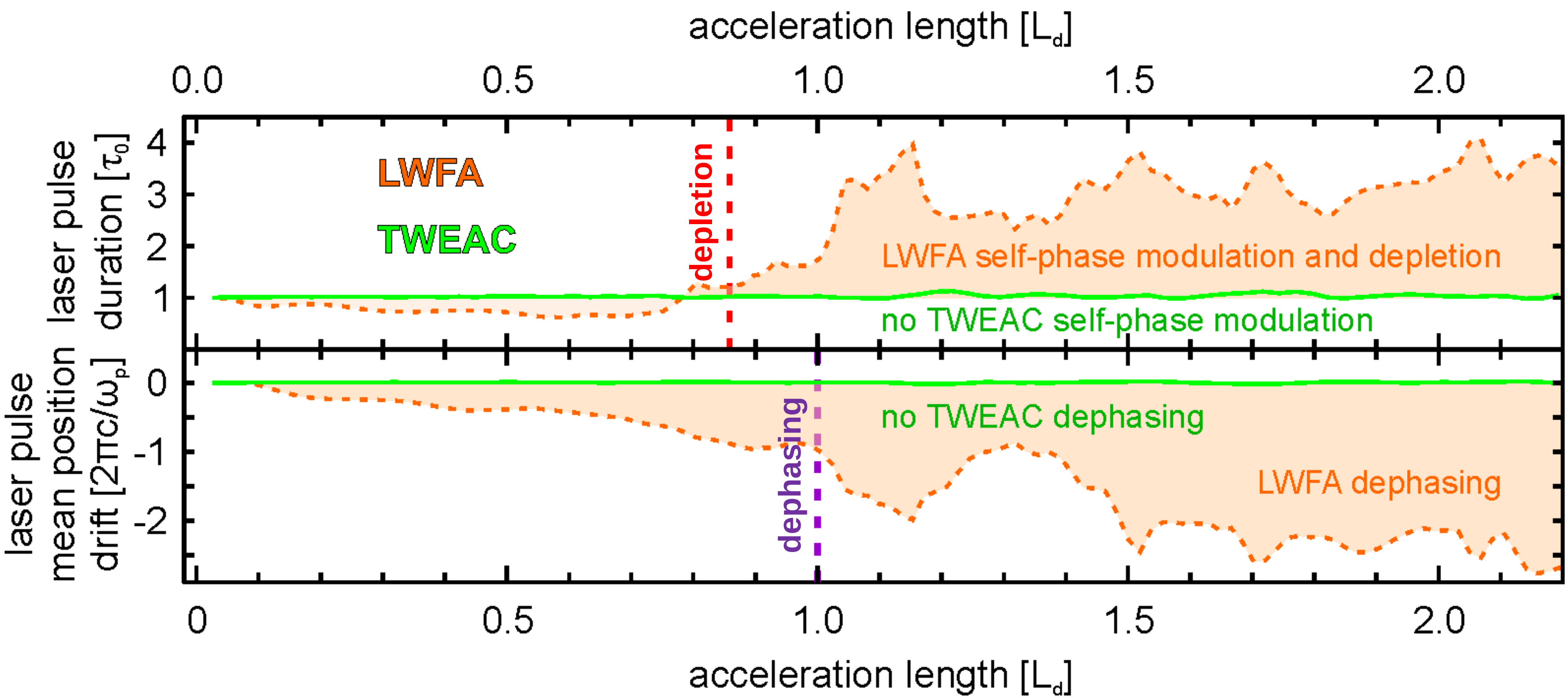
After 175% dephasing length

TWEAC mean electron electron energy evolves linearly with acceleration distance



12.5 mm total plasma length

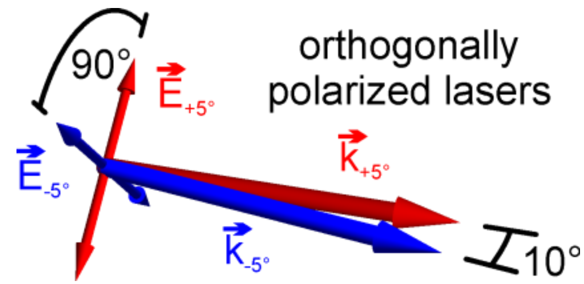
TWEAC maintains quasi-stationary plasma conditions

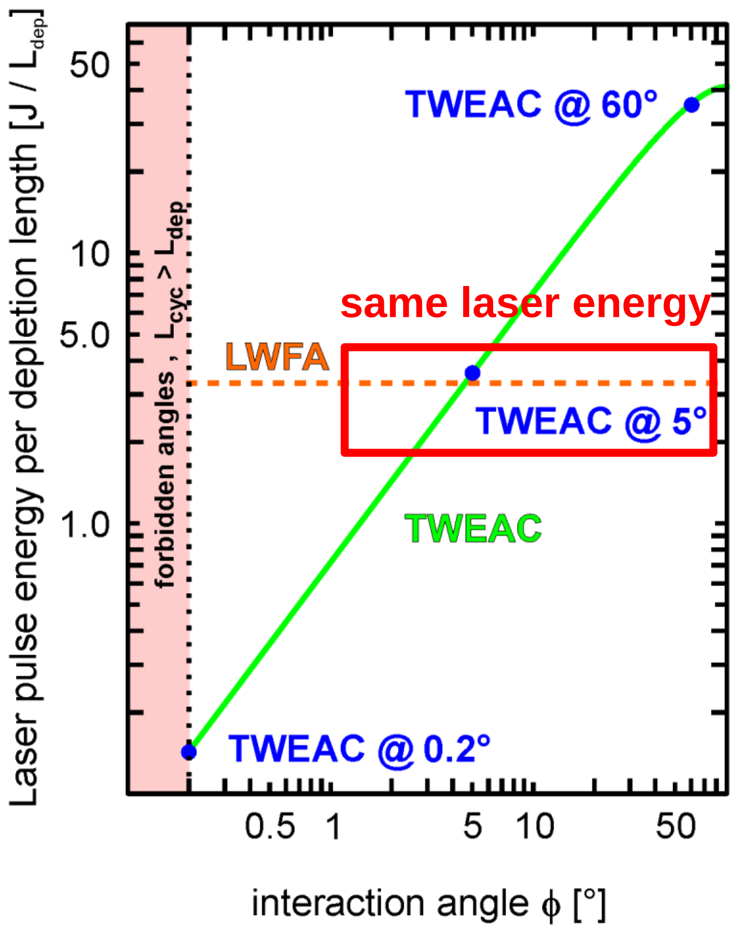


→ **TWEAC accelerator length can be made longer without dephasing or depletion.**

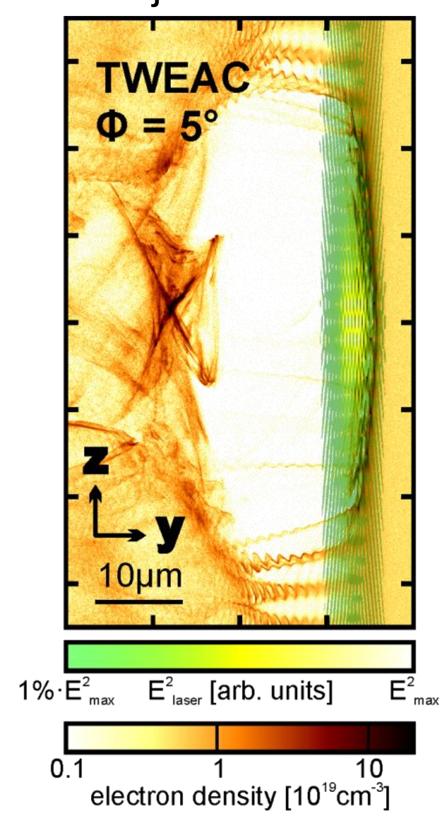
Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

How does TWEAC scale in laser energy?





At injection



$$W_{\text{laser}} \propto a_0^2 \tau_0 L_{\text{int}} w_x \sin(\phi)$$

Low incidence angles ϕ reduce required laser energy, provided that

$$L_{\text{cyc}} < L_{\text{dep}}$$

where $L_{\text{cyc}} = L_{\text{trans}} / \sin(\phi)$ is independent of the total interaction distance L_{int}.

Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

DRESDEN concept HZDR

Degrees of freedom for high-energy efficiency operation of TWEAC

- **Use small incidence angles**
  to increase time of laser within main interaction region.

- **Pump depletion lengths can be shorter than the LWFA dephasing length.**
  → **Use laser pulse durations that are shorter than the plasma wavelength.**

- **TWEAC lasers do not rely on guiding.**
  → **Laser spot sizes can be significantly smaller than the plasma wavelength.**

- **Exploit quasi-stationary acceleration conditions in TWEAC.**
  → **Wakefields locally can sustain high charges.**

- **TWEAC focal geometry can enable large interaction volumes.**
  → **Especially useful if flat beams are a goal.**

DRESDEN concept HZDR

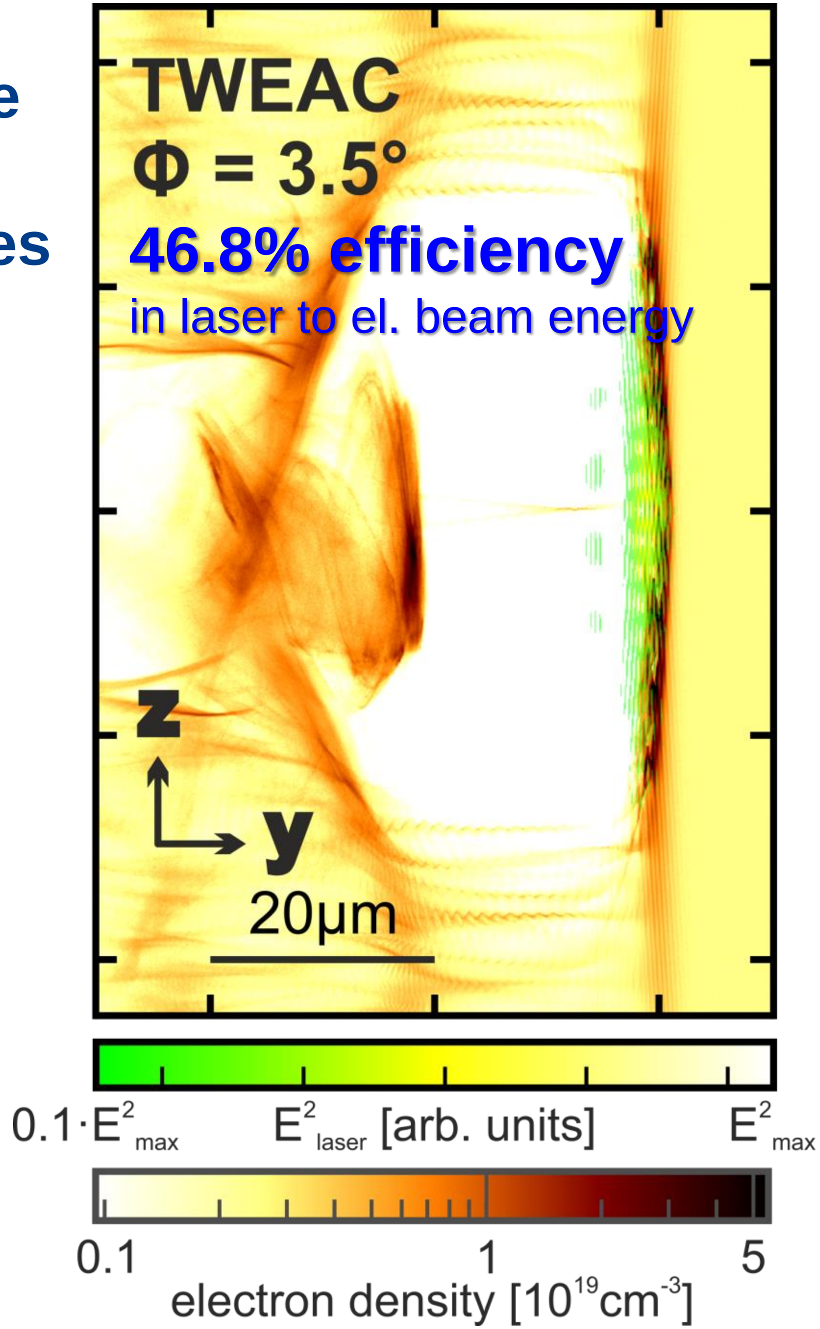
Low-angle TWEAC setups enable electron acceleration with high laser to electron beam efficiencies

- **High energy efficiencies can be reached**
  46.8% laser to electron beam energy efficiency,
  3.78 J/GeV energy-gain efficiency
  at 1.0 GeV/cm acceleration gradient

- **High electron beam charge**
  1.8nC down-ramp injected charge,
  330MeV with 18.9% energy spread (rms)

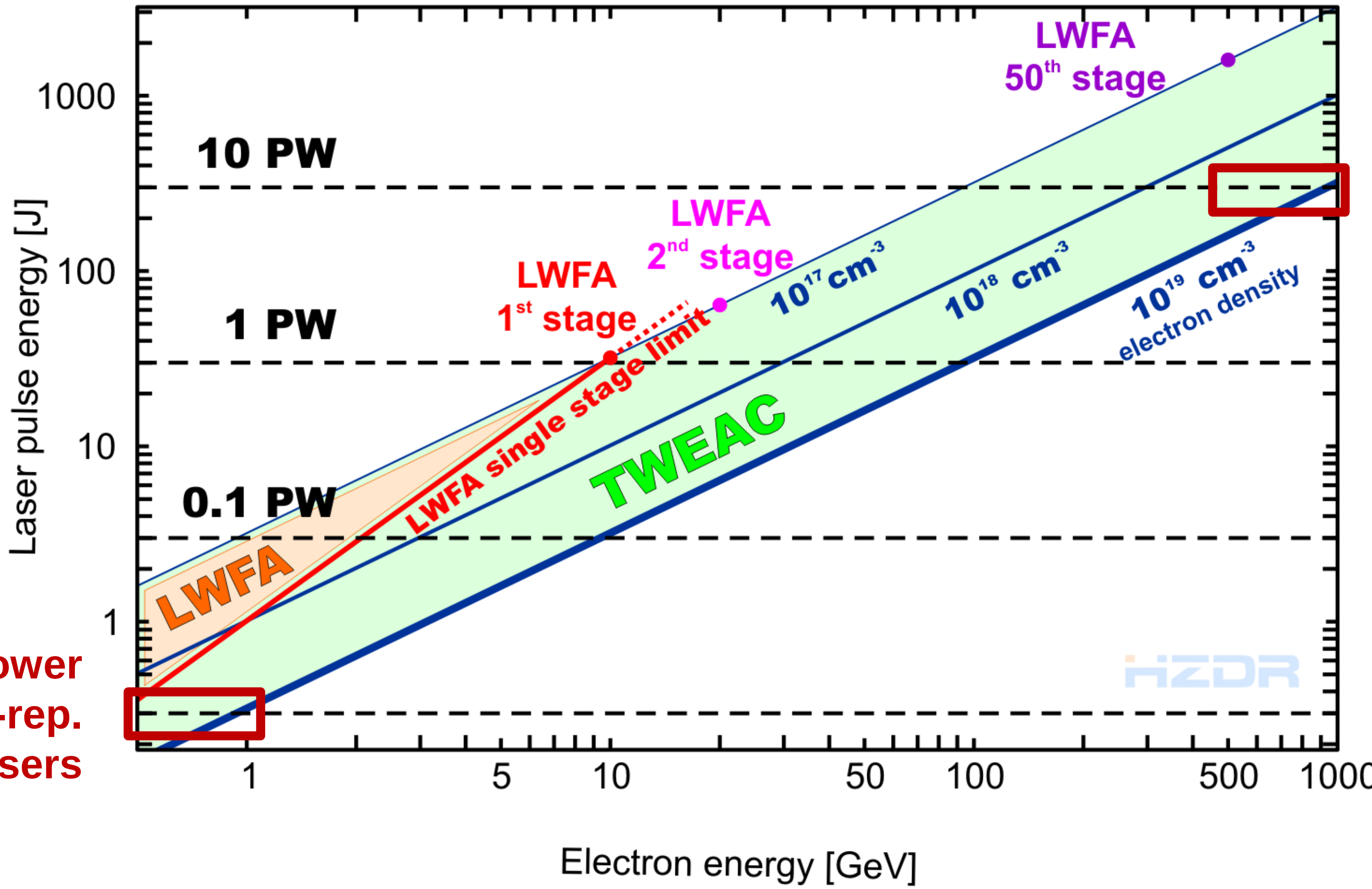
- **Flat electron beam**
  2.2µm x 4.8µm x 13µm (rms)
  from transversally extended cavity.

$2.5 \cdot 10^{18}\ cm^{-3}$, a_0=6.0, 800nm, $w_{0,x}$=1.2µm, 1.25J
330MeV with 18.9% (rms) energy spread



Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

How does TWEAC scale in laser energy?



ELI type lasers could reach the energy frontier

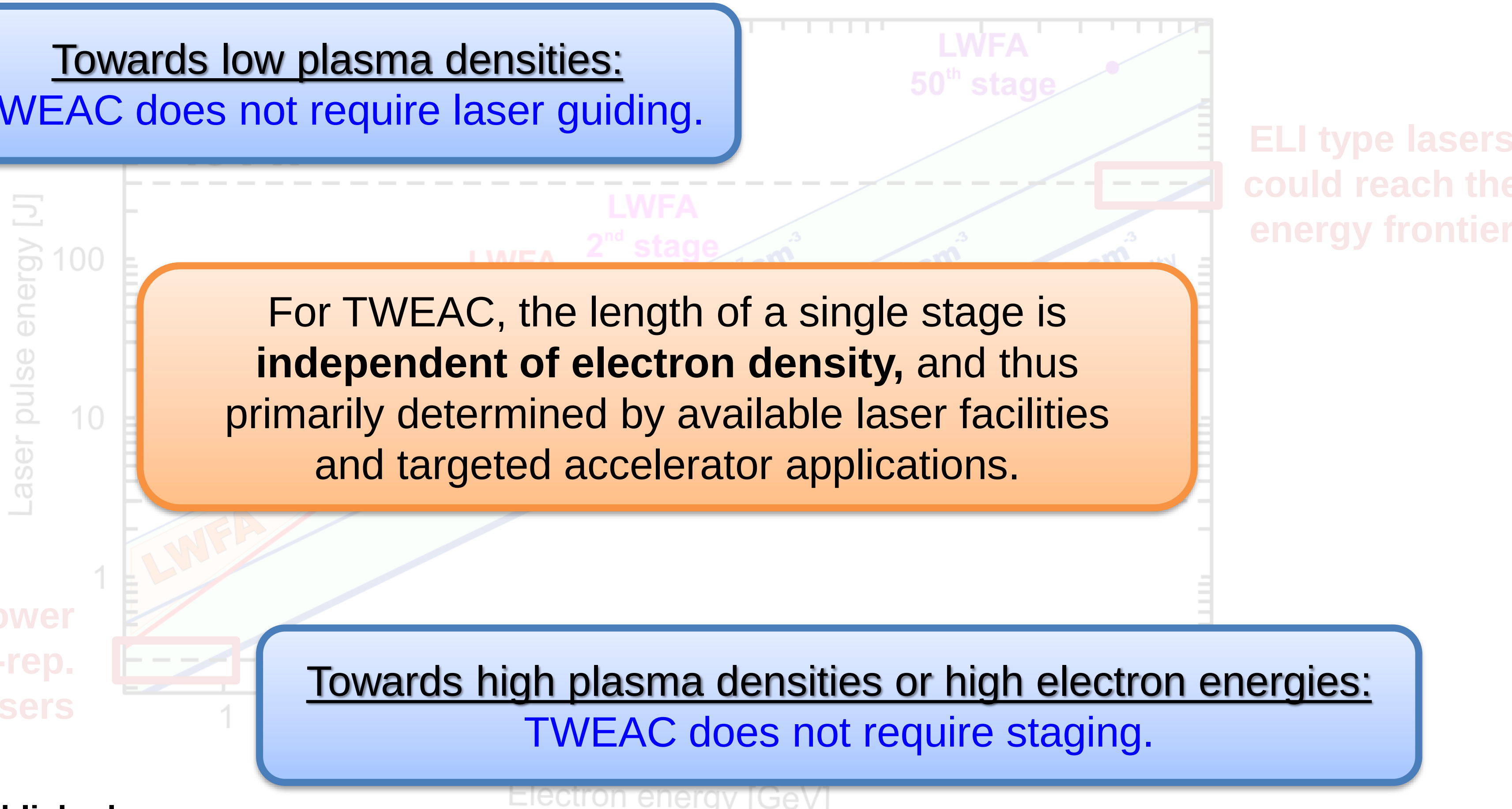
Low-power high-rep. lasers

Debus *et al.*, Phys. Rev. X **9**, 031044 (2019),
„Circumventing the dephasing and depletion limits of laser-wakefield acceleration"

LWFA scaling based on
C. B. Schroeder *et al.*, *Phys. Rev. Spec. Top. - Accel. Beams* **13,** 101301 (2010).

How does TWEAC scale in laser energy?

<u>Towards low plasma densities:</u>
TWEAC does not require laser guiding.



For TWEAC, the length of a single stage is **independent of electron density,** and thus primarily determined by available laser facilities and targeted accelerator applications.

<u>Towards high plasma densities or high electron energies:</u>
TWEAC does not require staging.

Paper published
Debus *et al.*, Phys. Rev. X **9**, 031044 (2019),
„Circumventing the dephasing and depletion limits of laser-wakefield acceleration“

LWFA scaling based on
C. B. Schroeder *et al.*, *Phys. Rev. Spec. Top. - Accel. Beams* **13,** 101301 (2010).

Conclusions

Traveling-wave electron acceleration (TWEAC)

- Eliminates the LWFA dephasing and depletion limits.
- Quasi-stationary plasma conditions without (parasitic) self-injection.
- No laser self-phase modulation along direction of electron acceleration.
- Can in principle be arbitrarily extended in a single stage up to the energy frontier.

Thank you for your attention!

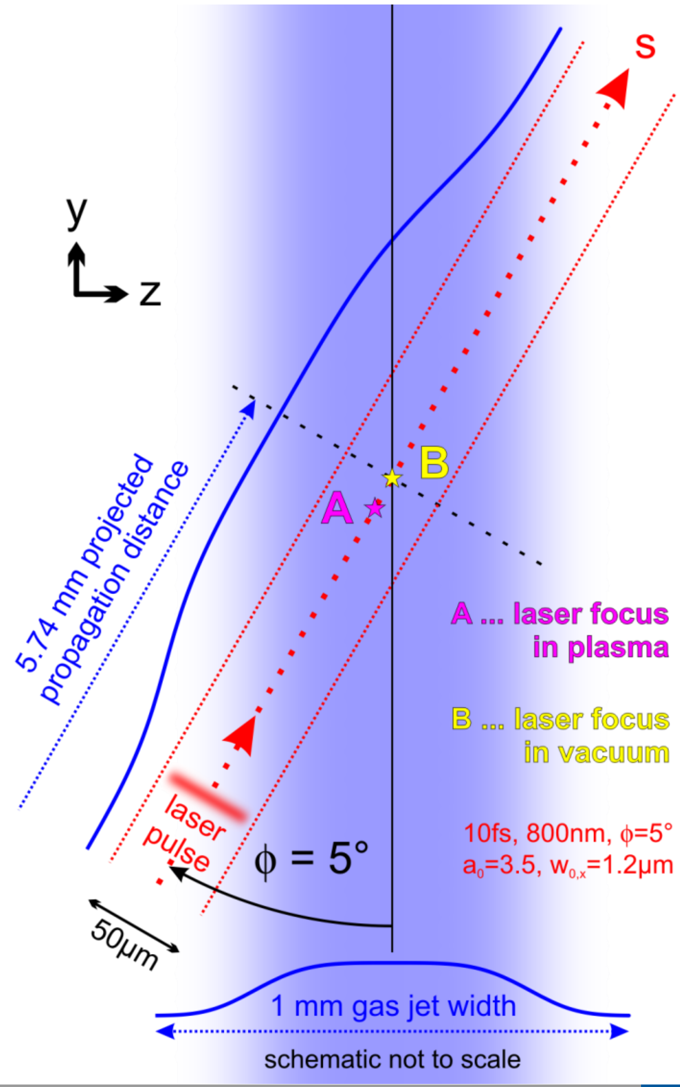
Debus *et al.*, Phys. Rev. X **9**, 031044 (2019), **DOI:** 10.1103/PhysRevX.9.031044
„Circumventing the Dephasing and Depletion Limits of Laser-Wakefield Acceleration“

DRESDEN concept

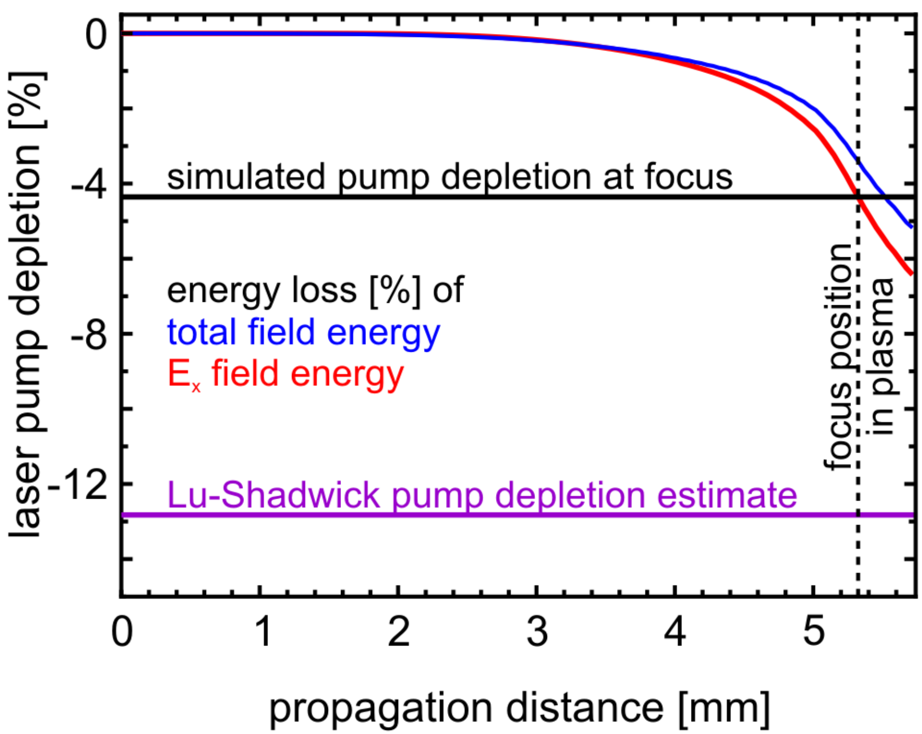
HZDR

Supplementary slides

Pump laser depletion within field cycling length is negligible

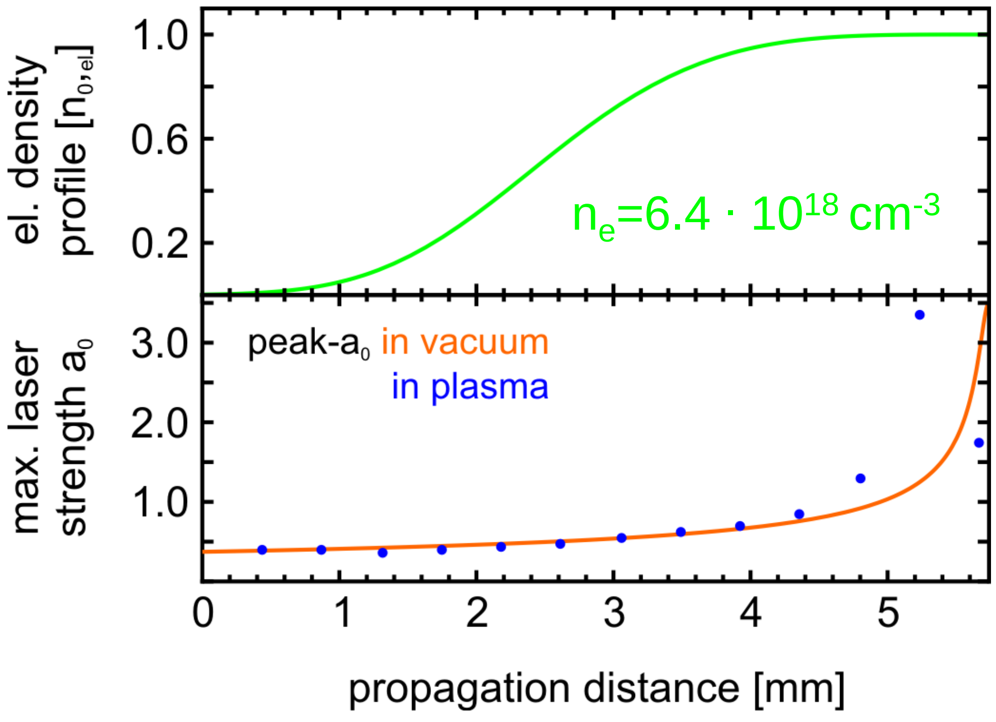


Numerical results from 3D PIC simulation (PIConGPU)

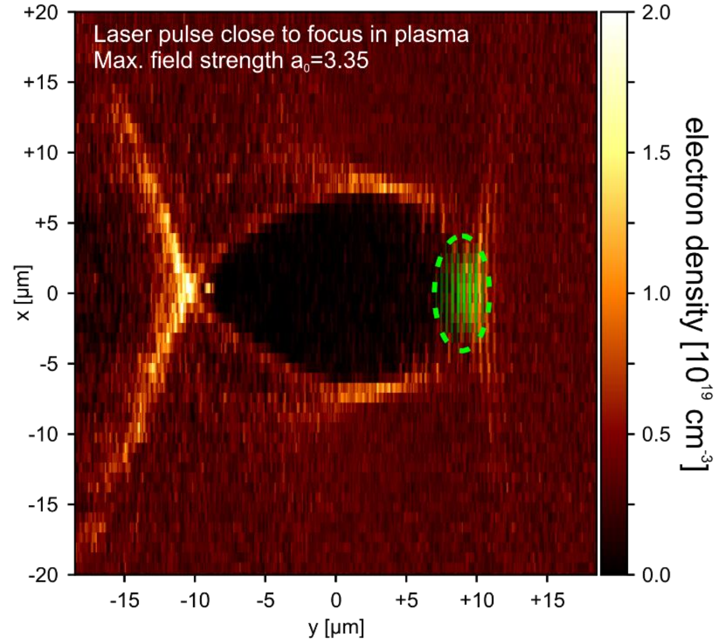


Simulated pump laser depletion smaller than analytical estimate

Pump laser depletion within field cycling length is negligible



Zoom-in of interaction region



Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

Tabulated energy efficiency results of LWFA and TWEAC 3D-PIC simulation scenarios

Accelerator configuration				
accelerator type	**LWFA**	**TWEAC**	**TWEAC**	**TWEAC**
incident angle φ	-	60°	5.0°	3.5°
electron density	$3.2 \cdot 10^{18}$ cm^{-3}	$3.2 \cdot 10^{18}$ cm^{-3}	$3.2 \cdot 10^{18}$ cm^{-3}	$2.5 \cdot 10^{18}$ cm^{-3}
peak-a_0	7.0	7.0	7.0	6.0
laser spot size $w_{0,x}$	7.9 µm	1.2 µm	1.2 µm	1.2 µm
pol. state of laser(s)	linearly	parallel	crossed	crossed

Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

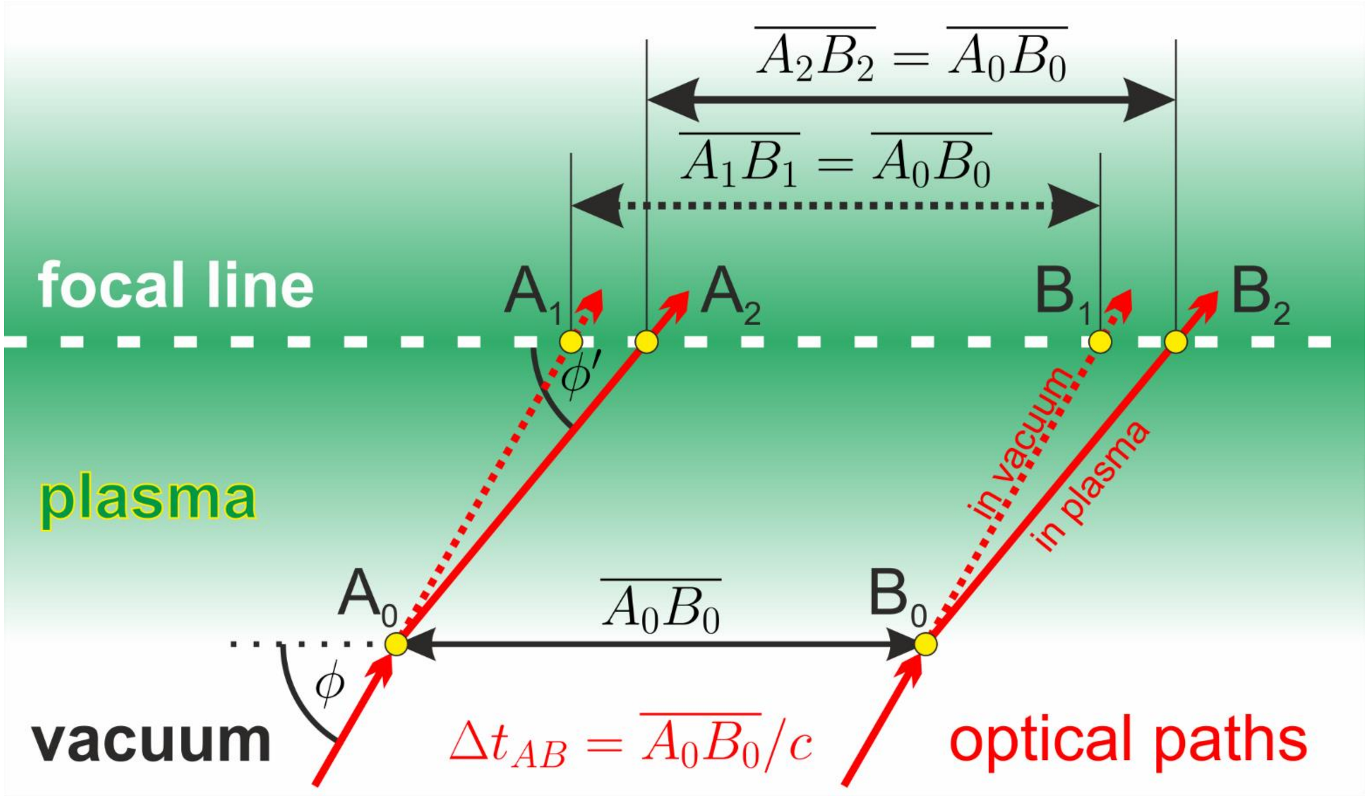
Tabulated energy efficiency results of LWFA and TWEAC 3D-PIC simulation scenarios

Accelerator performance

char. wakefield-driver-energy per L_{dep}	3.28 J	35.60 J	3.58 J	2.36 J
cavity volume	$7.90 \cdot 10^3$ µm^3	>$12.8 \cdot 10^3$ µm^3	$7.20 \cdot 10^3$ µm^3	$30.9 \cdot 10^3$ µm^3
mean acceleration gradient	1.44 GeV/cm	0.752 GeV/cm	0.799 GeV/cm	0.995 GeV/cm
injected charge	78 pC	177 pC	2520 pC	1770 pC
Energy-gain efficiency	4.65 J/GeV	96.6 J/GeV	9.15 J/GeV	3.78 J/GeV
Laser-electron beam-energy efficiency	**1.68 %**	**0.183 %**	**27.6 %**	**46.8 %**

Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

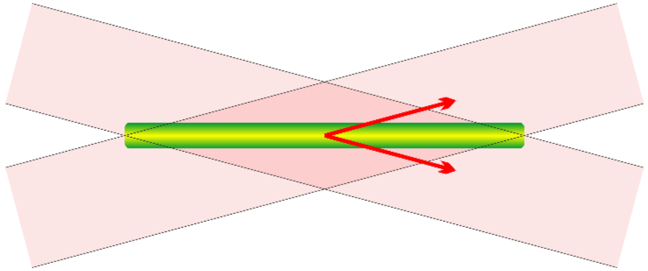
TWEAC synchronicity condition is independent of plasma density



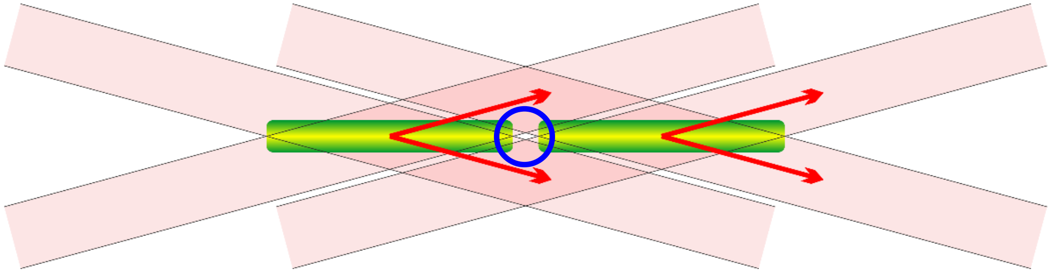
Translationary symmetry of gas target maintains the vacuum speed of light synchronicity condition for the laser pulse-front tilt: $\alpha = \phi/2$

Staging in TWEAC requires minimal electron beam transport distances

Single TWEAC stage
driven by two laser beams



Two shorter TWEAC stages
driven by four smaller laser beams.



Due to the oblique laser beam geometry TWEAC stages can be placed with only sub-mm to mm beam-transport distances in between.

TWEAC focusing fields