AAC'22 Advanced Accelerator Concepts Workshop
November 6 - 11, 2022
Hyatt Regency Long Island, NY

Traveling-wave electron accelerators

Towards scalable laser-plasma accelerators beyond 10 GeV

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[2]CASUS, Center for Advanced Systems Understanding, Görlitz, Germany
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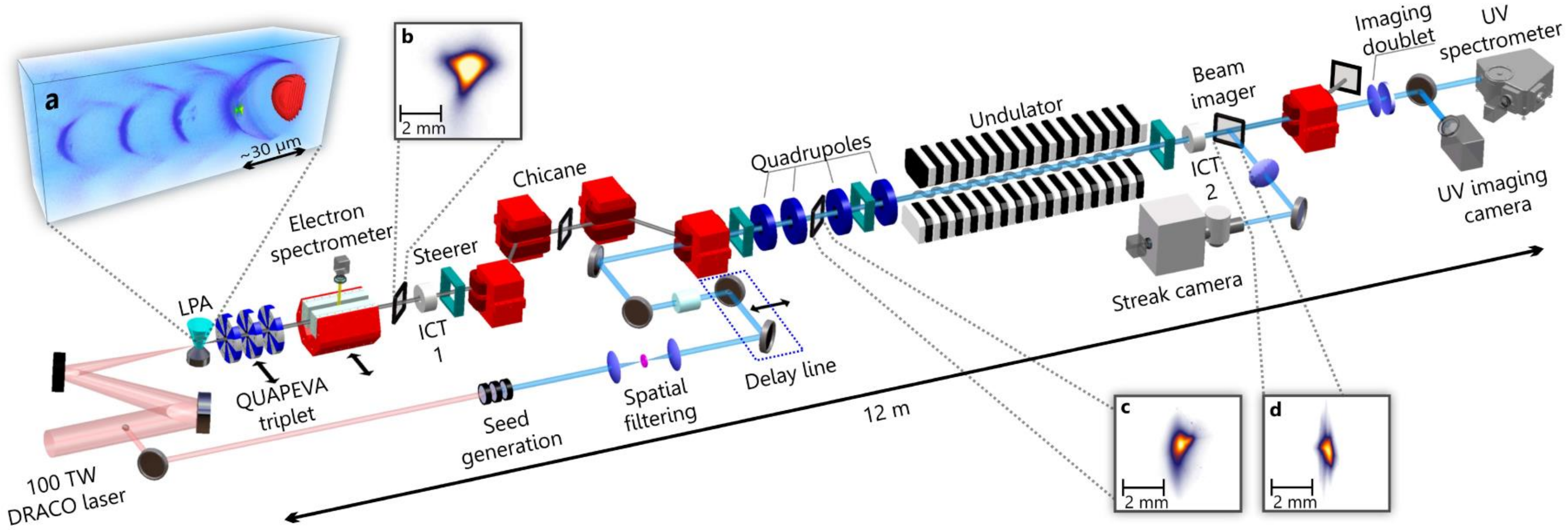
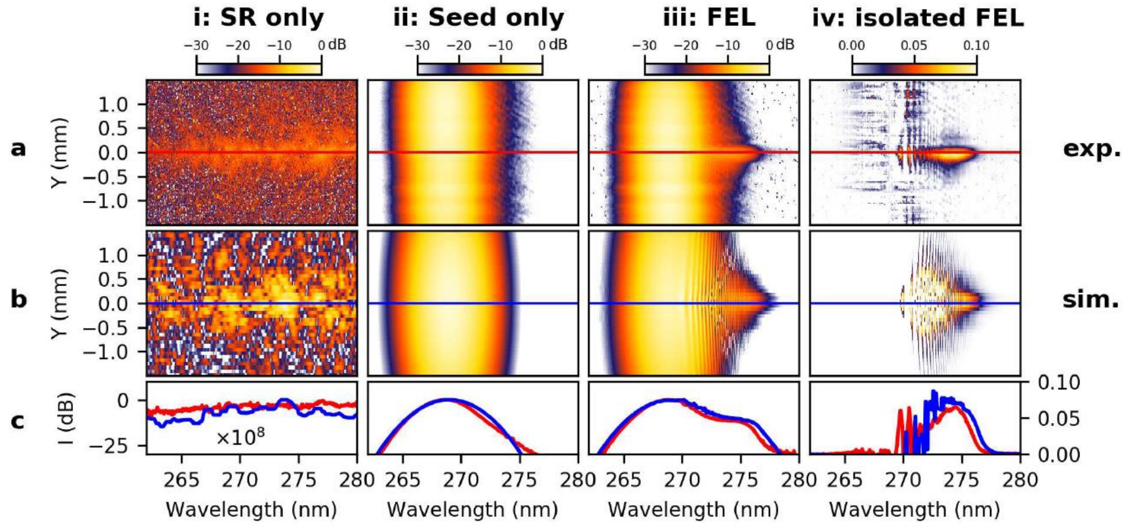
[5]Georgia Institute of Technology, Atlanta, GA, USA
[6]Oak Ridge National Laboratory, Knoxville, TN, USA

High brightness electron beams for compact FELs



First demonstration of a seeded FEL driven by a laser plasma accelerator at HZDR

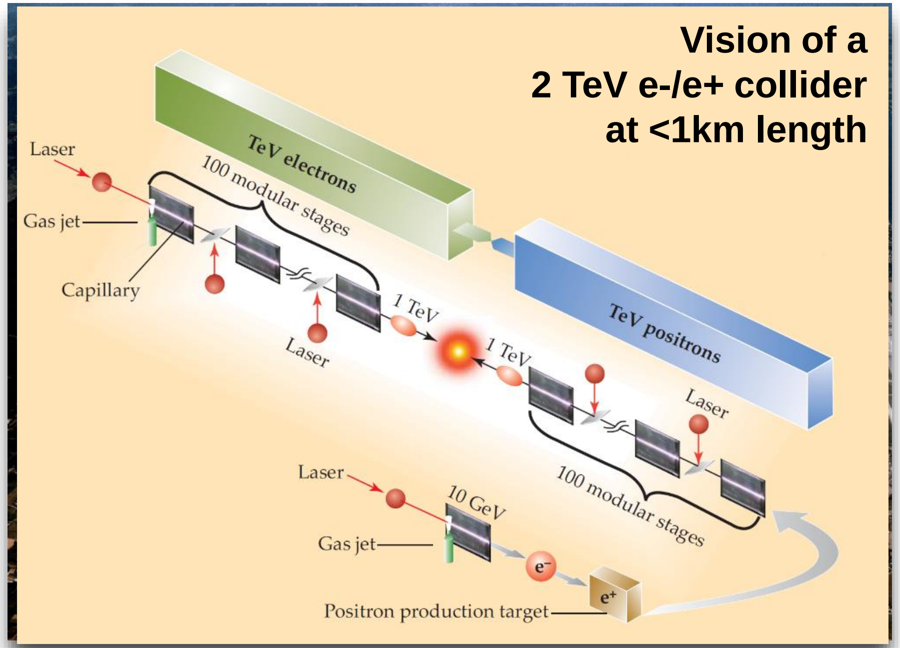
Total charge (FWHM): 213 ±13 pC (6%)
Analysis for 200±1 MeV energy slice:
Charge density: 8.1 ± 0.9 pC/MeV (11%),
Divergence: 1.2 ± 0.3 mrad



SOLEIL @ HZDR, COXINEL collaboration

M. Labat, J.P. Couperus Cabadağ, A. Ghaith, A. Irman, et al.
"Seeded free-electron laser driven by a compact laser plasma accelerator", accepted
Nature Photonics (2022), https://www.researchsquare.com/article/rs-1692828/v1

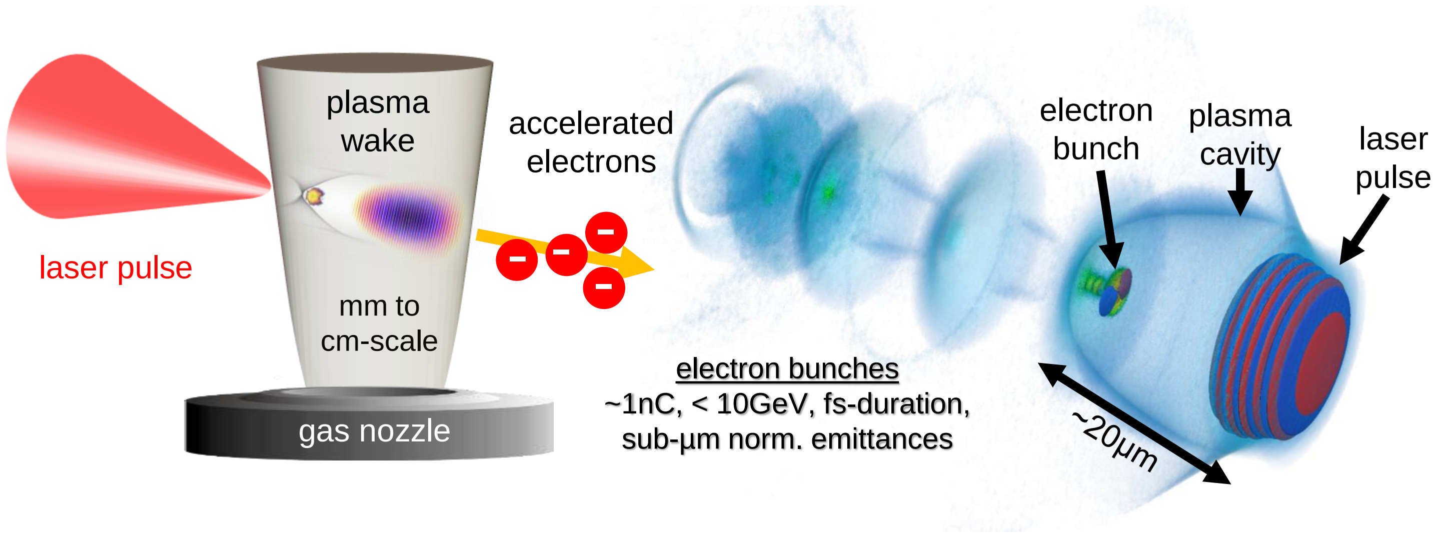
Dreams of reaching towards TeV-scale electron energies using plasma-based accelerators



W. Leemans, E. Esarey, Phys. Today 62(3), 44 (**2009**)

LHC 2008
CERN

Laser Plasma Accelerators (LPAs) are more compact and less costly

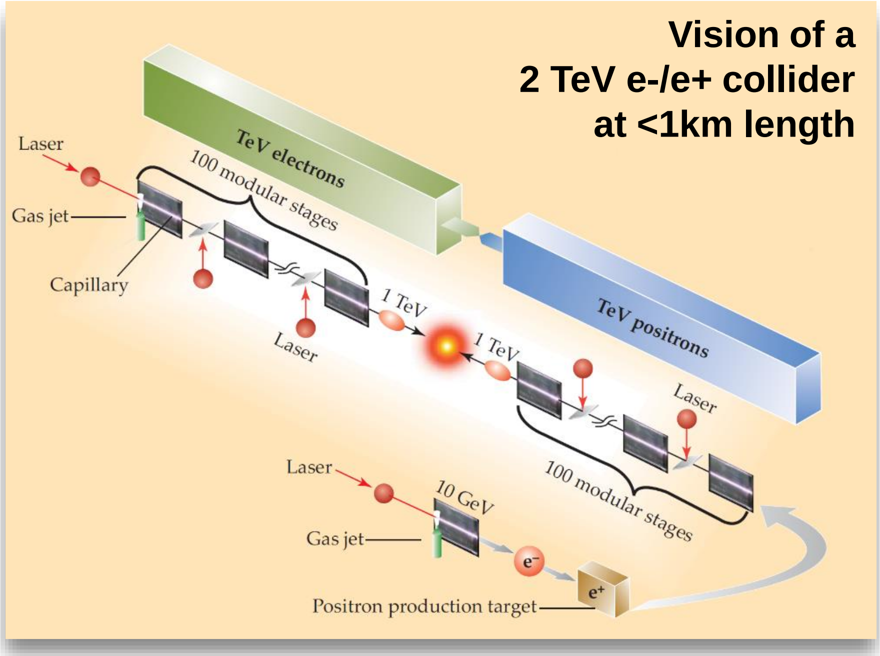


Grand challenges in Laser-plasma accelerators for reaching electron energies beyond 10 GeV

- **Dephasing limit**
- **Laser pulse guiding**
- **Self-phase modulation and laser pump depletion**
- **Staging and beam transport is hard!**

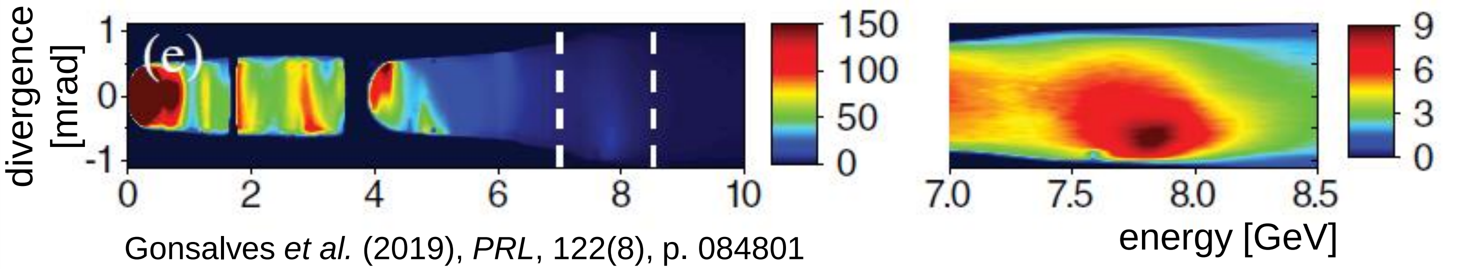
Synchronization, Beam size matching, charge loss,
Laser in/outcoupling, emittance growth
in beam transport, etc.

Dreams of reaching towards TeV-scale electron energies using plasma-based accelerators

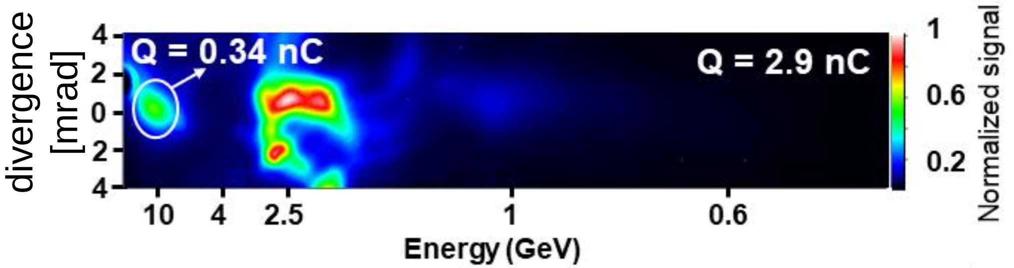


W. Leemans, E. Esarey, Phys. Today 62(3), 44 (**2009**)

Current energy records for LPA range between 7.8 GeV and 10.4 GeV



Gonsalves *et al.* (2019), *PRL*, 122(8), p. 084801
doi: 10.1103/PhysRevLett.122.084801



Aniculaesei *et al. (2022)*
arXiv: 2207.11492

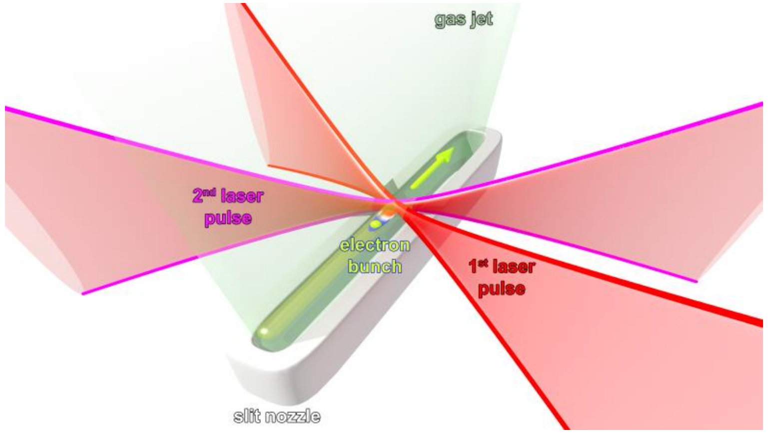
Grand challenges in Laser-plasma accelerators for reaching electron energies beyond 10 GeV

Beyond staging, what are other options for energy-scalable LPAs beyond 10 GeV?

- **Dephasing limit**
- **Laser pulse guiding**
- **Self-phase modulation and laser pump depletion**
- **Staging and beam transport is hard!**

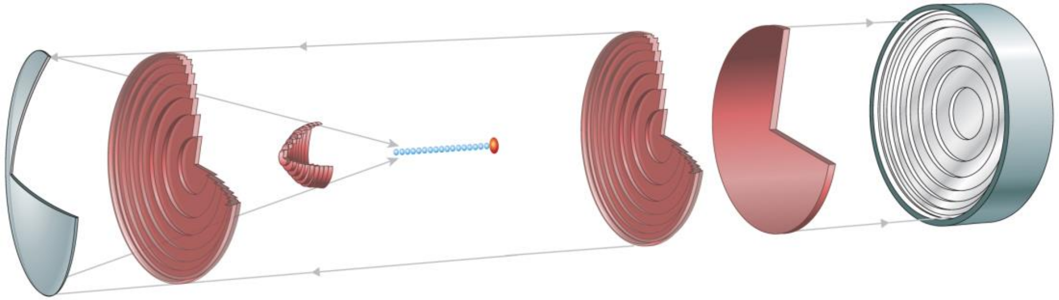
Synchronization, Beam size matching, charge loss, Laser in/outcoupling, emittance growth in beam transport, etc.

Dephasing-free laser-plasma accelerators use lasers that exploit spatio-temporally couplings



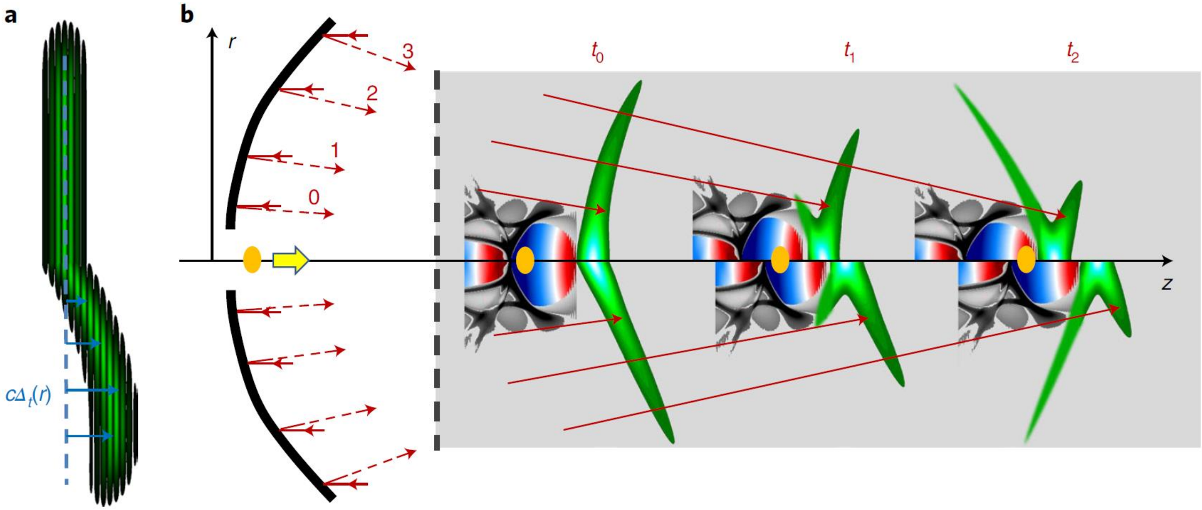
Circumventing the Dephasing and Depletion Limits of Laser-Wakefield Acceleration

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



Phase-locked laser-wakefield electron acceleration

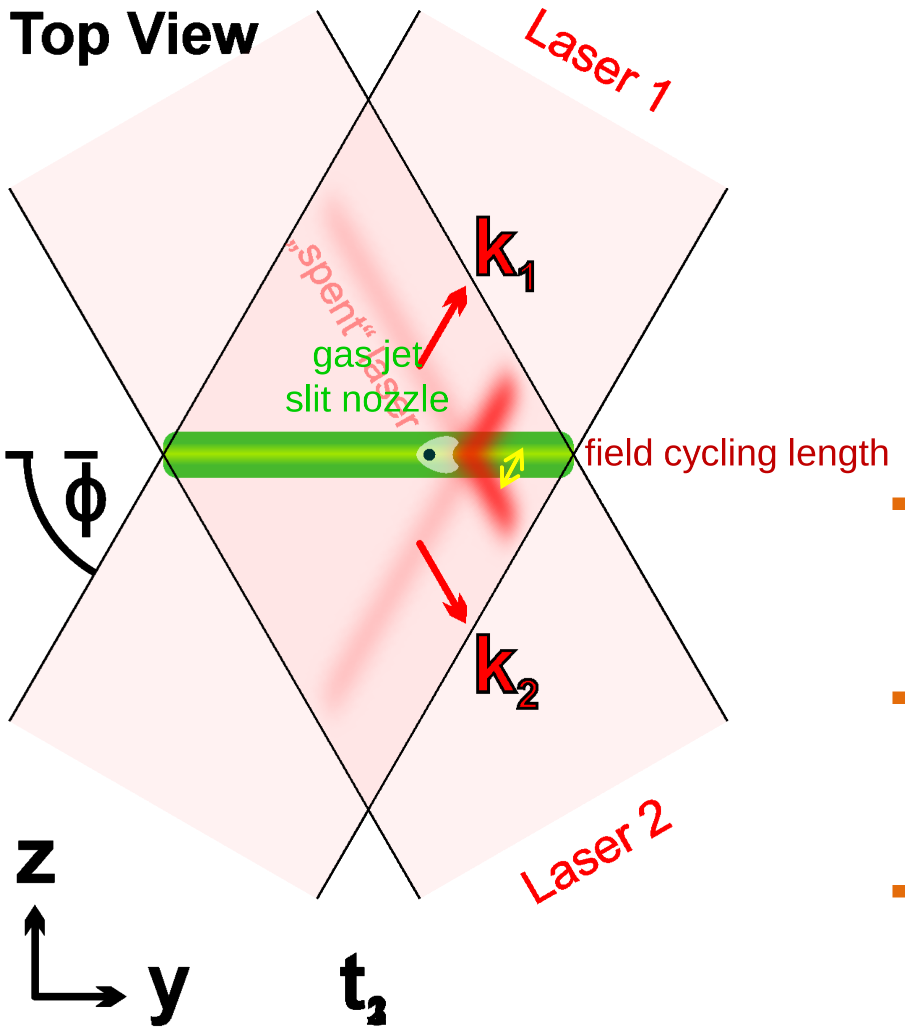
Caizergues *et al.* (2020), *Nature Photonics* 14(8), 475-479
doi: 10.1038/s41566-020-0657-2.



Dephasingless Laser Wakefield Acceleration

J. P. Palastro *et al.*, *PRL* 124, 134802 (2020)
doi: 10.1103/PhysRevLett.124.134802

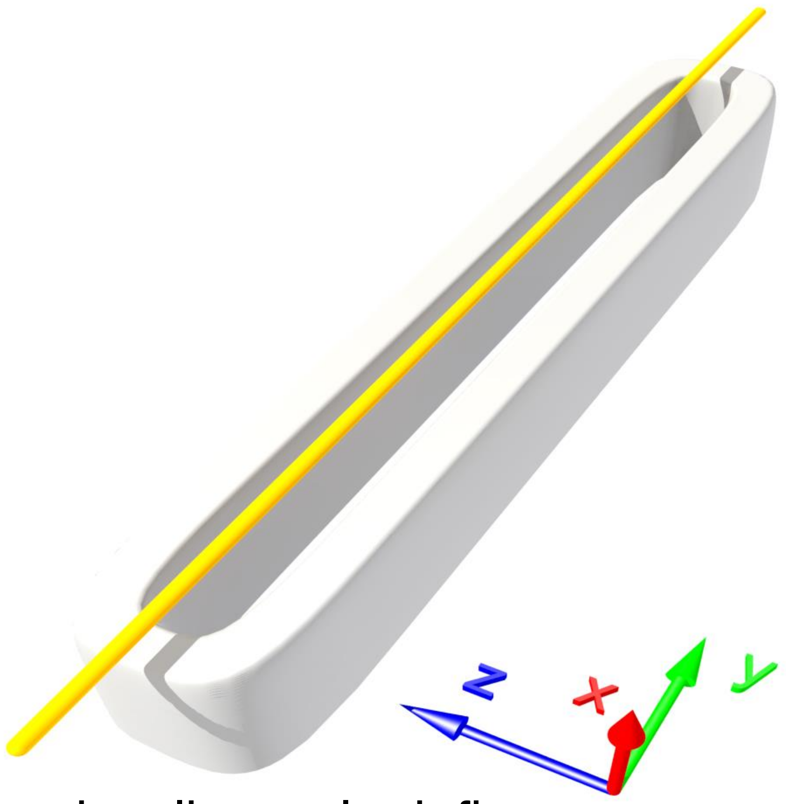
Traveling-Wave Electron Acceleration (TWEAC)



TWEAC circumvents major limitations:
Dephasing, Depletion and Defocusing

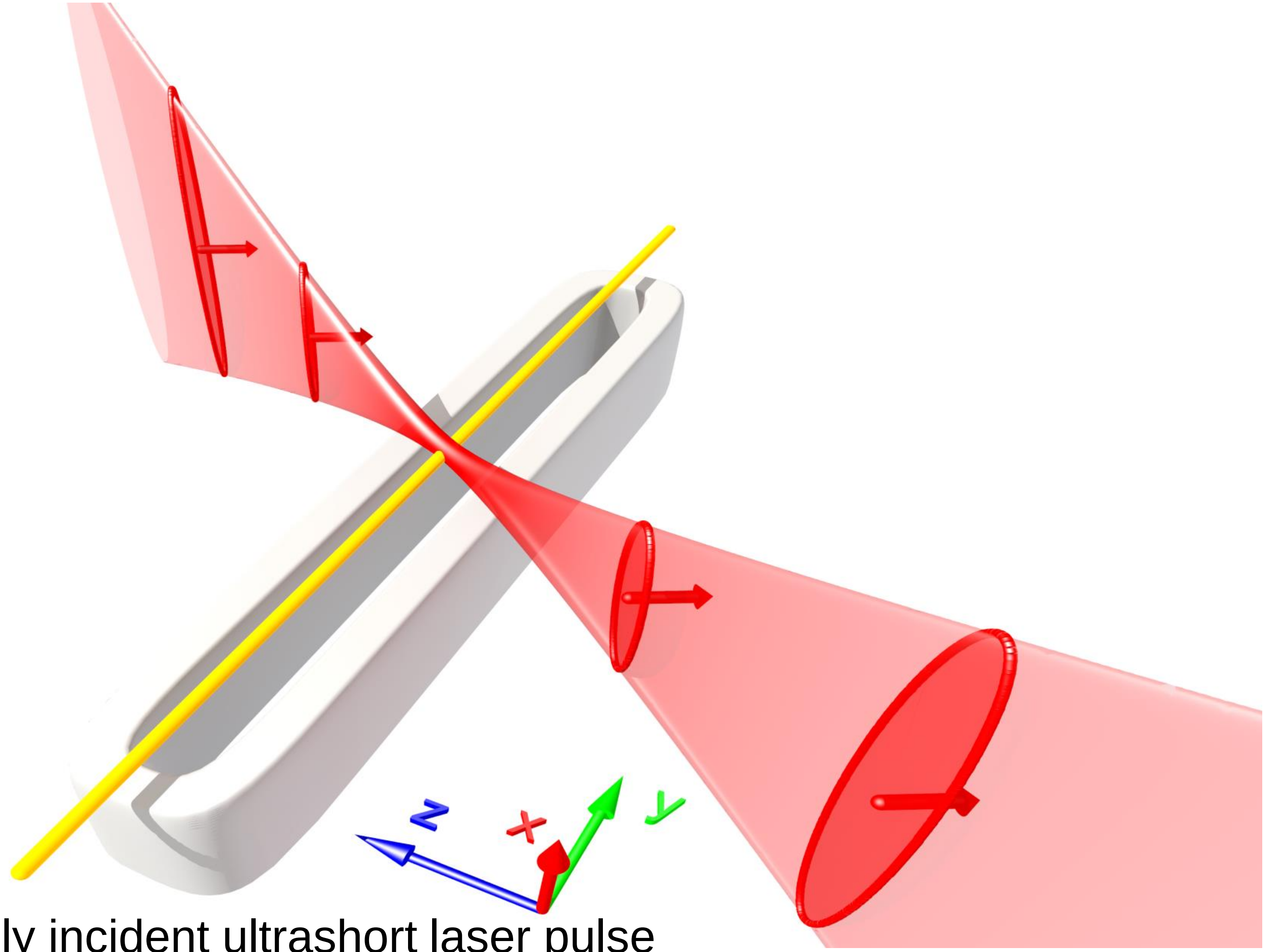
- Pulse-front tilted laser enforces vacuum speed of light propagation of laser overlap in plasma.
  → **Circumvents dephasing**
- Oblique laser beam geometry continuously feeds a „fresh“ portion of the laser beams into an unperturbed plasma.
  → **Averts laser depletion**
- Line-focus geometry
  → **Circumvents laser defocusing**

TWEAC geometry in a nutshell



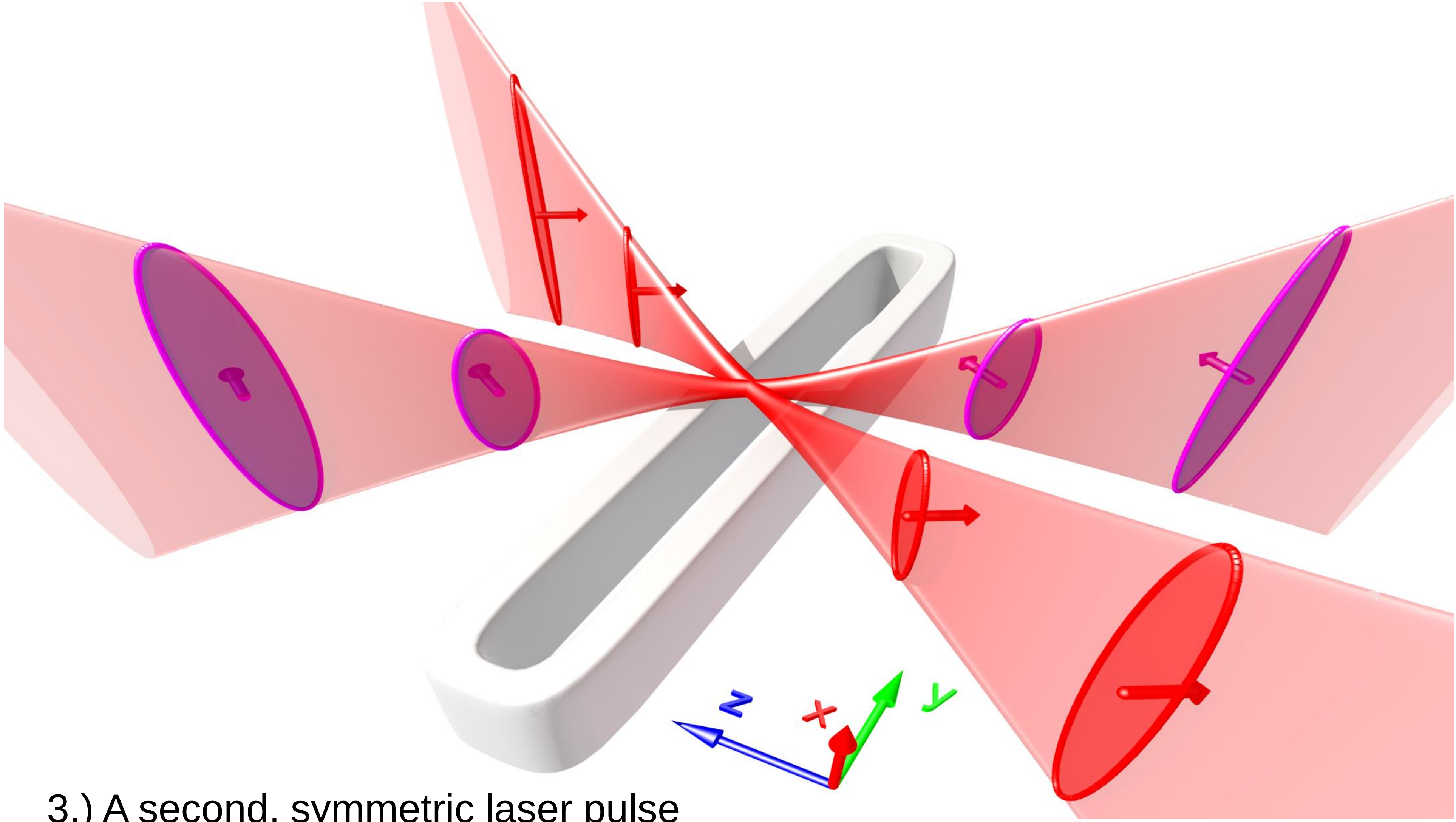
1.) An extended gas jet slit nozzle defines a line focus axis for cylindrical optics.

TWEAC geometry in a nutshell



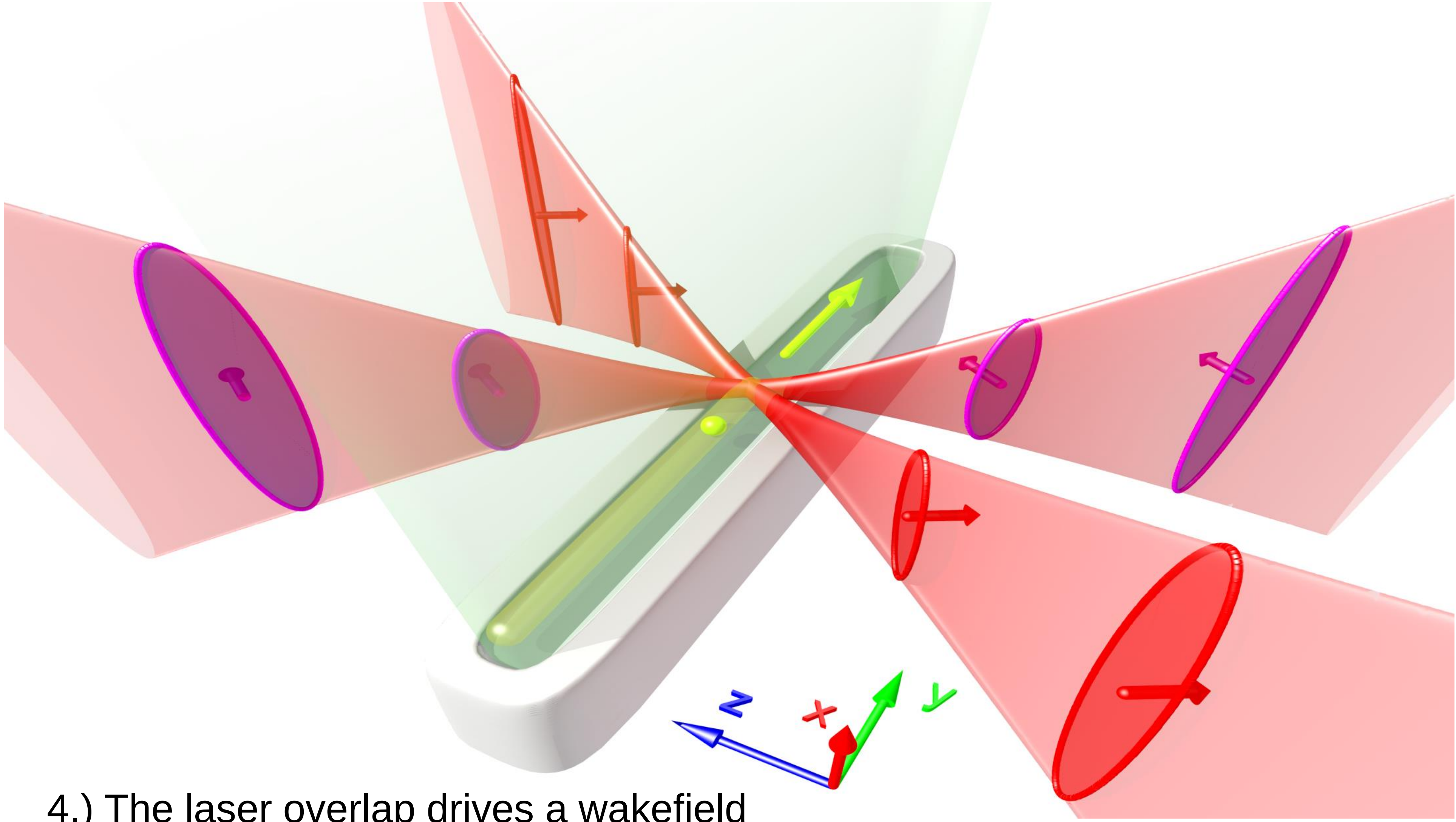
2.) A first, obliquely incident ultrashort laser pulse
with a carefully tuned pulse-front tilt creates a comoving focus.

TWEAC geometry in a nutshell



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

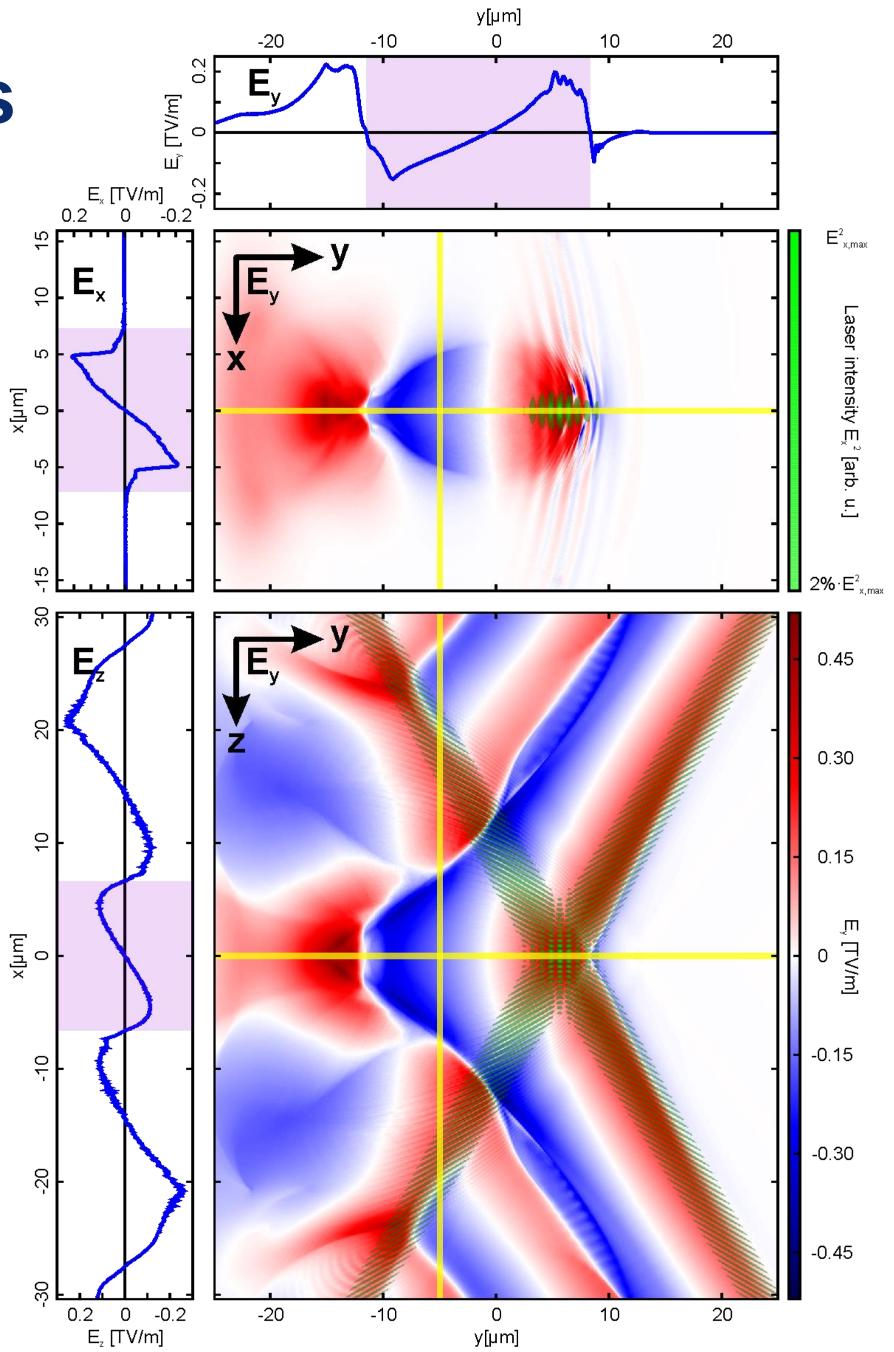
TWEAC geometry in a nutshell



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

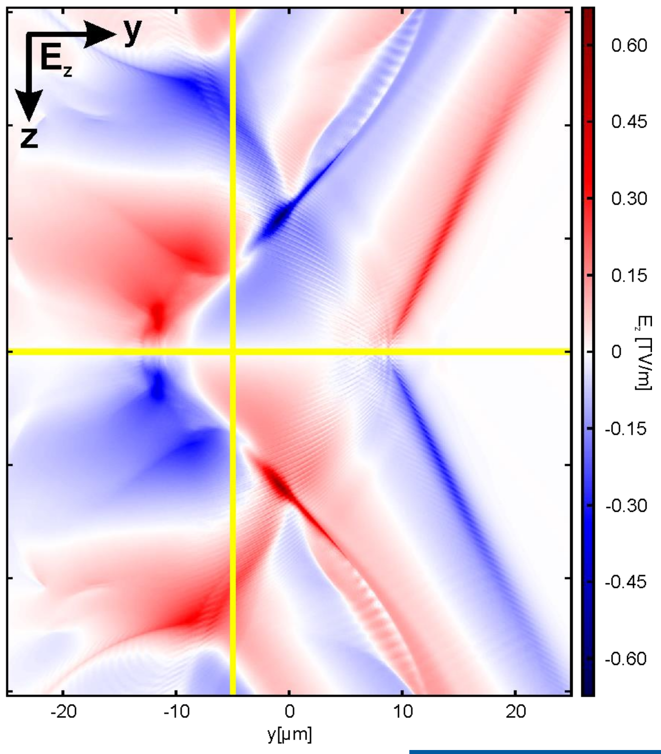
TWEAC cavity fields

- V-shaped cavity profile in the plane of laser propagation.
- Multiple side plasma cavities exist.
- At constant density self-injection is absent.
- Here*:* parallel polarization of TWEAC laser pulses



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

- Field strengths of plasma cavity and focusing fields are comparable to LWFA.

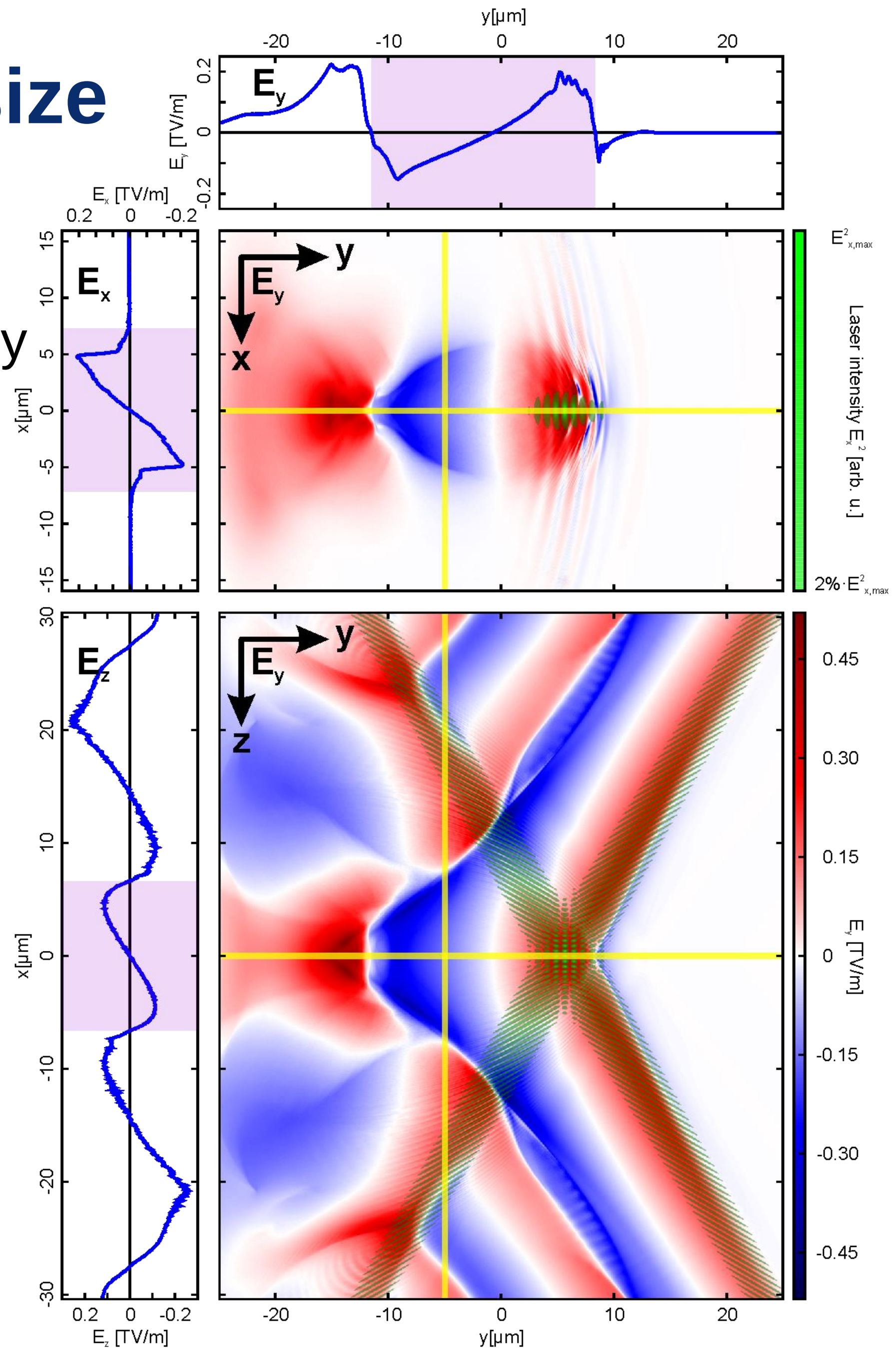


Smaller laser spot size

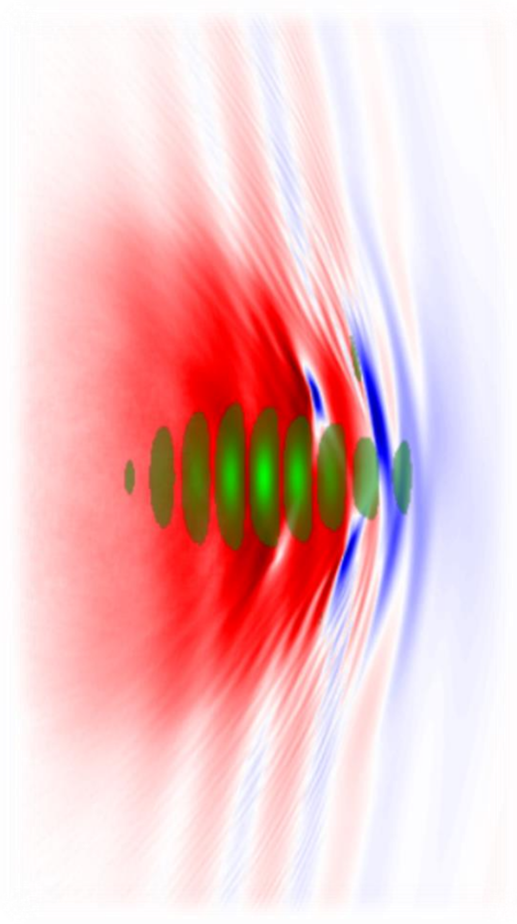
- The cylindrical focusing geometry does not require laser self-focusing or laser guiding.

  → Relaxed laser spot size matching criterion in TWEAC

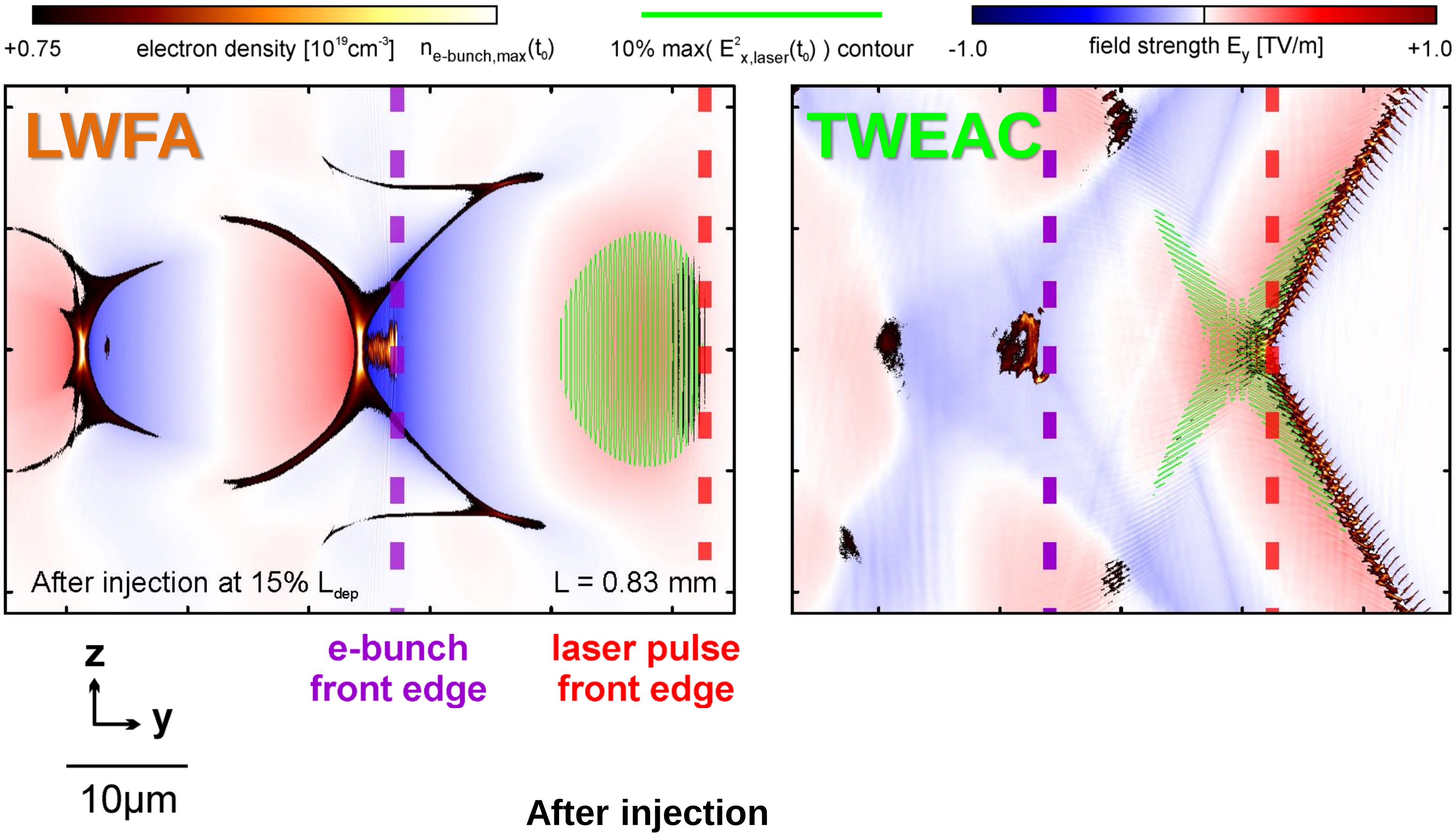
- The cavity size exceeds the vertical laser extent, caused by the density shock of the luminal TWEAC intensity-front.



- TWEAC laser spot sizes can be smaller than in LWFA.

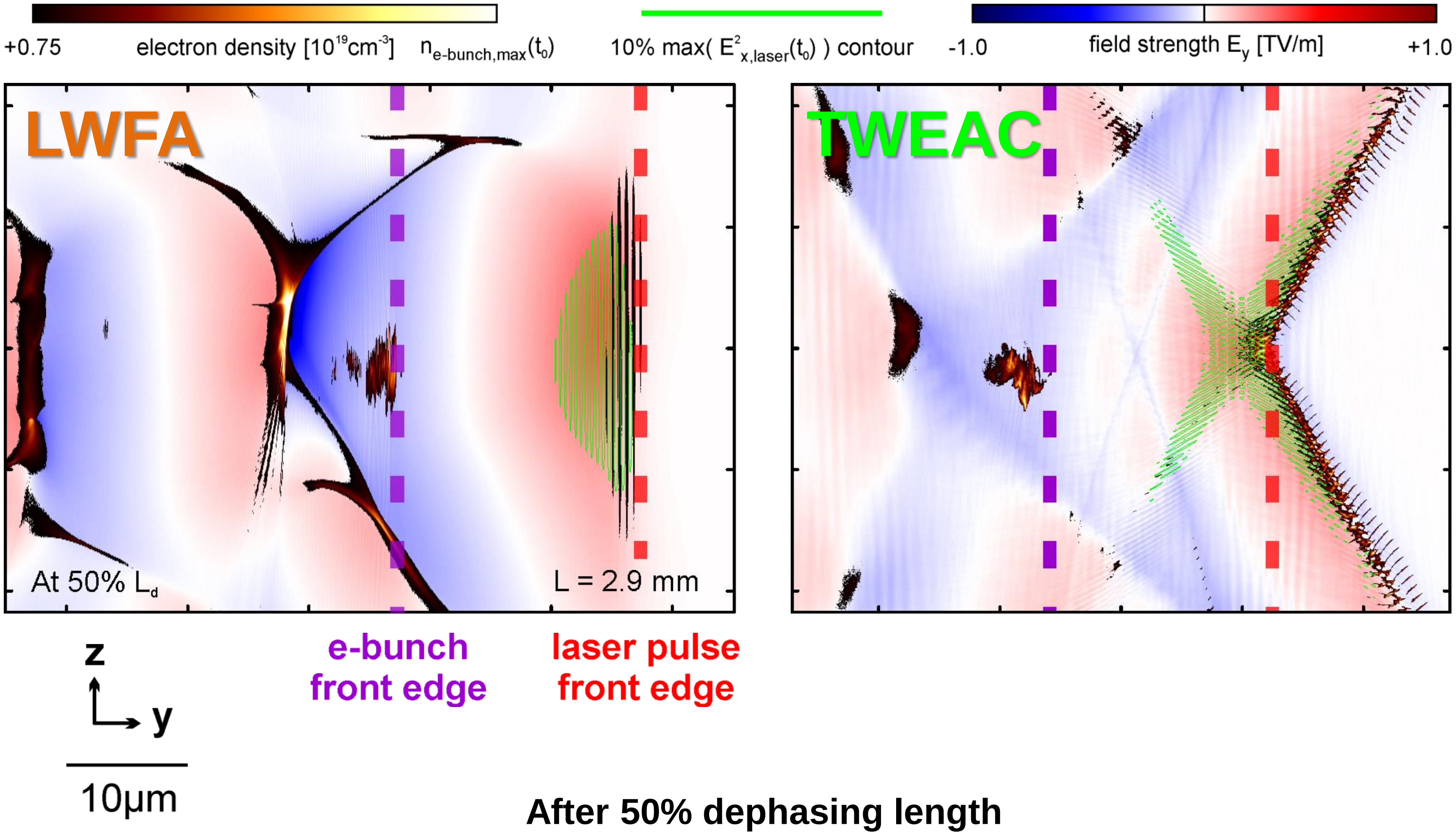


TWEAC eliminates the dephasing and depletion limit.



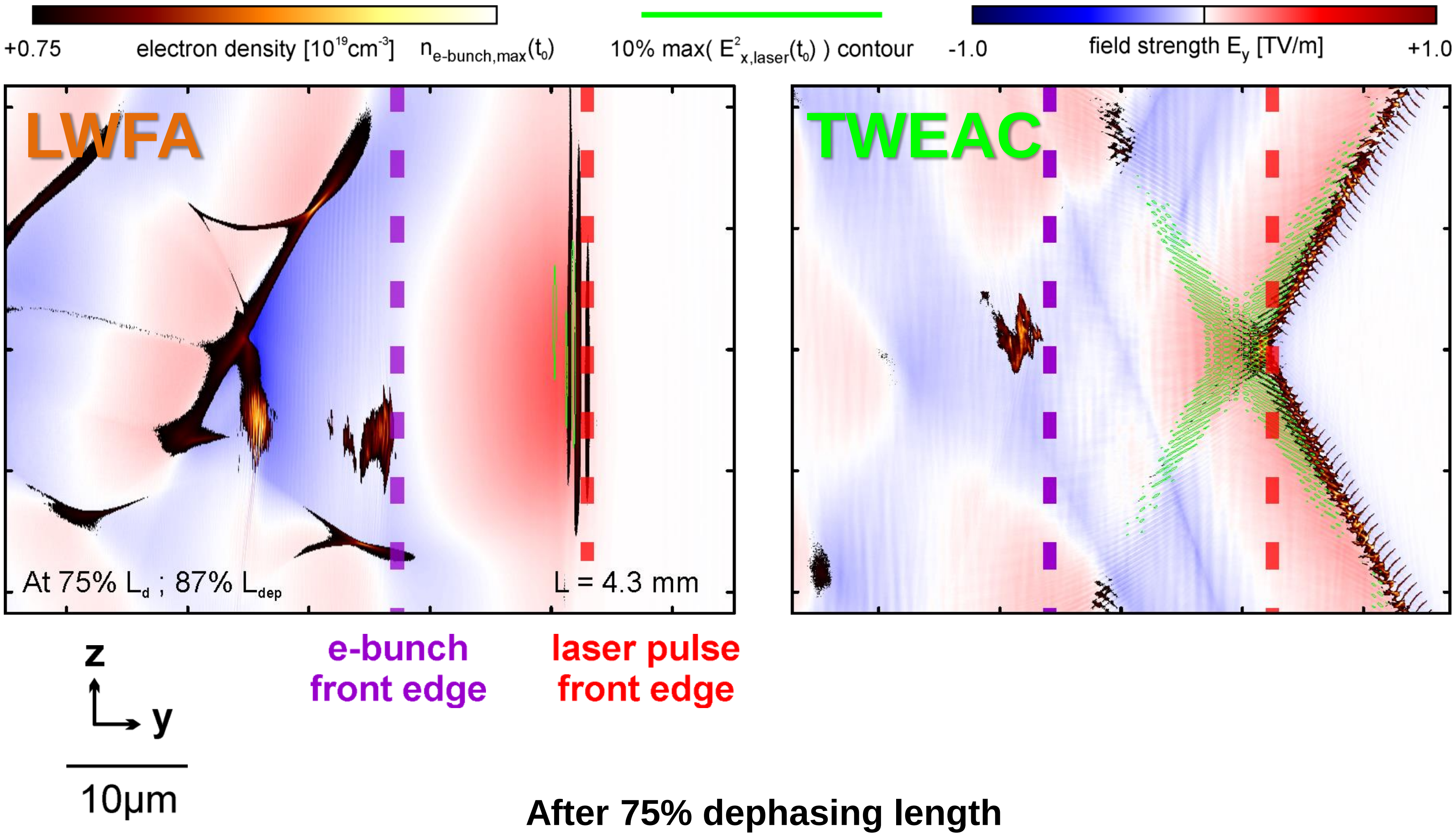
After injection

TWEAC eliminates the dephasing and depletion limit.



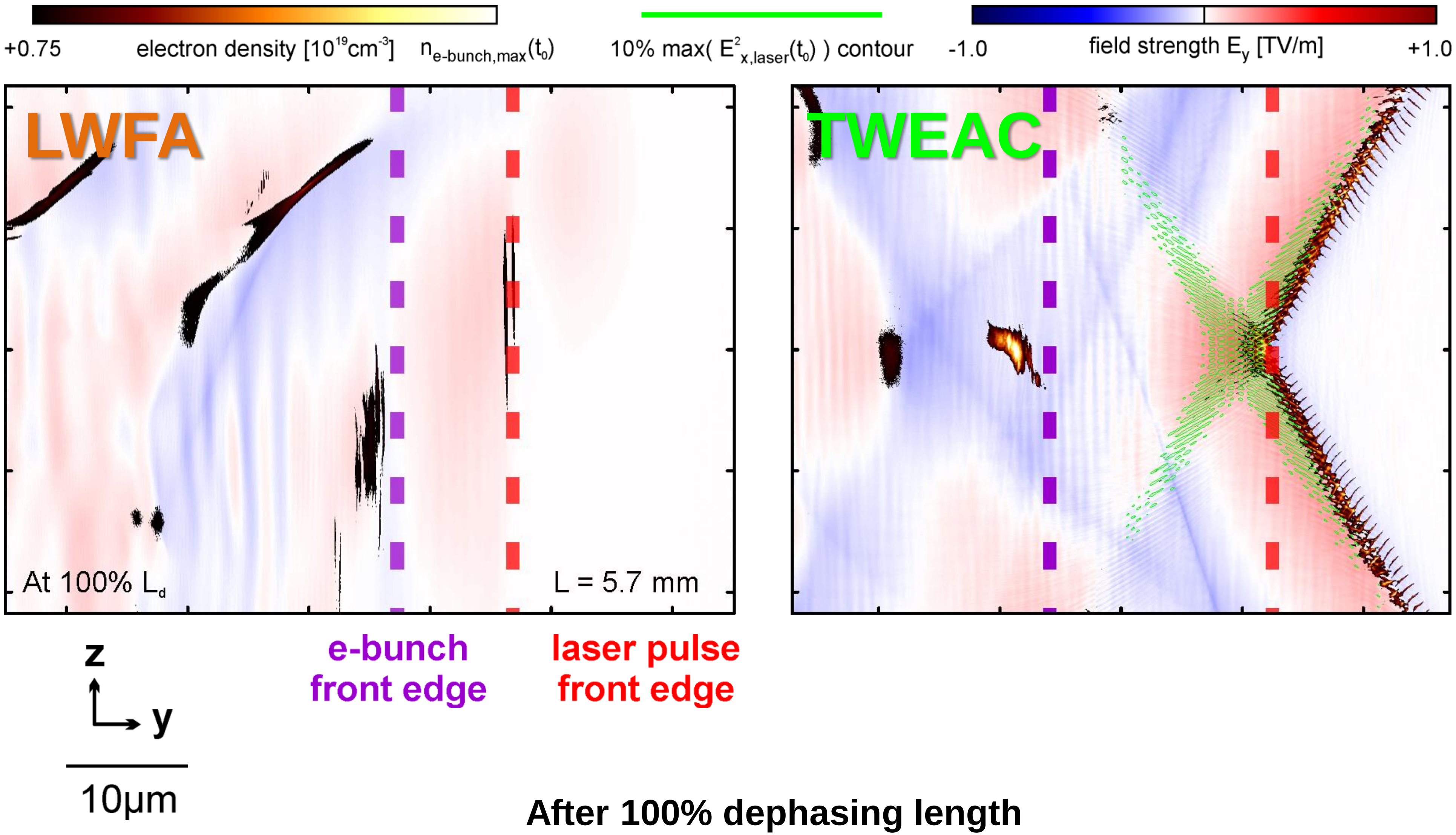
After 50% dephasing length

TWEAC eliminates the dephasing and depletion limit.



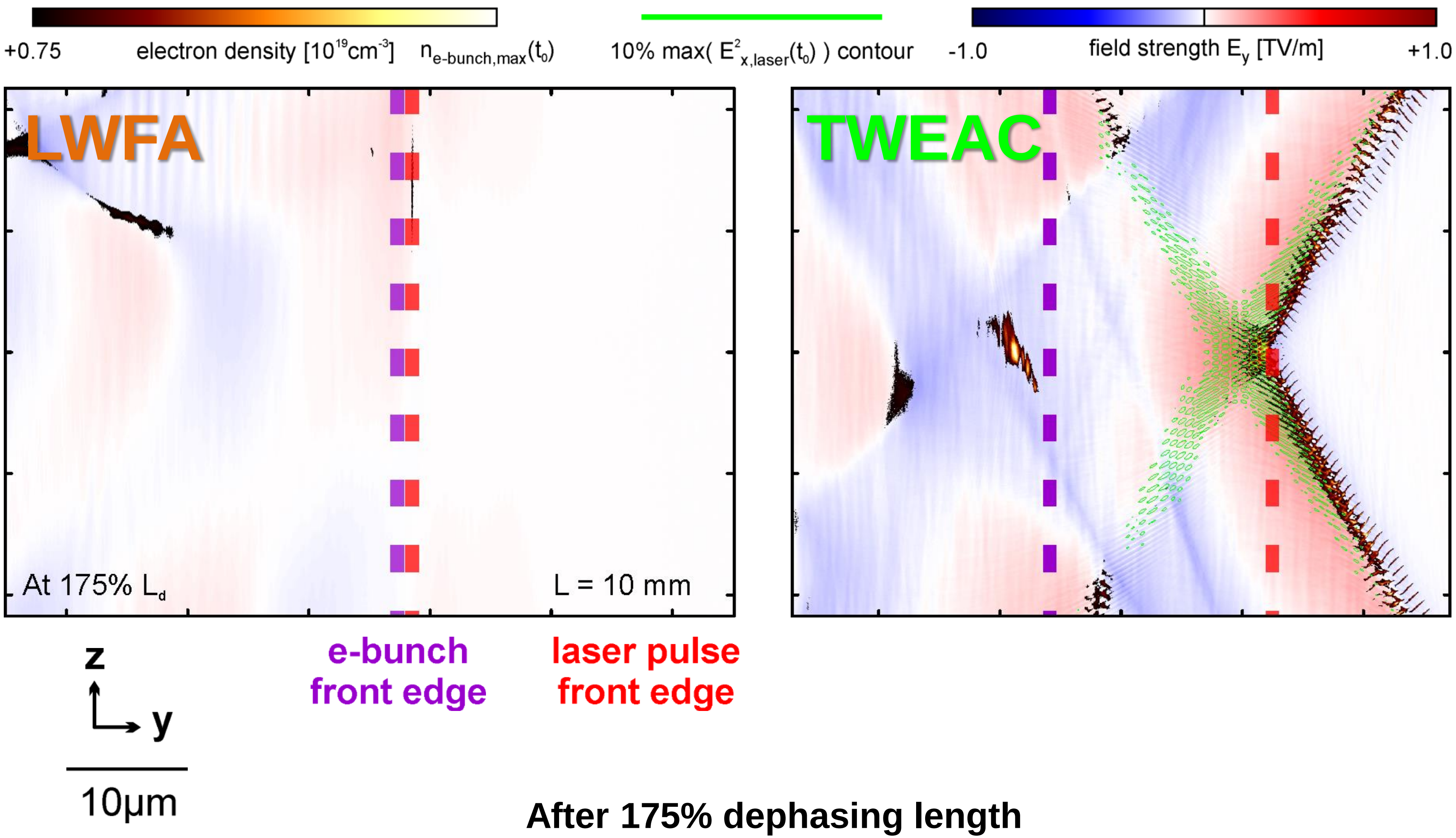
After 75% dephasing length

TWEAC eliminates the dephasing and depletion limit.



After 100% dephasing length

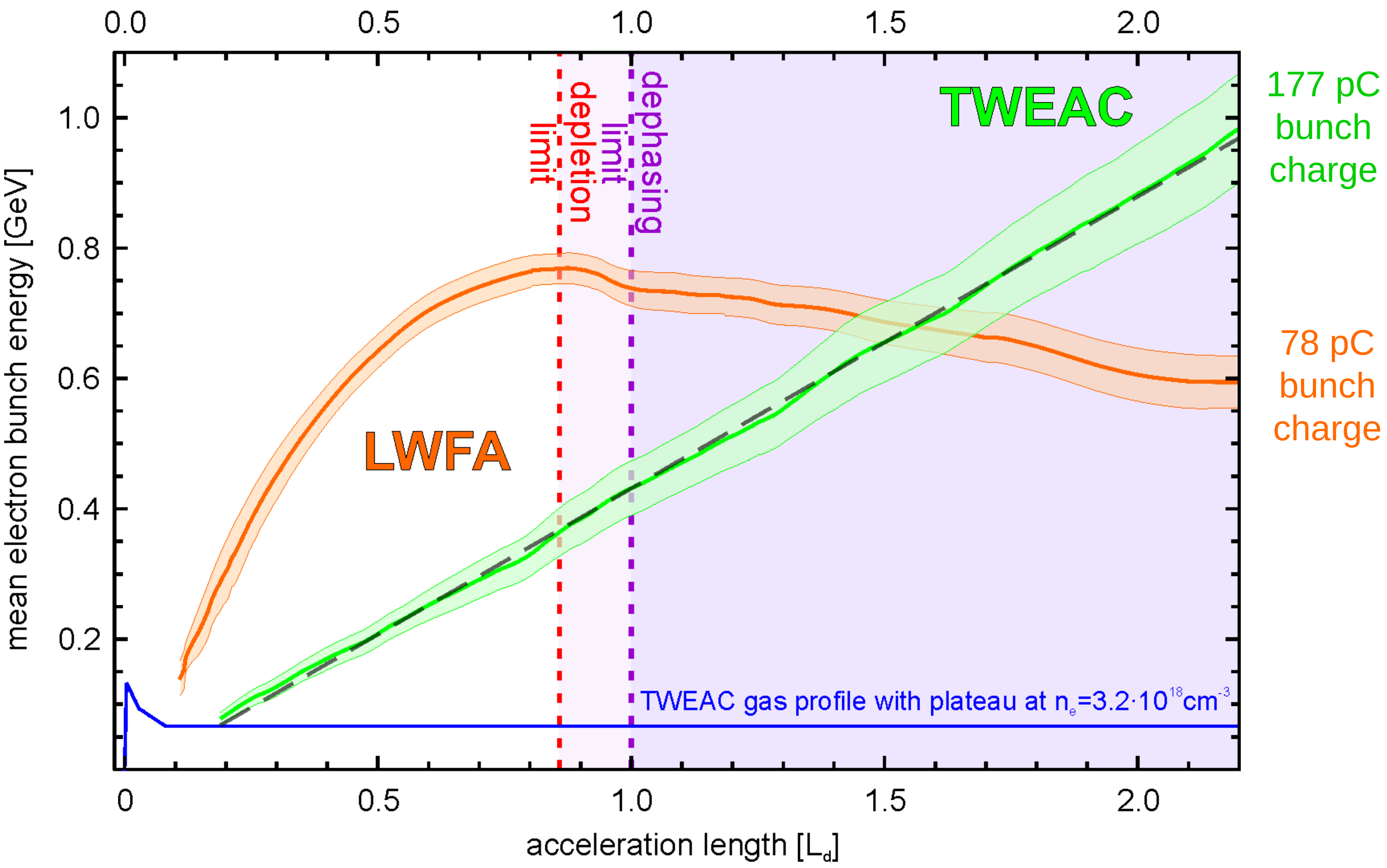
TWEAC eliminates the dephasing and depletion limit.



After 175% dephasing length

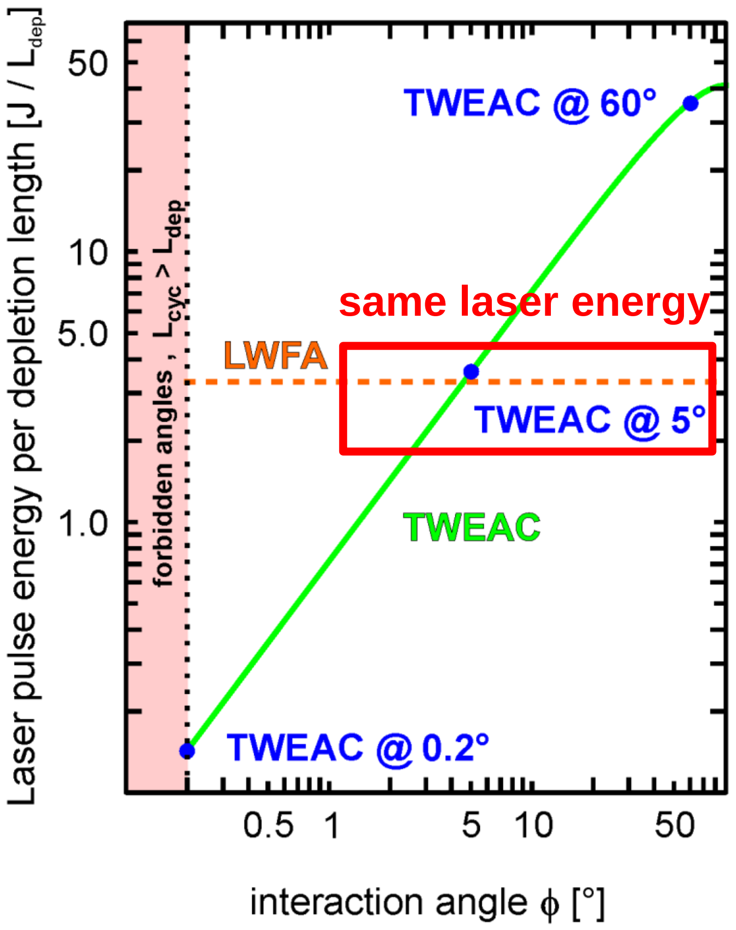
TWEAC reaches a quasi-stationary acceleration regime

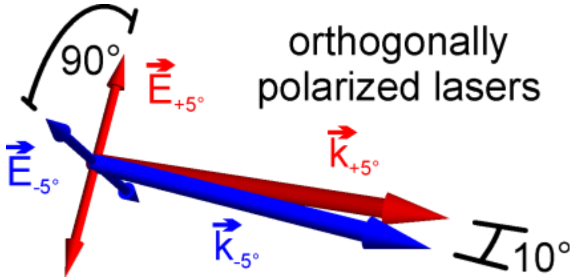
The mean electron electron energy evolves linearly with acceleration distance

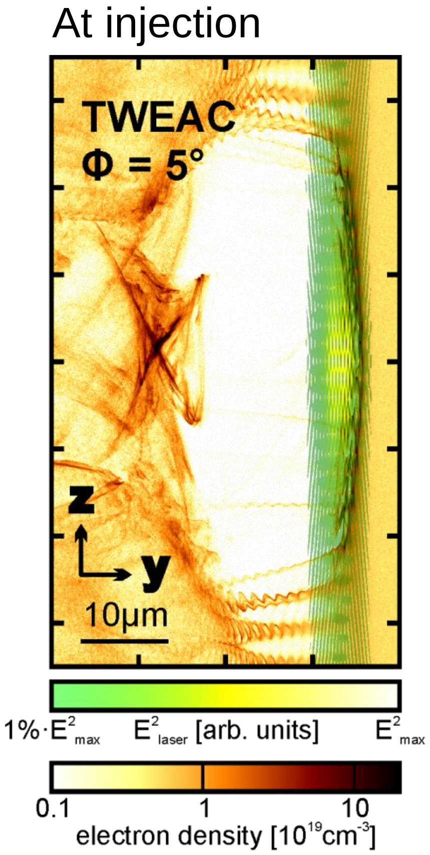


12.5 mm total plasma length

How does TWEAC scale in laser energy?







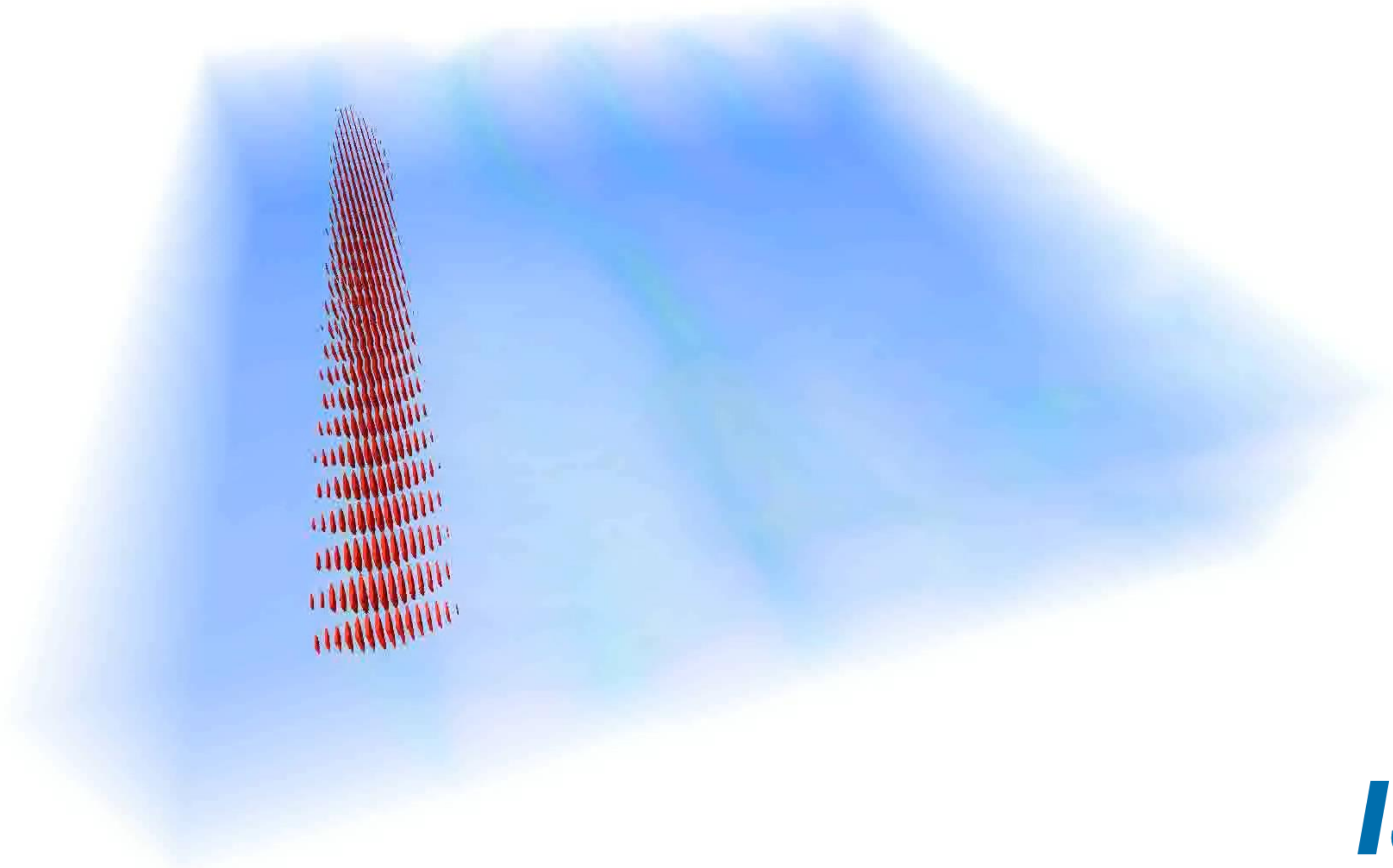
$$W_{\mathrm{laser}} \propto a_0^2 \tau_0 L_{\mathrm{int}} w_x \sin(\phi)$$

Low incidence angles ϕ reduce required laser energy, provided that

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

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

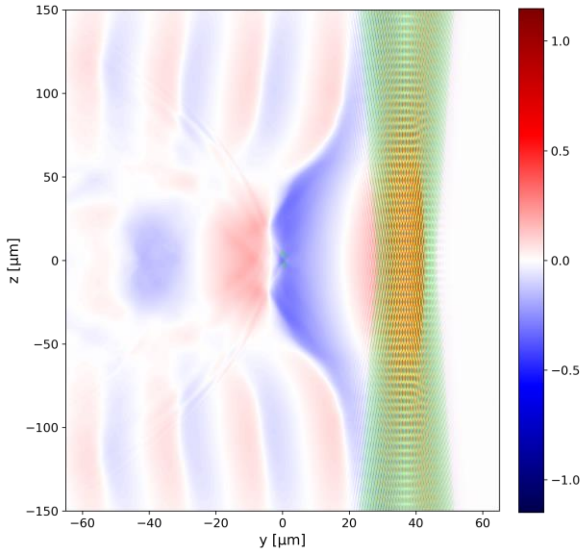
In-situ visualization of TWEAC at 5° incidence angle



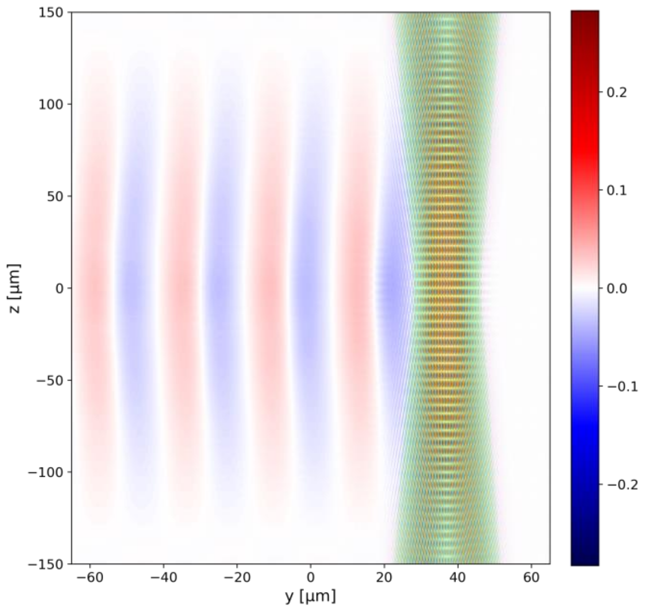
a_0=2.0, $w_{0,x}$=2.4µm, n_e=2.0·10^{18}

Practical considerations of a TWEAC beamline

Lasers | Dispersion control | Beam-delivery | TWEAC



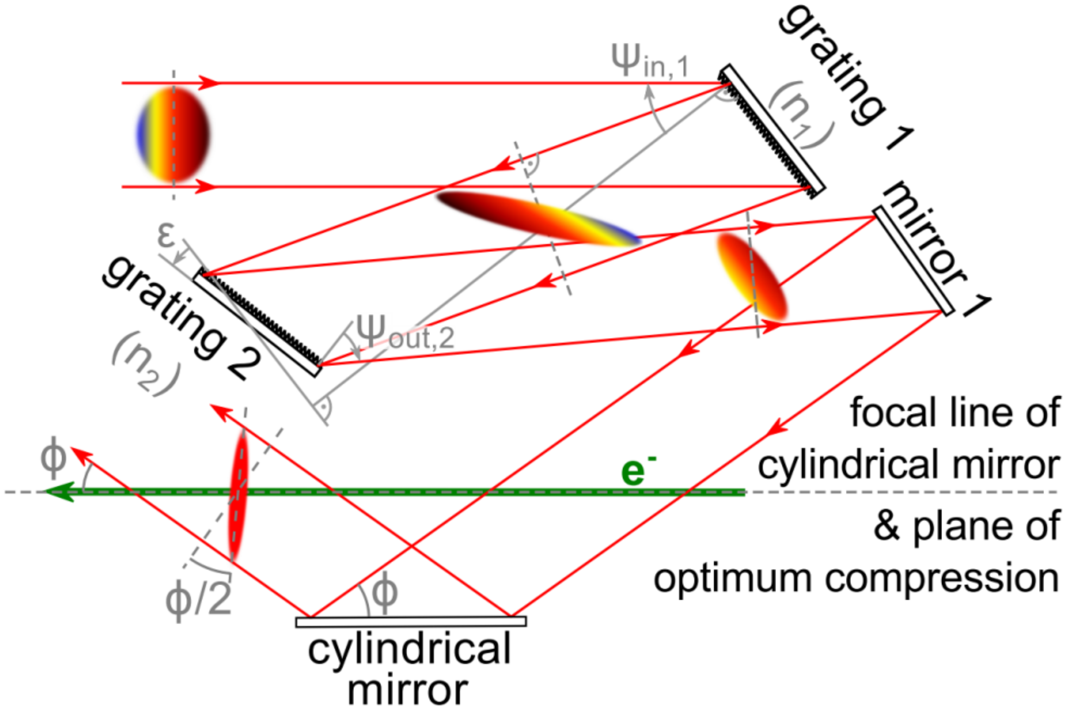
Scenario	Non-linear, "bubble-like" plasma cavity	Quasi-linear accelerator at lower intensity
Interaction distance	3cm	3cm
Total laser energy	23.5J / 30fs	~1J / 30fs
laser incidence angle ϕ	3.5°	3.5°
peak laser strength a_0 in line-focus	5.0	1.0
Acceleration gradient	~1 GeV/cm	0.3 GeV/cm



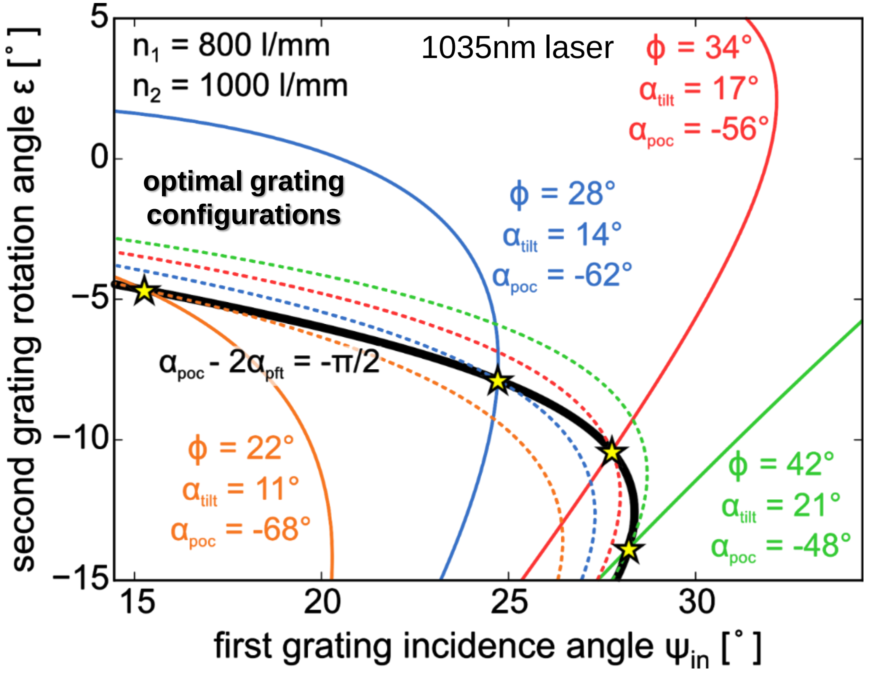
Practical considerations of a TWEAC beamline

Laser | **Dispersion control** | Beam-delivery | TWEAC

Optical setups for TWEAC require two extra gratings in the beamline



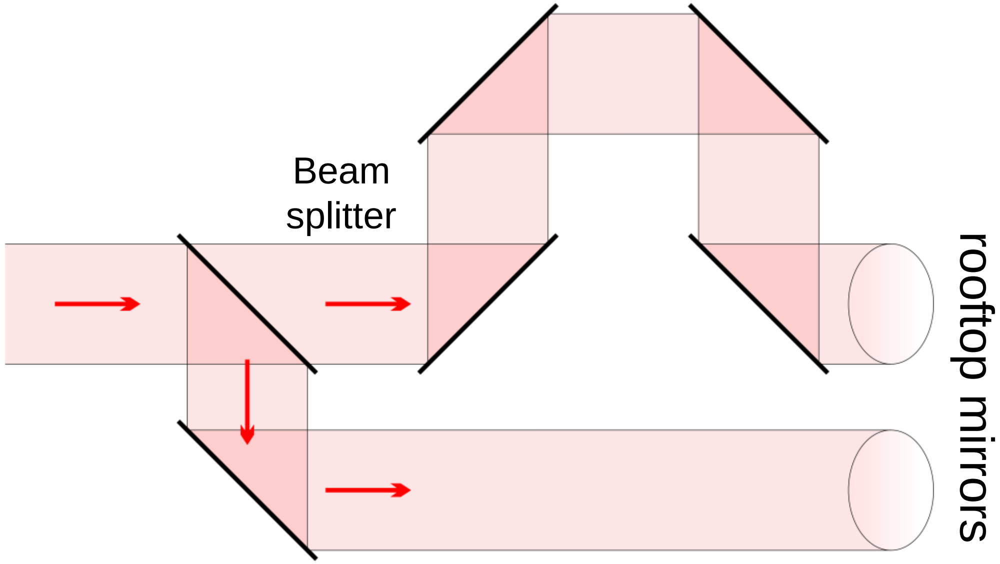
Pulse synthesis using two-grating setups provides tunability by varying pulse-front tilt.

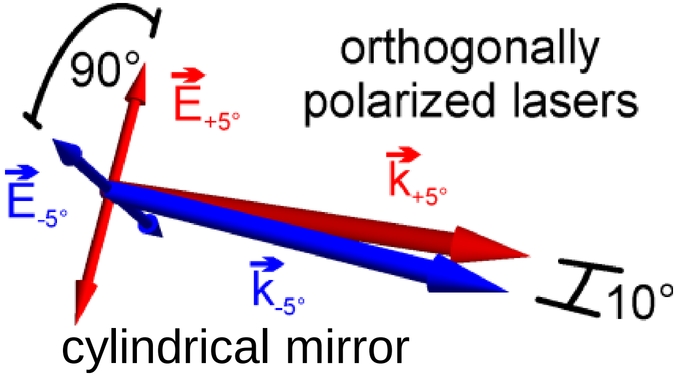


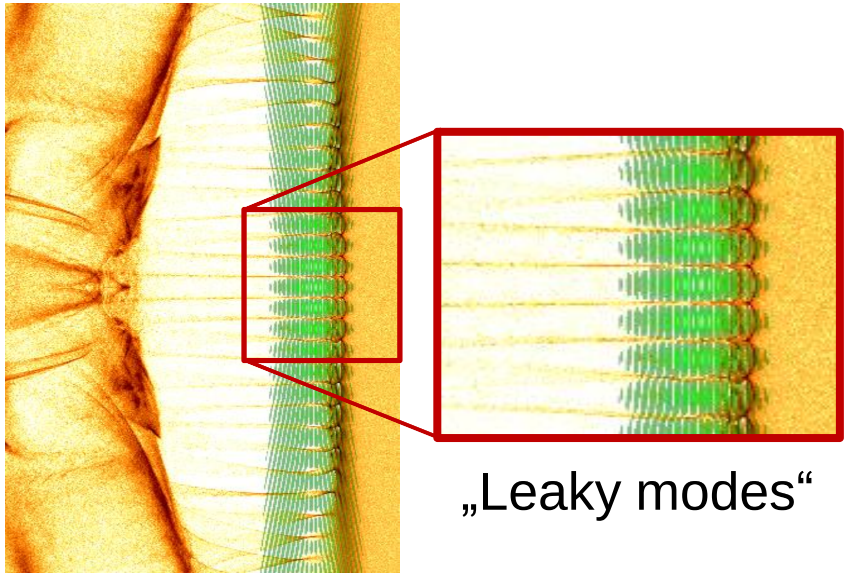
A. Debus *et al*., *Appl. Phys. B* **100** (2010) 1, 61 K. Steiniger *et al., J. Phys. B* **47** (2014) 23, 234011 **K. Steiniger *et al.*, Front. Phys. 6 (2019)**

Practical considerations of a TWEAC beamline

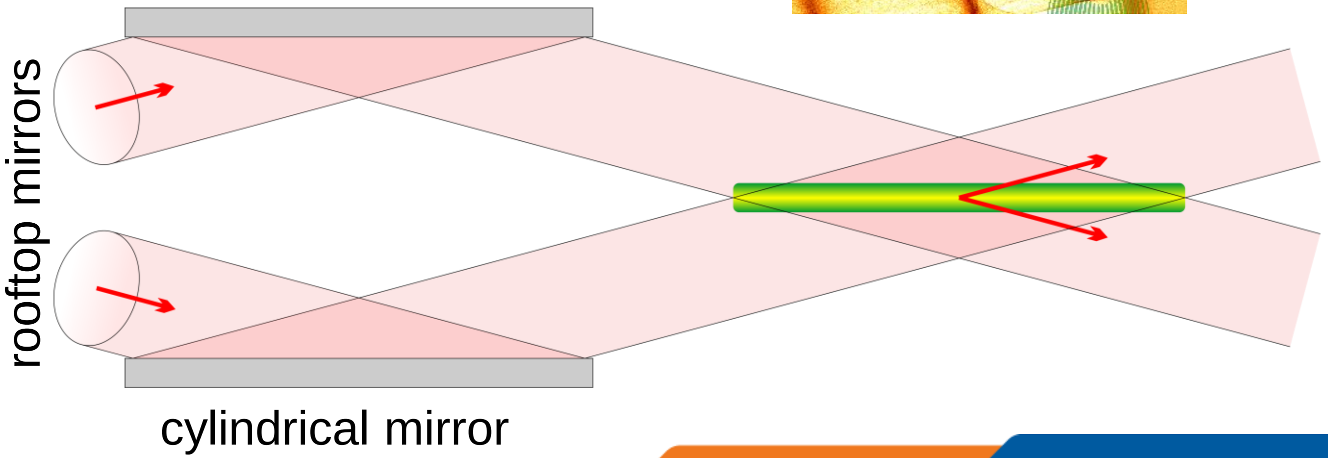
Laser	Dispersion control	Beam-delivery	Interaction zone





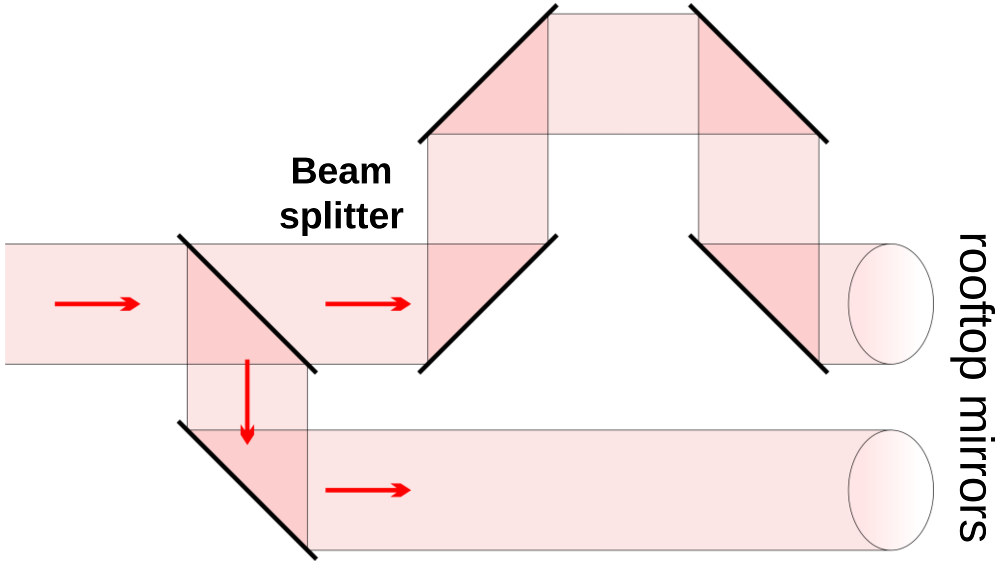


- For small interaction angles φ < 20°: Avoid leaky-modes via near-orthogonal polarizations of the TWEAC beam.



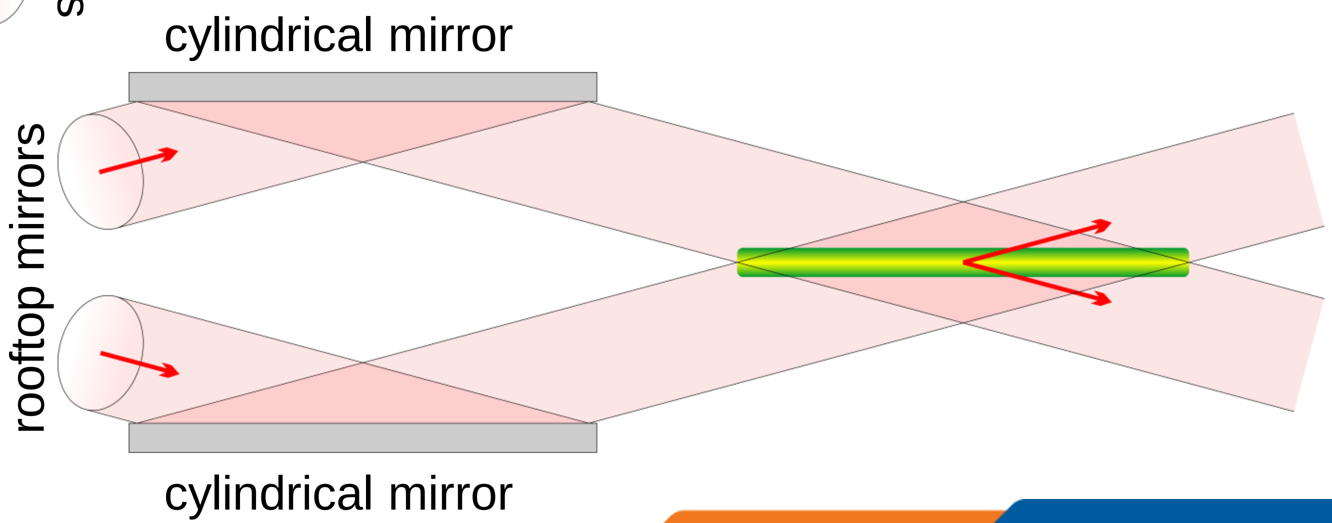
Practical considerations of a TWEAC beamline

Laser | Dispersion control | Beam-delivery | Interaction zone

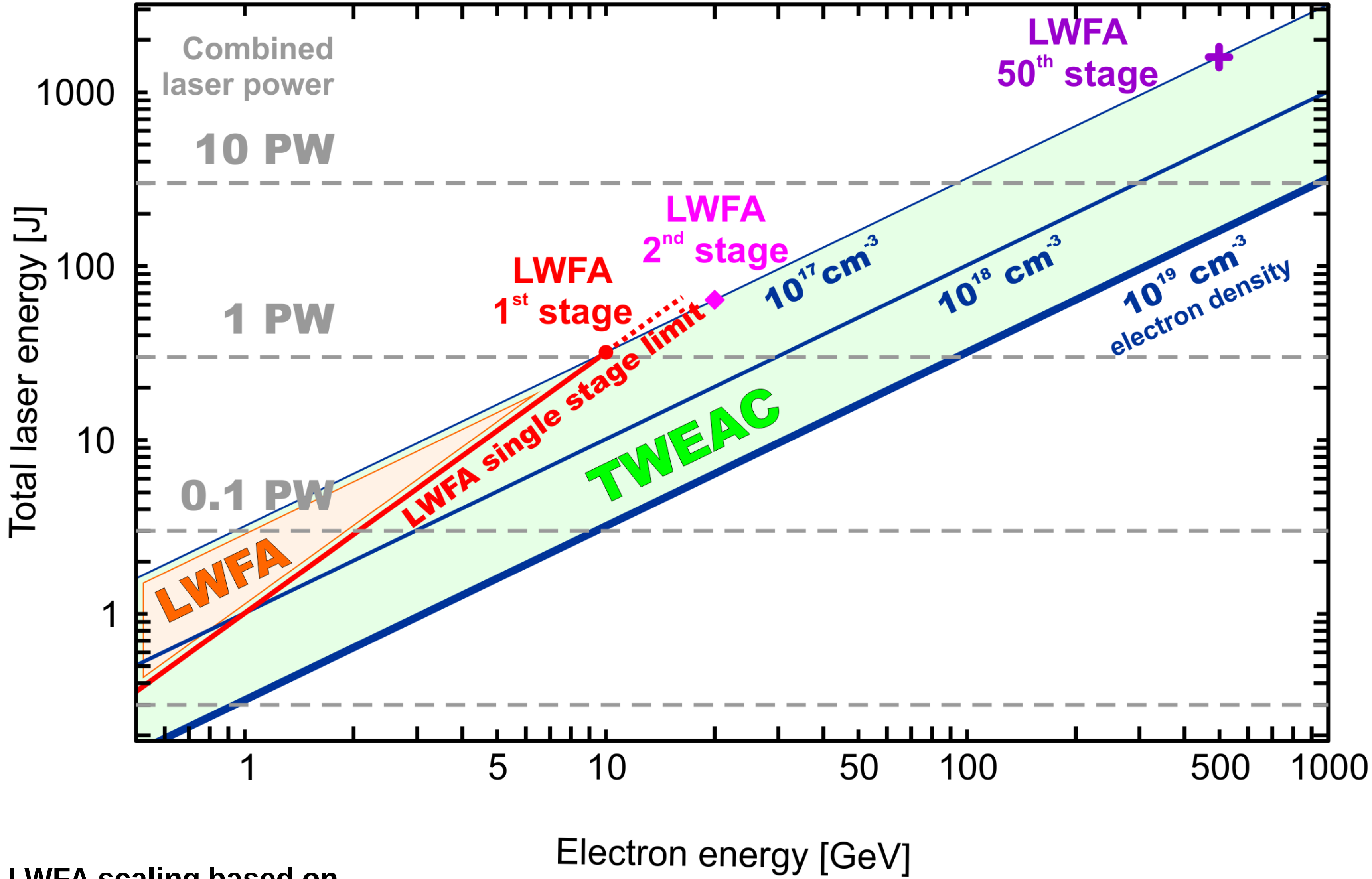


- Including dispersion pre-compensation optics, the entire beamline inside the vacuum chamber extends 7 - 10 meters in total.
- On a side note: Small is not always easier: A 1cm-TWEAC stage can be more challenging with respect to beam delivery.

- Provide two pulse front-tilted laser pulses with opposite pulse-front tilts.
- Avoid hitting intensity related damage thresholds and avoid extreme laser beam aspect ratios and angles.



How does TWEAC scale in laser energy?

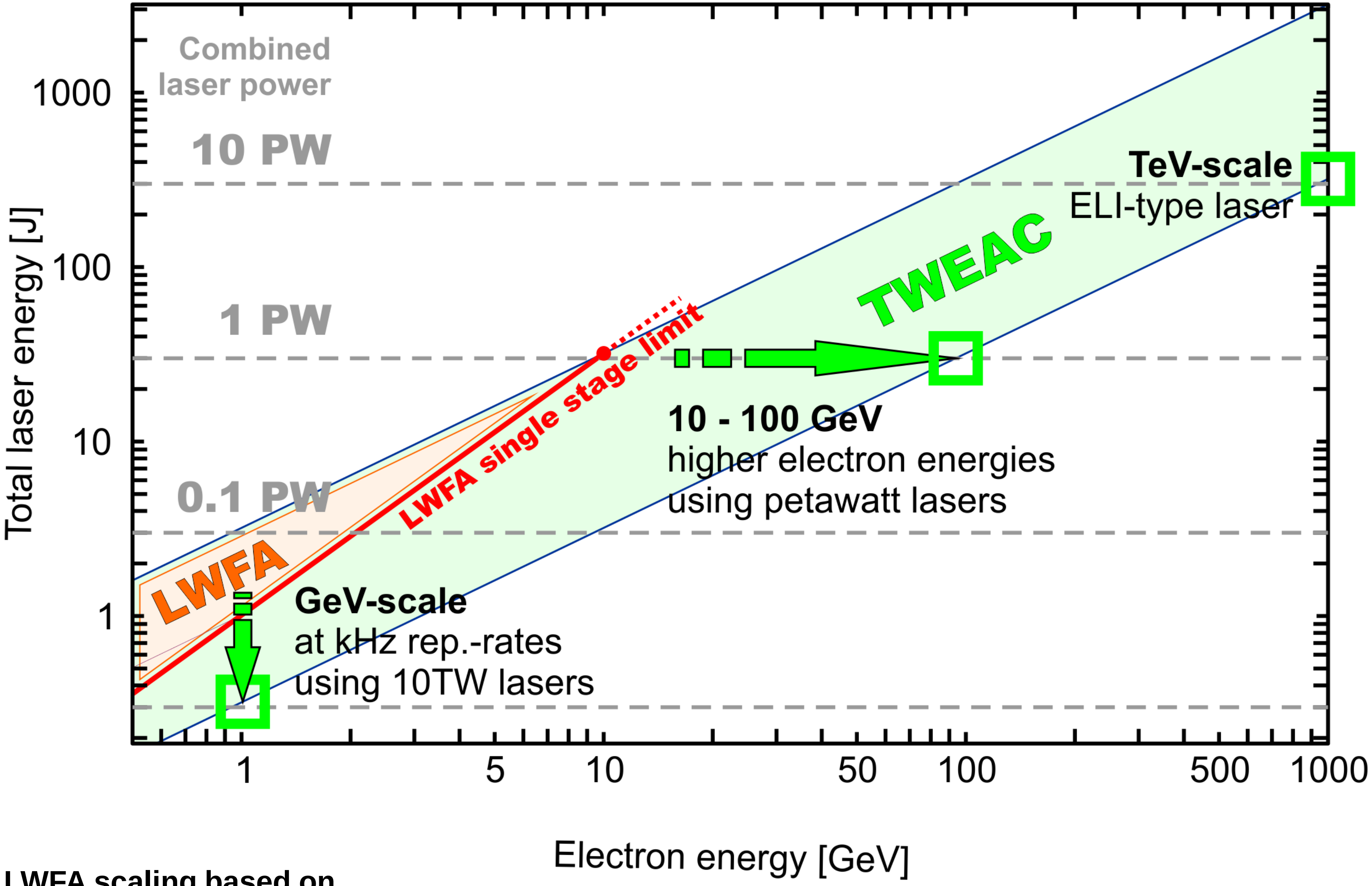


- **TWEAC does not require staging**, as accelerator can be extended in length by using extending the width of lasers and optics.
- **Longitudinal stage partitioning is still possible**, allowing to accommodate to different laser technologies and specific plasma beamline designs.
- **Reduces e-beam and laser transport challenges.**
- Limited by available laser pulse energy only.
- **Achieves stationary plasma dynamics and electron acceleration**.
  Avoids premature interaction with gas target in the slit nozzle plane.

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

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

How does TWEAC scale in laser energy?



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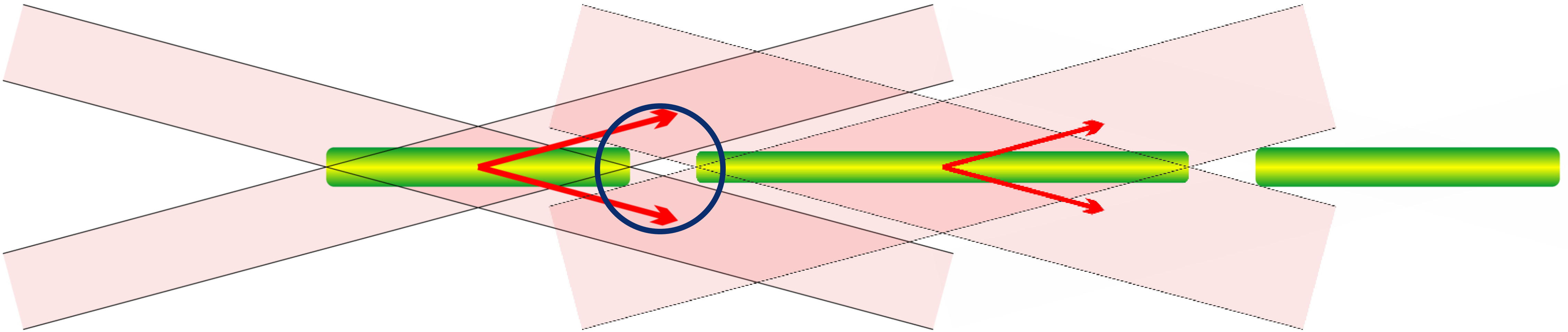
Debus *et al.*, Phys. Rev. X **9**, 031044 (2019)

Lateral laser in- and outcoupling enables novel capabilities in plasma beamline designs

Injection stage

Dedicated acceleration stage at different laser intensity

Plasma lense for refocusing, or alternatively a **PWFA stage**



Minimal beam transport maintains beam quality.

No laser blocker foil needed, maintains beam quality.
Compatible with high-rep laser systems

The oblique laser beam geometry of TWEAC enables placement of consecutive stages with only sub-mm to mm beam-transport distances in between.

PIConGPU

github.com/ComputationalRadiationPhysics/picongpu

picongpu.readthedocs.io

Challenges for simulating Traveling-wave electron acceleration

Even low-res tests require several hundred GPUs

- Non-rotationally symmetric 3D geometry
  → increased transverse resolution
- Long acceleration lengths beyond LWFA depletion and dephasing lengths
  → 10^6 - 10^7 of timesteps at reasonable time to solution
- Requires robust laser insertion, extraction and absorption techniques at simulation boundaries and a larger simulation volume (~ 4 - 10x).

→ **High requirements on performance, resolution, memory and boundary conditions → Need for exascale computing**

Compared to typical LWFA simulations, TWEAC requires
100x more memory and 100x more timesteps

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Road to Exascale for PIConGPU

Juwels Booster (Nov 2020), JSC at FZ Juelich

73 PetaFLOPS (11th Top 500)

936 nodes, 3744 NVIDIA Volta A100s

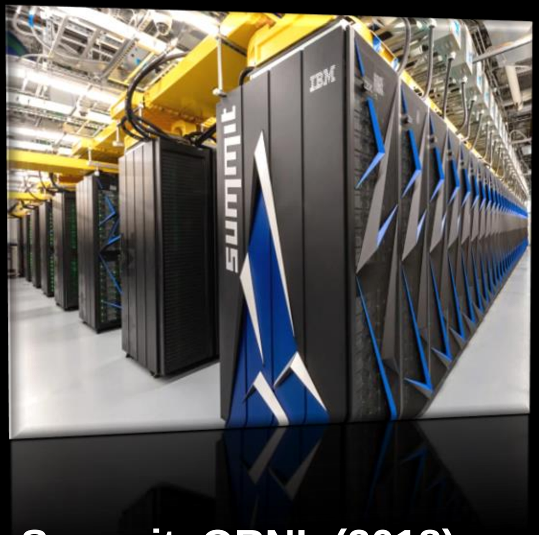
AMD EPYC Rome CPU

Perlmutter, ORNL (2021)

94 PetaFLOPS (7th Top 500)

1536 nodes, 6144 NVIDIA Volta A100s

AMD EPYC Milan CPU



Summit, ORNL (2018)

200 PetaFLOPS (3rd Top500)

4,608 nodes

27,648 NVIDIA Volta V100s

IBM POWER9 CPU

Frontier, ORNL (2022)

1,7 ExaFLOPS (1st Top 500)

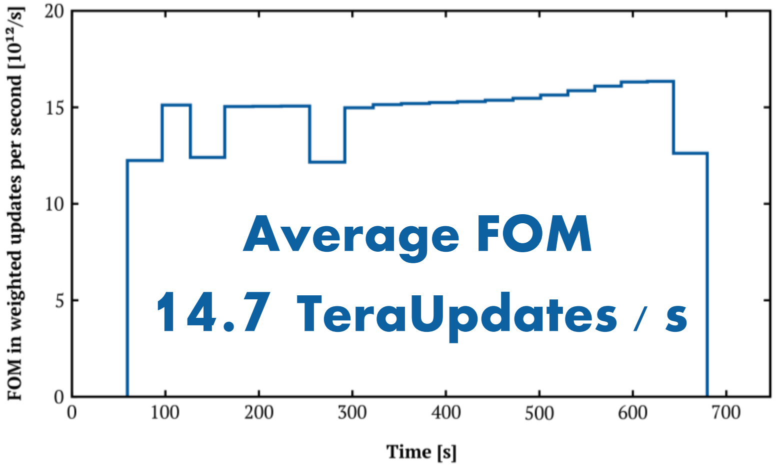
AMD GPU hardware

Cray architecture / compilers

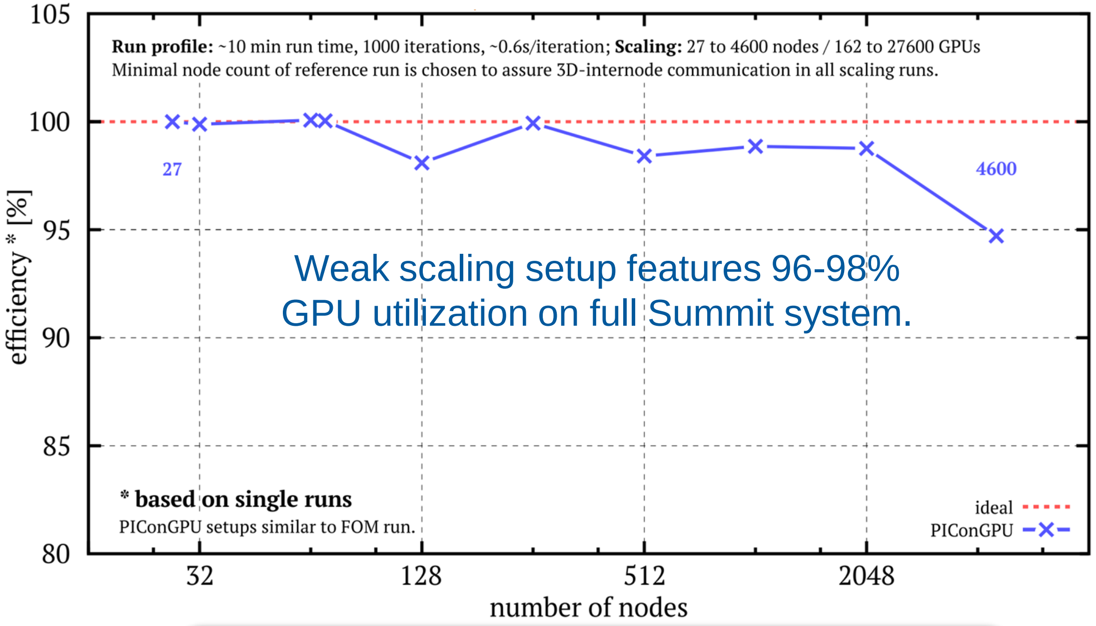
Early-access project **CAAR for Frontier**
Center for Application Readiness

PIConGPU scales up to exascale machines
Summit and Frontier figure-of-merit runs

Early-access project
Center for Application Readiness
for Frontier (CAAR)

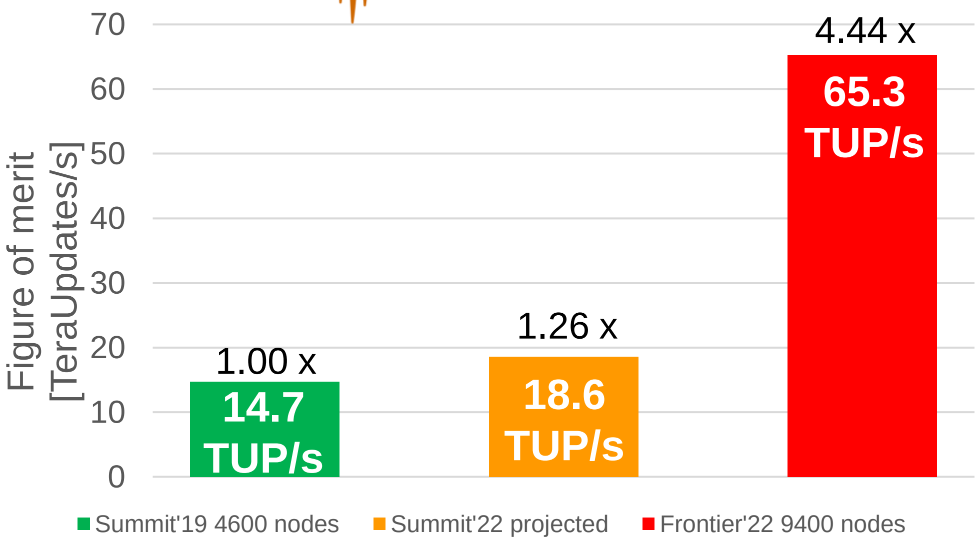


FOM = (0.9 × particle updates + 0.1 × cell updates) / second



$$\text{FOM} = \frac{(\ 90\%\ \text{x particle updates} + 10\%\ \text{x cell updates}\ )}{\text{second}}$$

PIConGPU scales to full Frontier !



Baseline | **Algorithmic improvements** | **Exascale on full Frontier**

Conclusions

Traveling-wave electron acceleration (TWEAC)

- Circumvents the LWFA diffraction, dephasing and depletion limits.
- Can in principle be arbitrarily extended in a single stage up to the energy frontier.
- Provides more freedoms in plasma accelerator designs.
- Non-axialsymmetric lateral in- and output coupling maintains quasi-stationary accelerator dynamics.
- Simulating TWEAC beyond 10GeV requires exascale computing resources.

- **PIConGPU**
- Is performance portable to latest AMD GPUs.
- Scales up to full the Frontier cluster at ORNL and is now ready for exascale.