EAAC2025

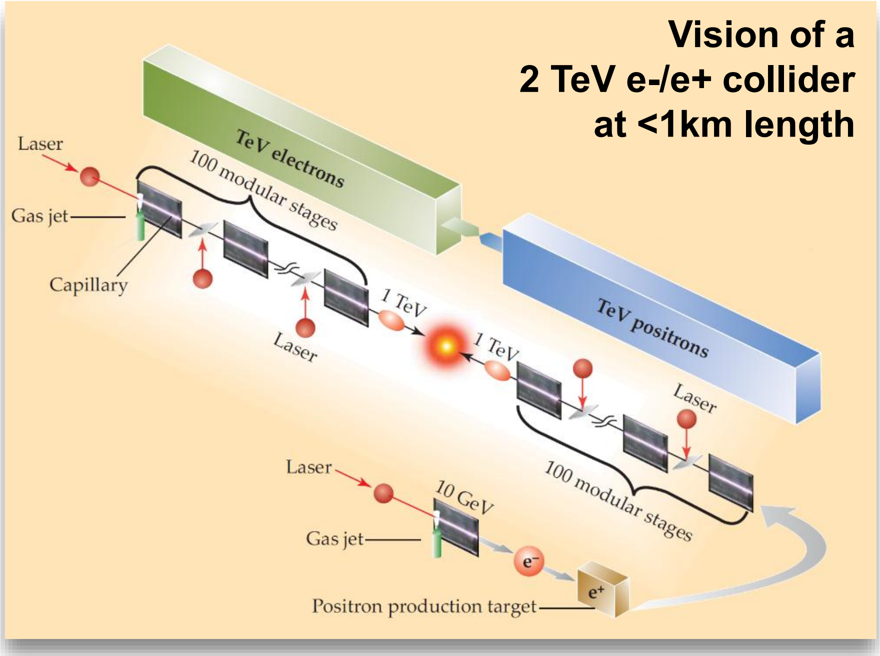
Beyond Dephasing: Scalable laser-plasma accelerators

via Traveling-wave electron acceleration

Alexander Debus[1], Klaus Steiniger[1], Finn-Ole Carstens[1], Richard Pausch[1], Julian Lenz[1], Franz Pöschel[2], René Widera[1], Sunita Chandrasekaran[2,3], Michael Bussmann[2,1], Ulrich Schramm[1]

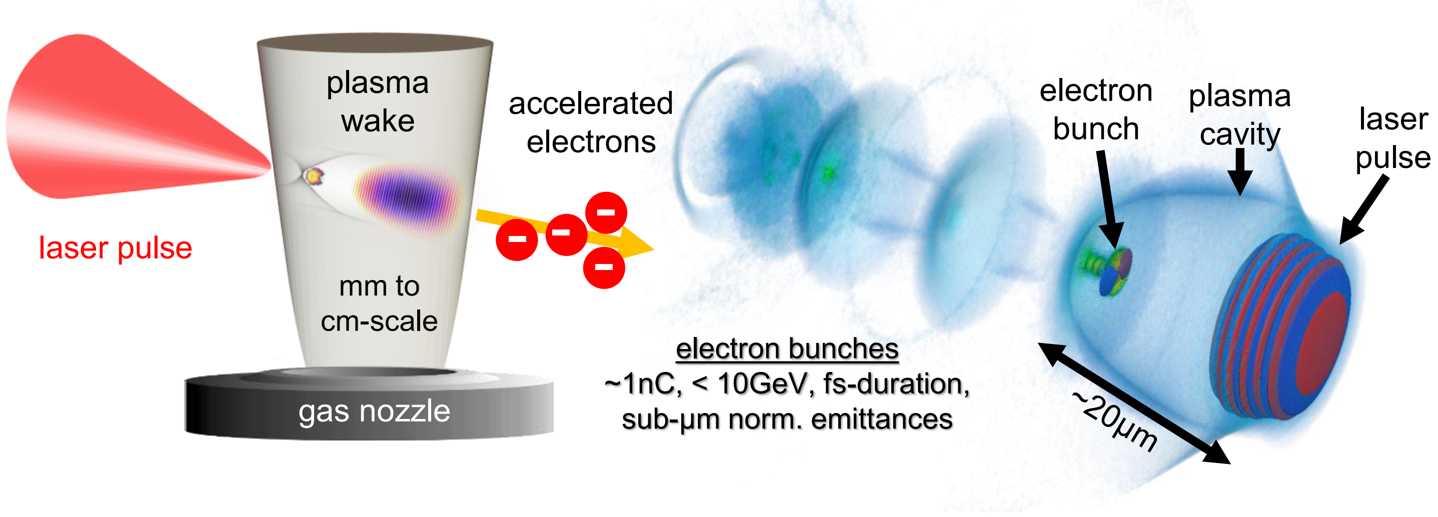
[1]Helmholtz-Zentrum Dresden – Rossendorf, Dresden, Germany
[2]CASUS, Center for Advanced Systems Understanding, Görlitz, Germany
[3]University of Delaware, Newark, Delaware, USA

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



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

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



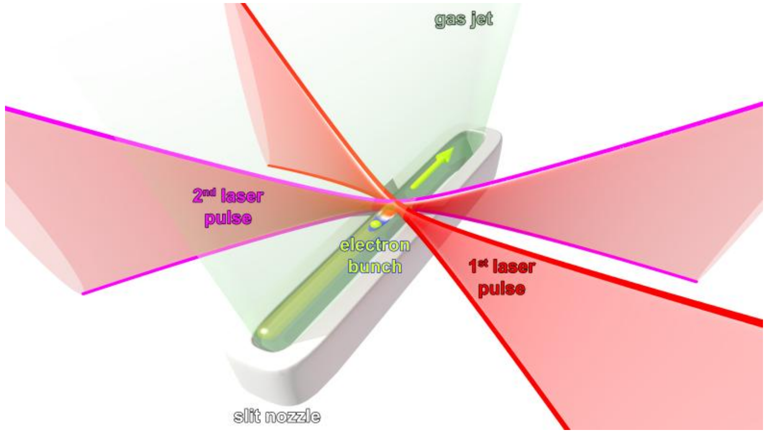
Beyond high-energy applications: Structured - light approaches enable control over LPA acceleration phase, Providing new ways to control electron injection and acceleration.

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!**

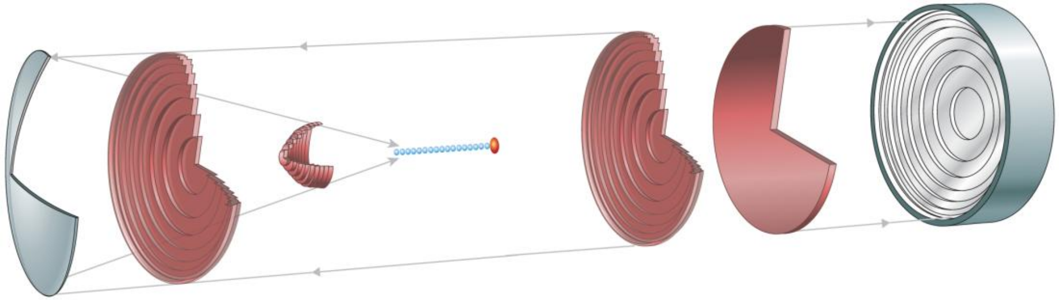
Synchronization, Beam size matching, charge loss, Laser in- & out-coupling, emittance growth in beam transport, etc.

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



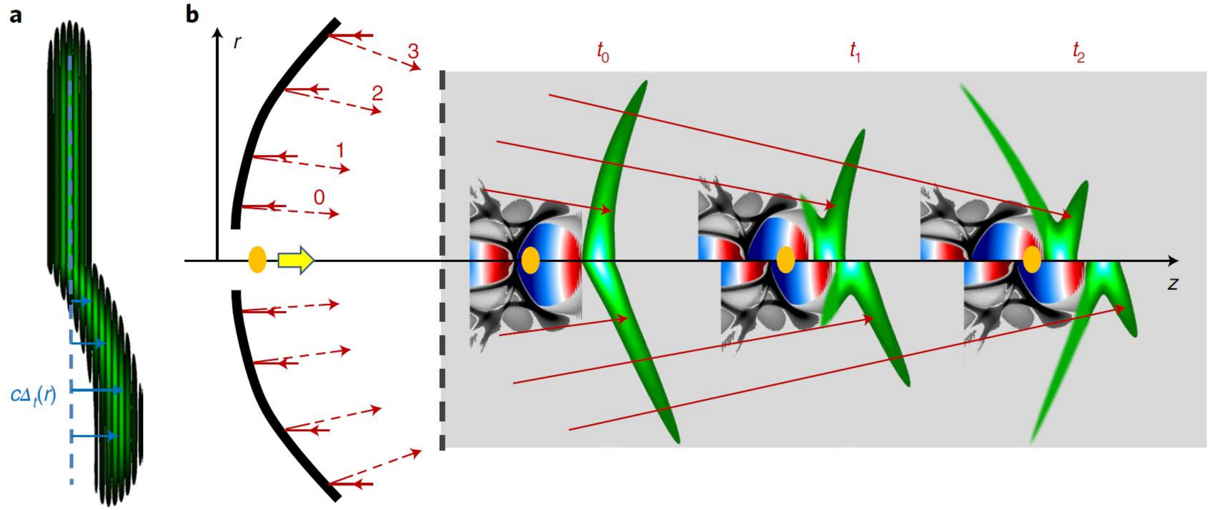
Circumventing the Dephasing and Depletion Limits of Laser-Wakefield Acceleration

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



Phase-locked laser-wakefield electron acceleration

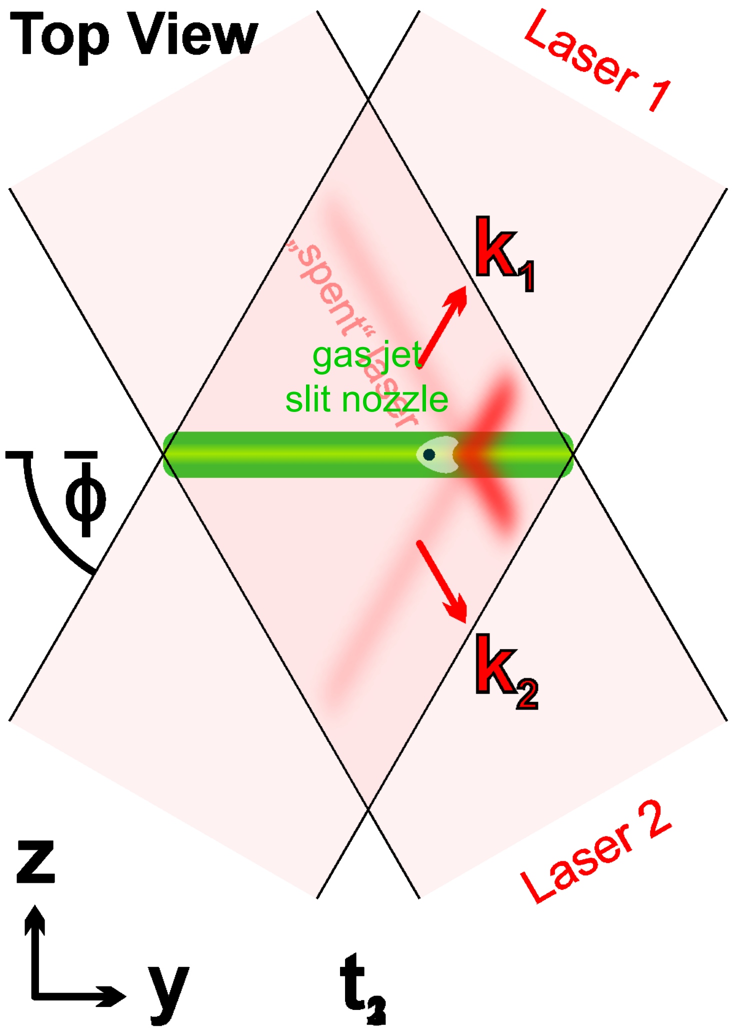
Caizergues *et al.* (2020), *Nature Photonics* 14(8), 475-479
doi: 10.1038/s41566-020-0657-2.



Dephasingless Laser Wakefield Acceleration

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

Traveling-Wave Electron Acceleration (TWEAC)

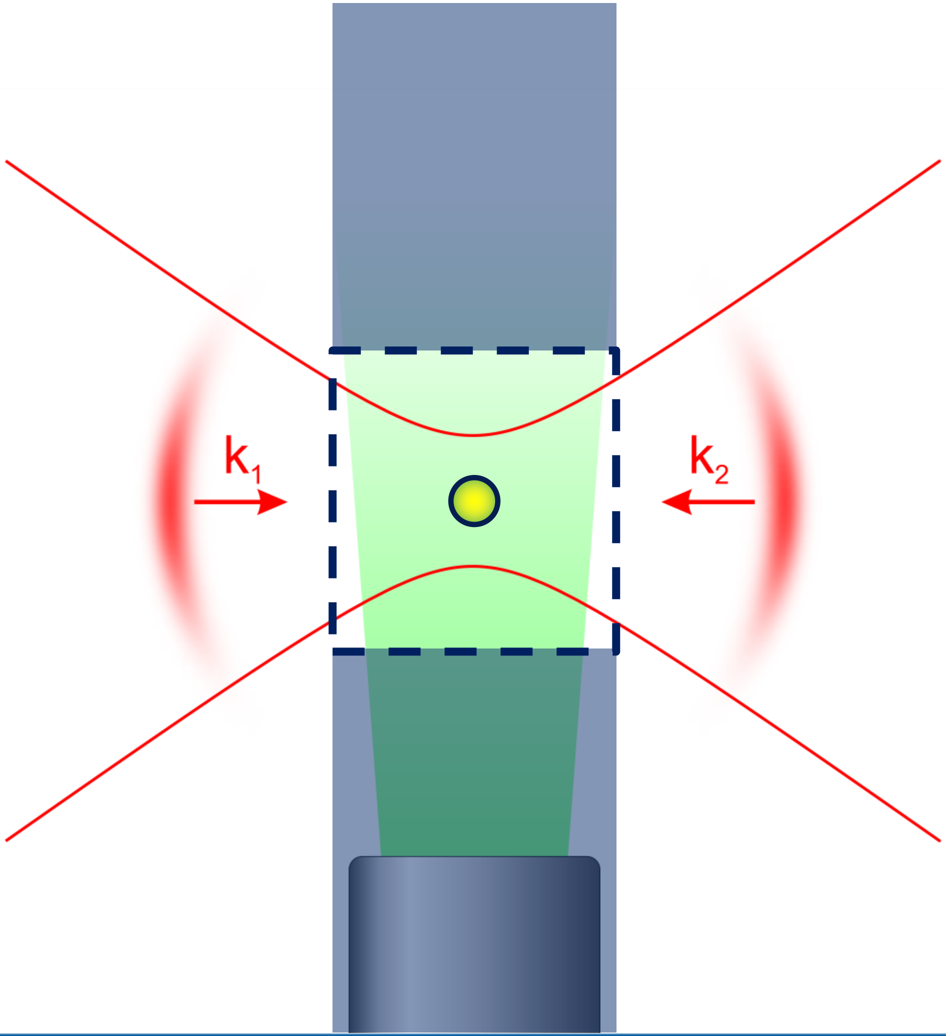


TWEAC circumvents major limitations:
Dephasing, Depletion and Defocusing

- 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**

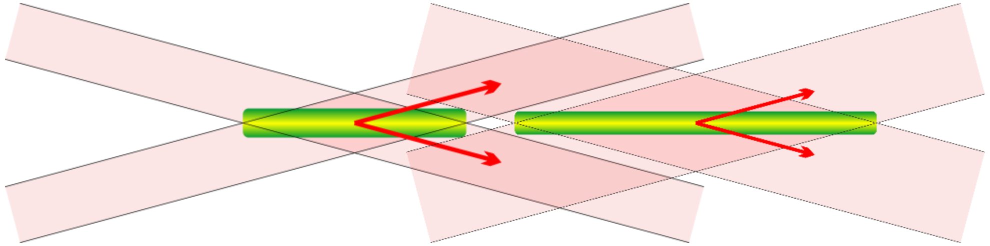
Debus *et al.*, *Phys. Rev. X* **9**, 031044 (2019)
10.1103/PhysRevX.9.031044

Practical considerations for energy-scalable Laser-plasma accelerators
Advantages of a lateral, non-axially symmetric geometry



Strictly lateral, laser in- and out coupling

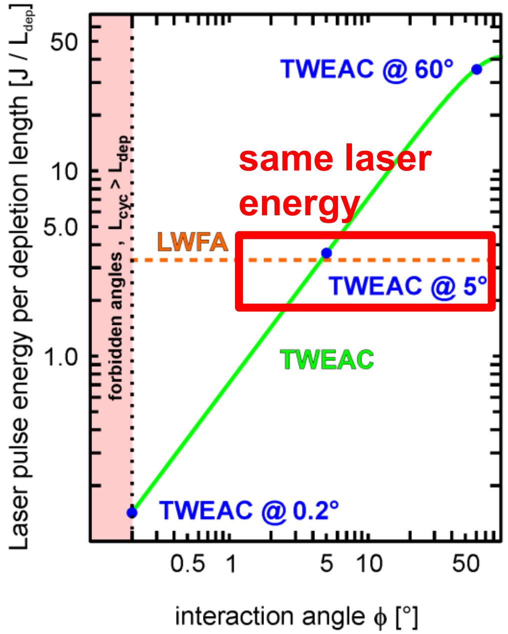
- Stationary propagation distances to center of interaction. Geometrically enforces of stationary acceleration conditions.
- No geometric occlusion from gas nozzle or scrapers.
- Reduces need to ionize an extended plasma volume compared to axial laser-coupling.
- **Easier accelerator scaling:** Subsequent stages can be placed right after one another. Length of stages depends on available lasers.



High-density TWEAC setups at low-incident angle beams (~5°) are an ideal testbed

- High-density plasmas have more pronounced plasma dynamics on **smaller spatial and shorter time scales**.
- Greatly **reduces simulation time** for exploring the regime.
- Benefits on controlling dephasing, depletion and diffraction are seen earlier.
- **Experimental perspective** of proof-of-principle experiments by **lower laser energy requirements**.
- Speeds up learning curve by **exposing potential problems** earlier, such as blowing up plasma dynamics, code numerics or both.

$L_{LWFA,dephasing}(n_e = 10^{19}\ cm^{-3}, a_0 = 3.0) \sim\ 680\mu m$
$L_{LWFA,depletion}\ (n_e = 10^{19}\ cm^{-3}, a_0 = 3.0) \sim 1330\mu m$



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

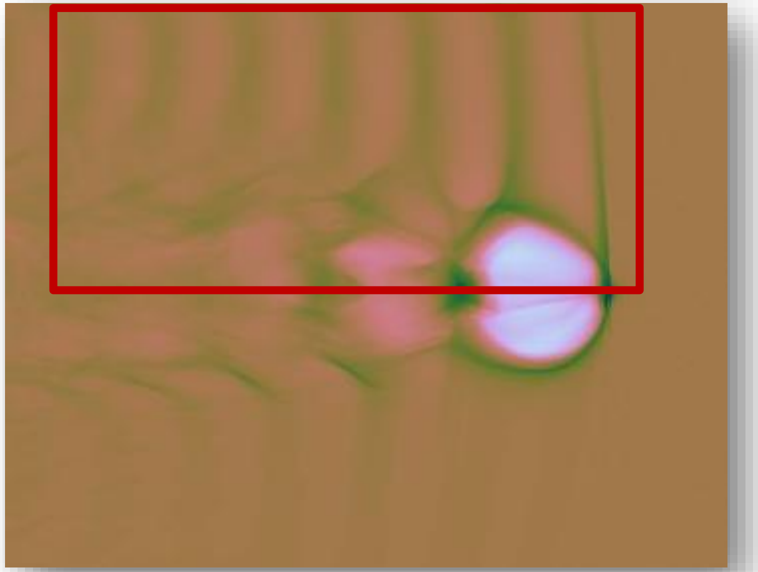
Maxwell-exact analytic TWEAC laser model required for strong focusing

- Small-angle incidence focusing increases effective laser spot sizes $\mathbf{w_{eff} \sim w_0 / \sin(\Phi)}$.
- This can still work for TWEAC scenarios at lower densities $<10^{19}$ cm^{-3} or at much larger angles $\Phi > 5°$.
  However, for matching at high densities 10^{19} cm^{-3},
  $w_{0,eff} \sim 6\mu m$ is needed.

  → Small $w_{0,eff}$ requires even smaller w_0,
  i.e. strong focusing required.

  → Requires strong focusing and paraxial approximation for cylindrical focusing breaks down.

  → **Required new TWEAC laser model for strong focusing.**



At small-angle incidence, paraxial TWEAC models over time expose unphysical asymmetries.

Maxwell-exact analytic TWEAC laser model for strong focusing

Maxwell-exact model of ultrashort TWEAC pulses

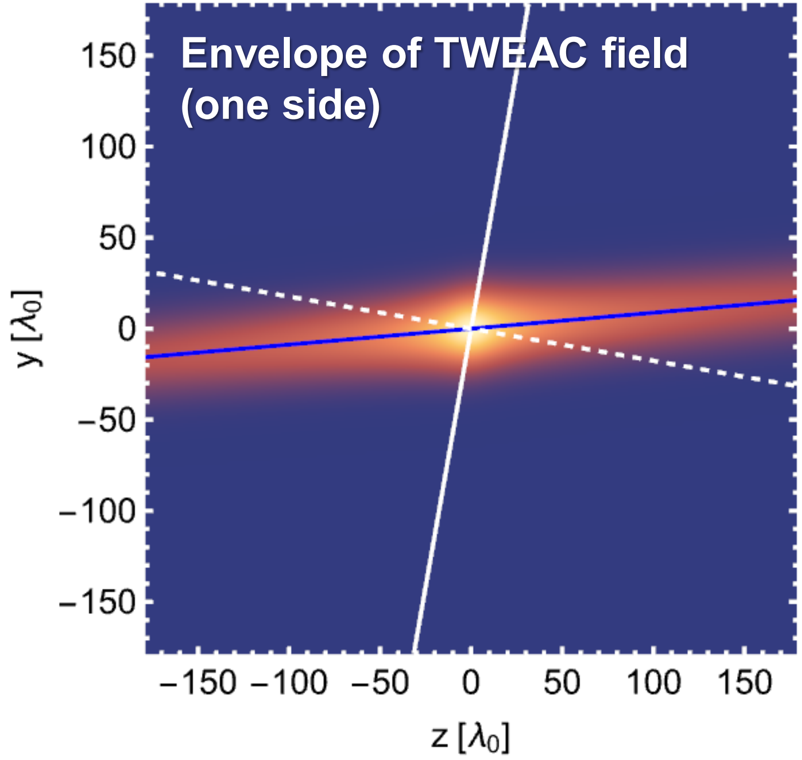
- Includes strong focusing down to the λ - scale.
- For all linear polarization angles α.
- For all incident angles Φ.
- Arbitrary comoving foci β_0.
- For all E- and B-fields.

Implemented and tested new laser model in PIConGPU

- Replaced legacy model, based on paraxial approximation.
- New implementation is shorter, faster and more maintainable (>1600 LOCs less).

Derivation

- Based on complex source method combined and a dual-field setup.
- Exploits zero-order cylindrical Bessel-function J_0 to be exact solution of Helmholtz equation.
- Specializes solution for ultrashort pulses with TWEAC-like dispersion properties.
- Exposes a suitable base of linear polarization states for TWEAC lasers.



- Steiniger et al., "Optical free-electron lasers with Traveling-Wave Thomson-Scattering", Journal of Physics B: AMOP, **47** (23) (2014)
- F. G. Mitri, "Cylindrical quasi-Gaussian beams", Opt. Lett., **38**(22), pp. 4727-4730 (2013)
- Hua, J. F., "High-order corrected fields of ultrashort, tightly focused laser pulses", Appl. Phys. Lett. **85**, 3705-3707 (2004)

Maxwell-exact analytic TWEAC laser model for strong focusing

Resulting E_x – field component in PIConGPU coordinates, i.e. focal axis along y-coordinate

$$E_x(x,y,z,t) = \frac{i}{2k\,\rho_-^3\; I_0\left(\frac{1}{2}k^2\sin\phi\, w_0^2\right)}\, e^{i(\omega_0 t - ky\cos\phi)}\, U_{\mathrm{pulse}}(\nu,\xi,t)\,\times$$

$$\Big\{ k\rho_- \boxed{J_0(k\rho_-\sin\phi)} \Big[(\rho_-^2 - x^2 + xX_-\cos\phi)\sin\alpha\sin^2\phi + \cos\alpha\left(\rho_-^2 + \rho_-^2\cos^2\phi - x^2\sin^2\phi - xX_-\cos\phi\sin^2\phi\right)\Big]$$

$$+ J_1(k\rho_-\sin\phi)\sin\phi\Big[\sin\alpha\left(-\rho_-^2 + 2x^2 - ik\rho_-^2X_-\sin\phi + x\cos\phi\,(-2X_- - ik\rho_-^2\sin\phi)\right) + \cos\alpha\left(-\rho_-^2 + 2x^2 + ik\rho_-^2X_-\sin\phi + x\cos\phi\,(2X_- + ik\rho_-^2\sin\phi)\right)\Big]\Big\}$$

Complex valued Bessel-functions not natively supported for GPUs by CUDA or HIP software stacks.

$$\rho_- = \sqrt{x^2 + X_-^2}$$

$$X_- = -\left(z + \tfrac{i}{2}kw_0^2\right)$$

TWEAC pulse including pulse front tilt and dispersion properties

$$U_{\mathrm{pulse}}(\nu,\xi,t) = \frac{\tau_G\sqrt{\omega_0}}{\sqrt{2\Psi}}\exp\left(-\frac{\omega_0\,(t-\nu+\xi)^2}{\Sigma}\right)$$

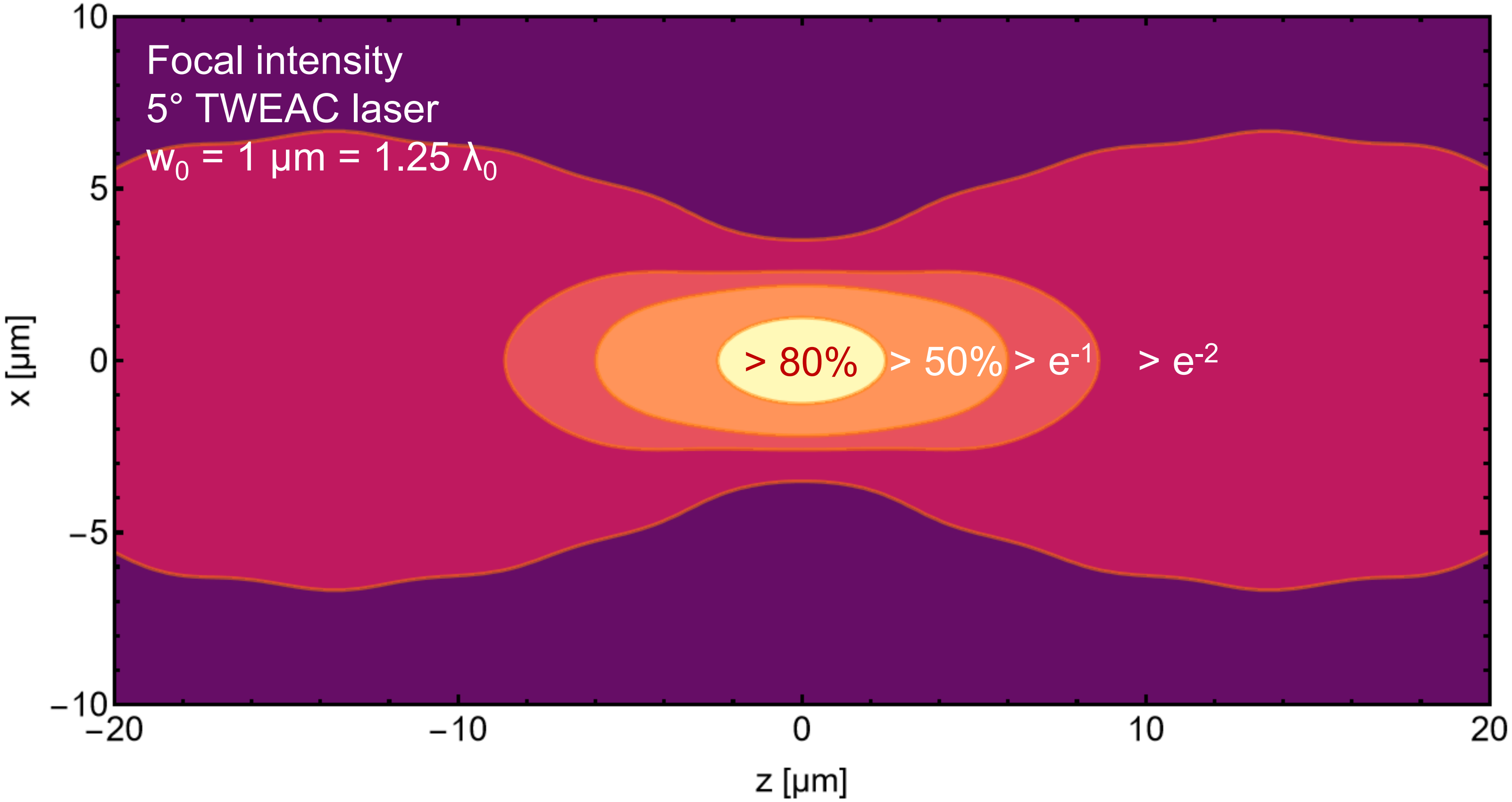
$$\Psi = \tfrac{1}{2}\,\omega_0\,\tau_G^2 - i(\nu-\xi)\cot^2\phi + \frac{i}{\beta_0}(2\nu-\xi)\;\cot\phi\csc\phi - \frac{i}{\beta_0^2}\,\nu\csc^2\phi$$

$$\Sigma = \omega_0\,\tau_G^2 - 2i(\nu-\xi)\cot^2\phi + \frac{2i}{\beta_0}(2\nu-\xi)\;\cot\phi\csc\phi - \frac{2i}{\beta_0^2}\,\nu\csc^2\phi$$

$$\nu = \frac{y\cos\phi - z\sin\phi}{c}$$

$$\xi = \frac{(\beta_0\cos\phi - 1)\,(z\cos\phi + y\sin\phi)}{\beta_0 c\sin\phi}$$

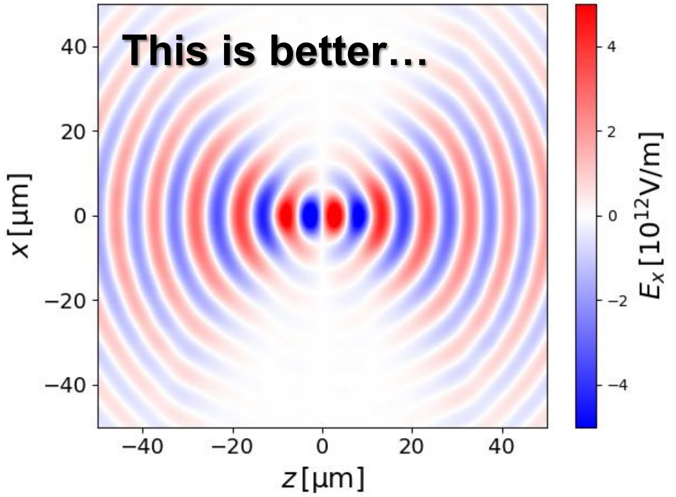
„Matching" a 5° incidence angle TWEAC pulse to 10^{19} cm^{-3} plasma in strong focus geometry

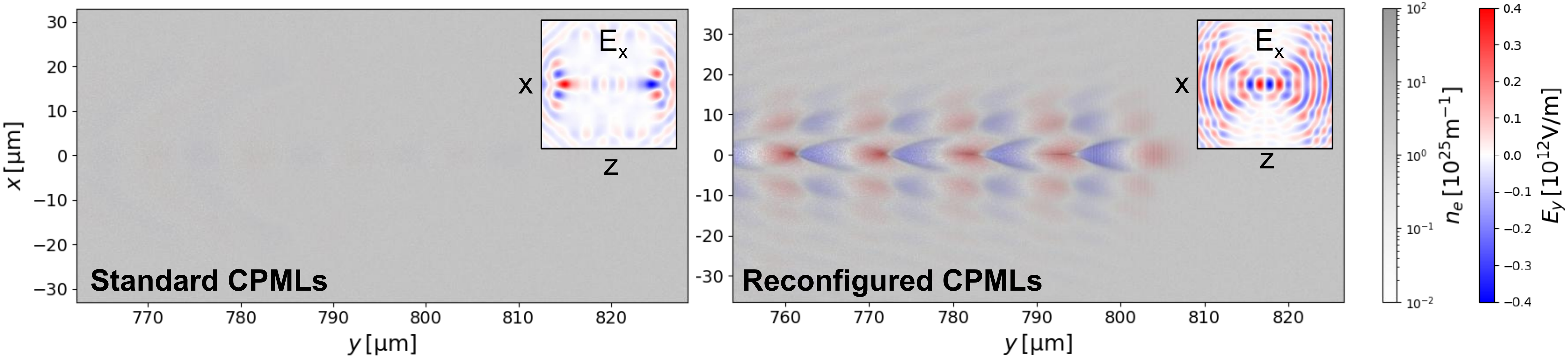


- Plasma wavelength at 10^{19} cm^{-3} corresponds to 10.7µm.
- LWFA matching diameter for a_0=3.0 suggests $w_{0,eff}$ = 5.8 µm. Fullfills criterion normal to propagation plane.
- In focal-direction, the situation is more complicated and likely not fully described by the LWFA matching criterion.
- TWEAC does not strictly require meeting matching conditions since self-guiding is not needed.

Grazing incidence laser beams are challenging for absorbing boundaries

- Standard perfectly-matched layer (PML) thickness (12 cells) was not enough for 5° incident angle. Very efficient reflection at simulation boundary.
- Increased to 80 cells and reconfigured PML properties to be more susceptible for grazing incidence.
- Supression of reflections still not perfect.

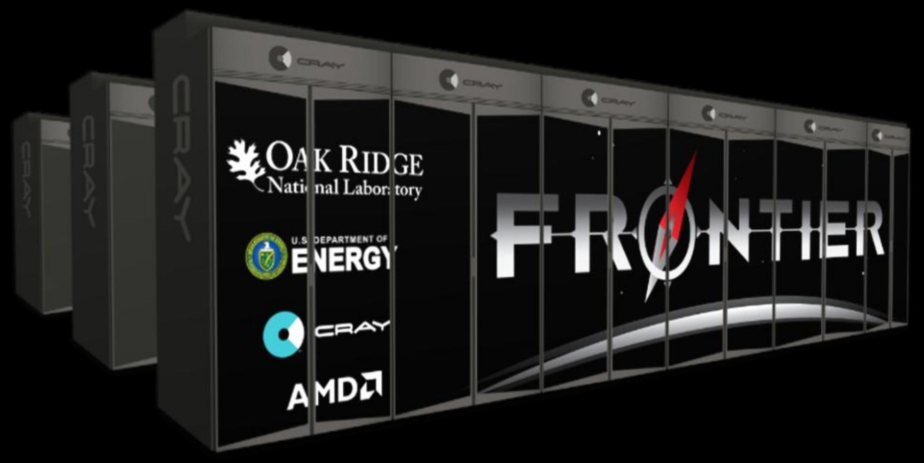




TWEAC is an Exascale challenge

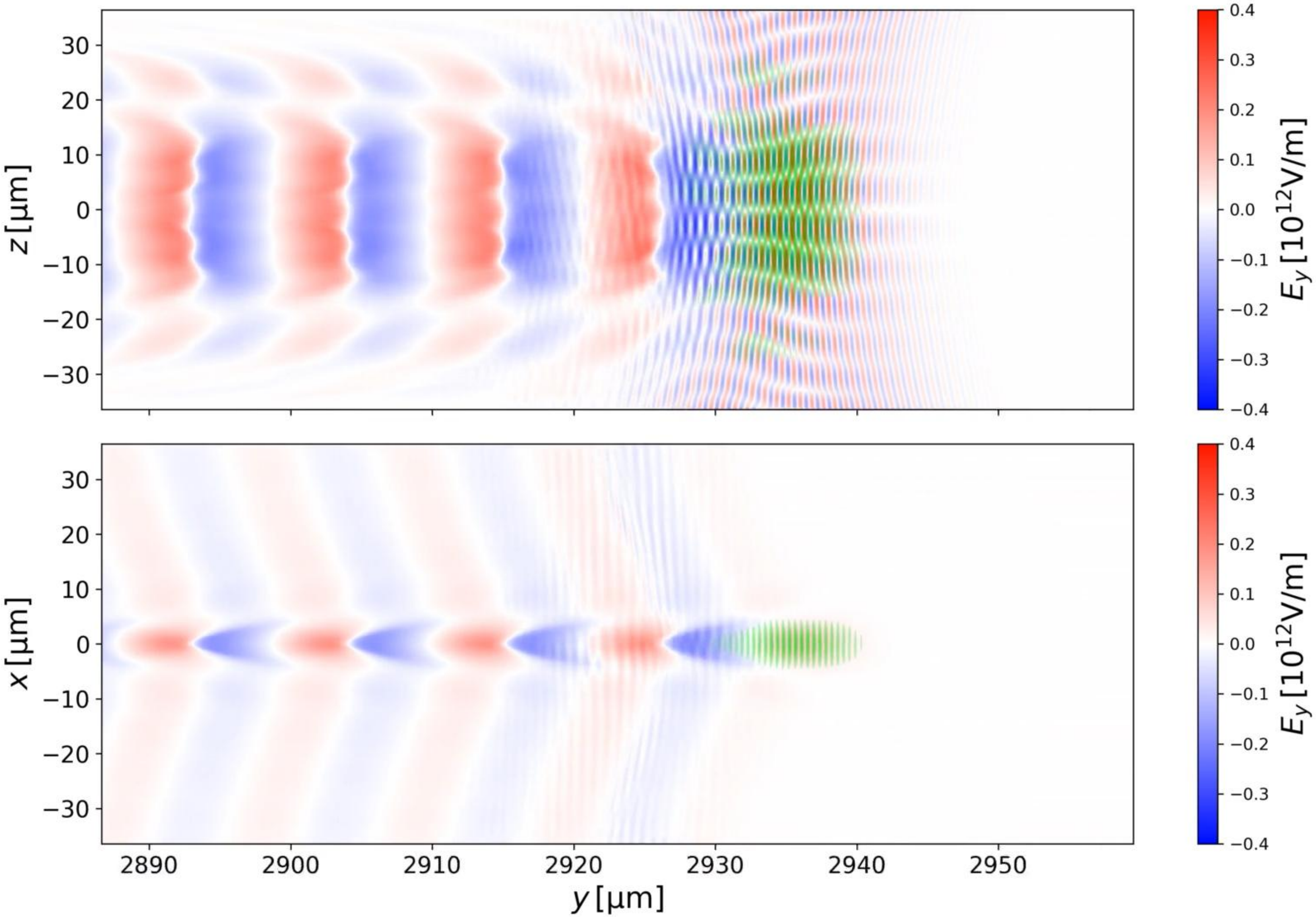
PIConGPU

- **Typical small test simulation for TWEAC**
  221 x 111 x 111 µm, 3mm acceleration length
  2048x MI250X GPUs, 80 min walltime
  (compute time w/o output)
- **A projected 30 GeV run requires > 100x more**



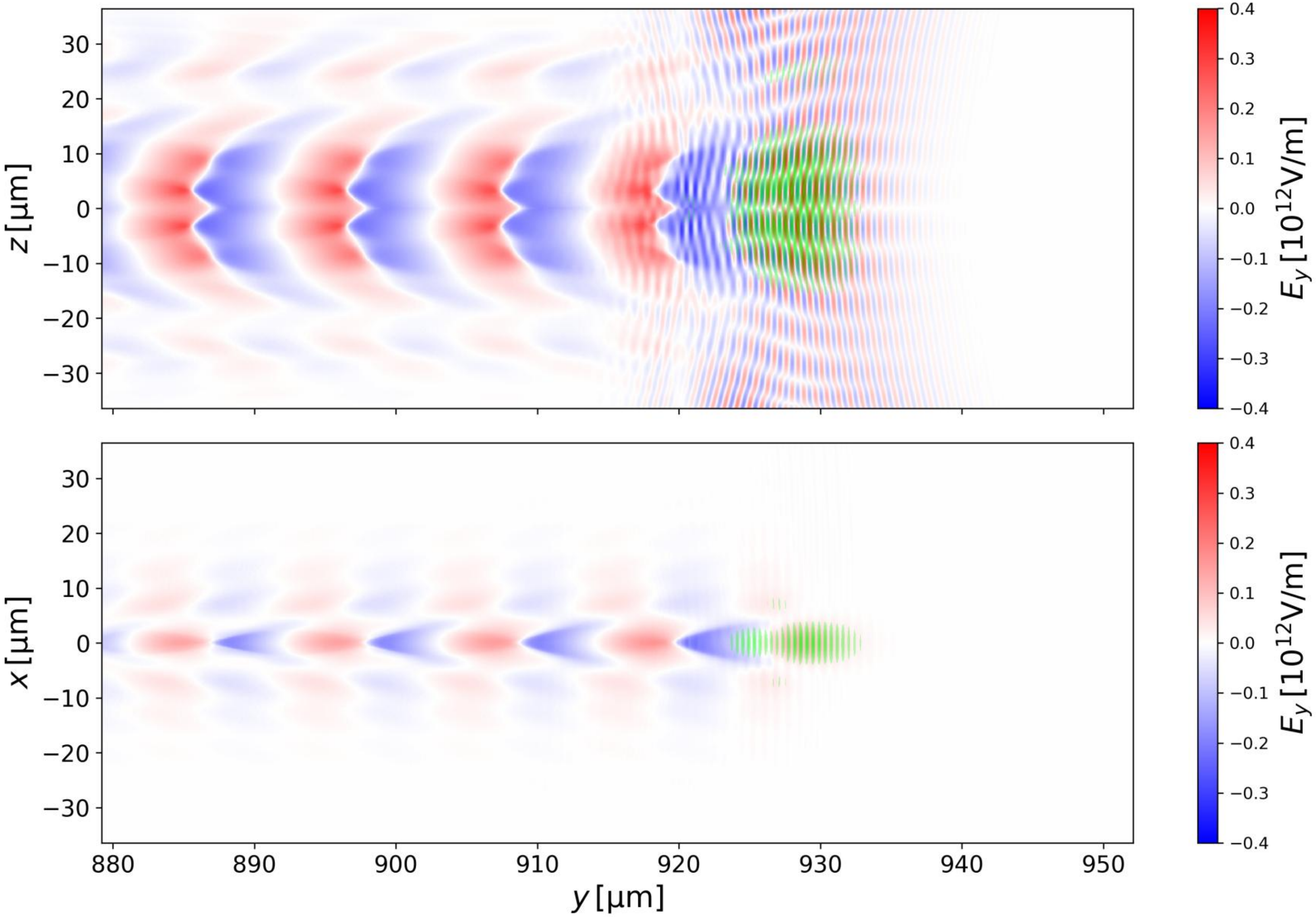
PLASMA PEPSC

Stationary acceleration conditions for small-angle TWEAC

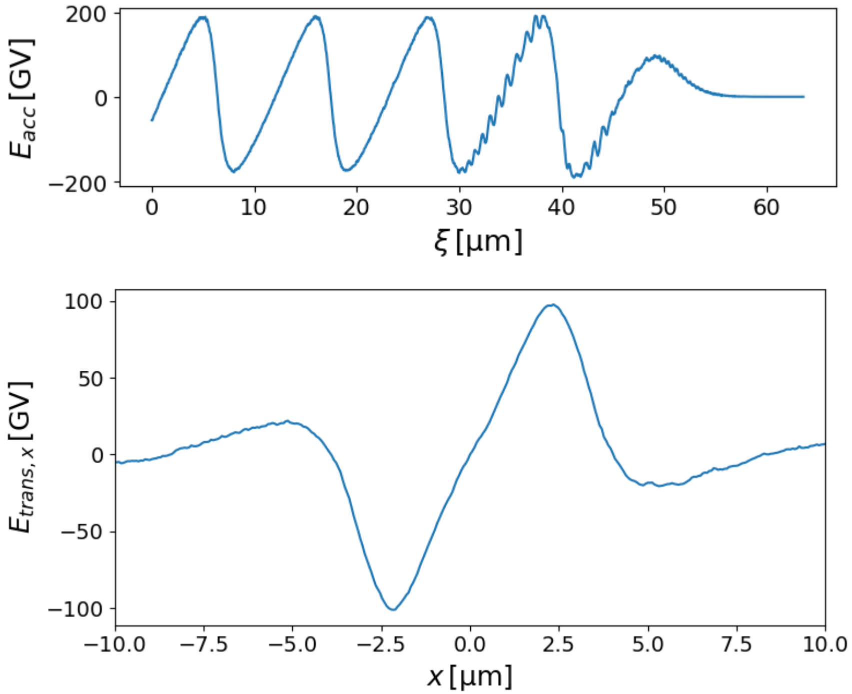


- Symmetric cavities also after extended simulation.
- Well-formed cavities without leaky-modes or parasitic injection.
- Transversely narrow cavities <20μm.
- Nonlinear wakefields with acceleration gradients of 200 GV/m and linear focusing fields.

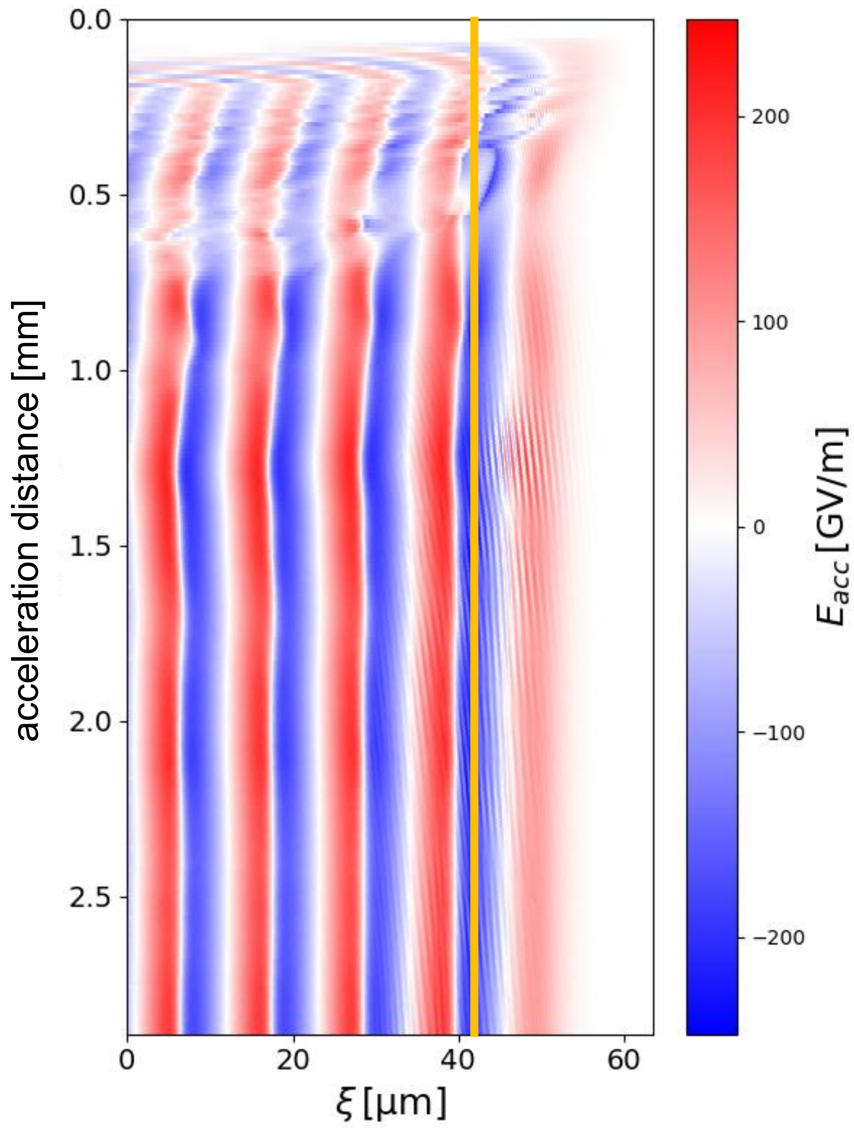
Acceleration fields reach 200 GV / m acceleration gradients



- Nonlinear wakefields at a_0=3.0 with acceleration gradients of 200 GV/m and linear focusing fields.

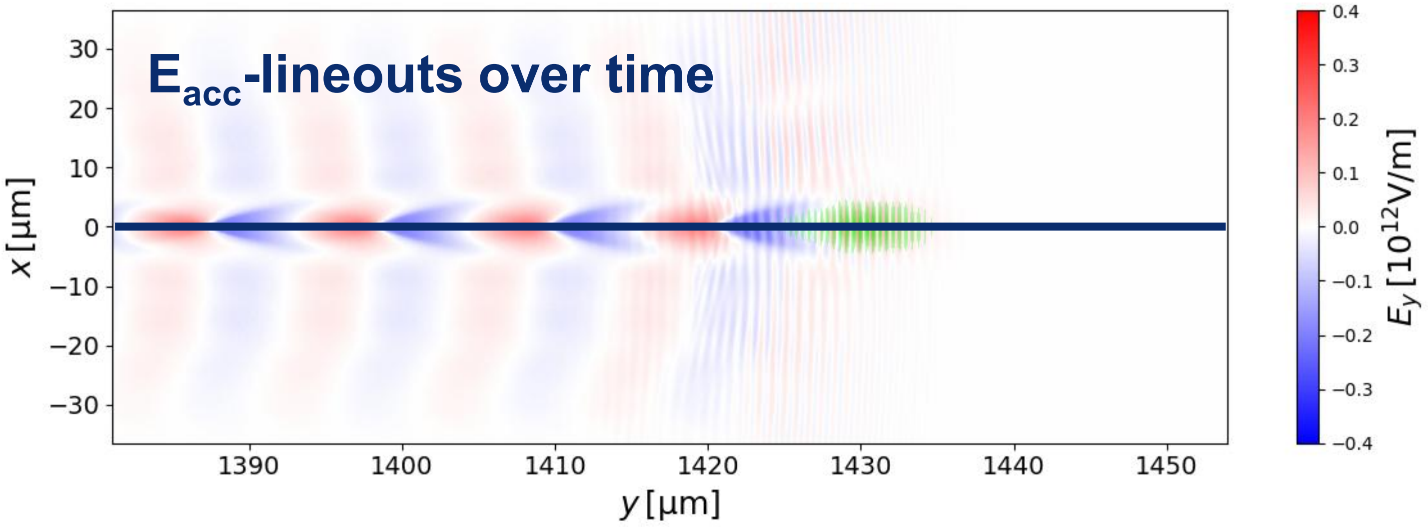


Beyond dephasing – low-angle TWEAC achieves steady state acceleration

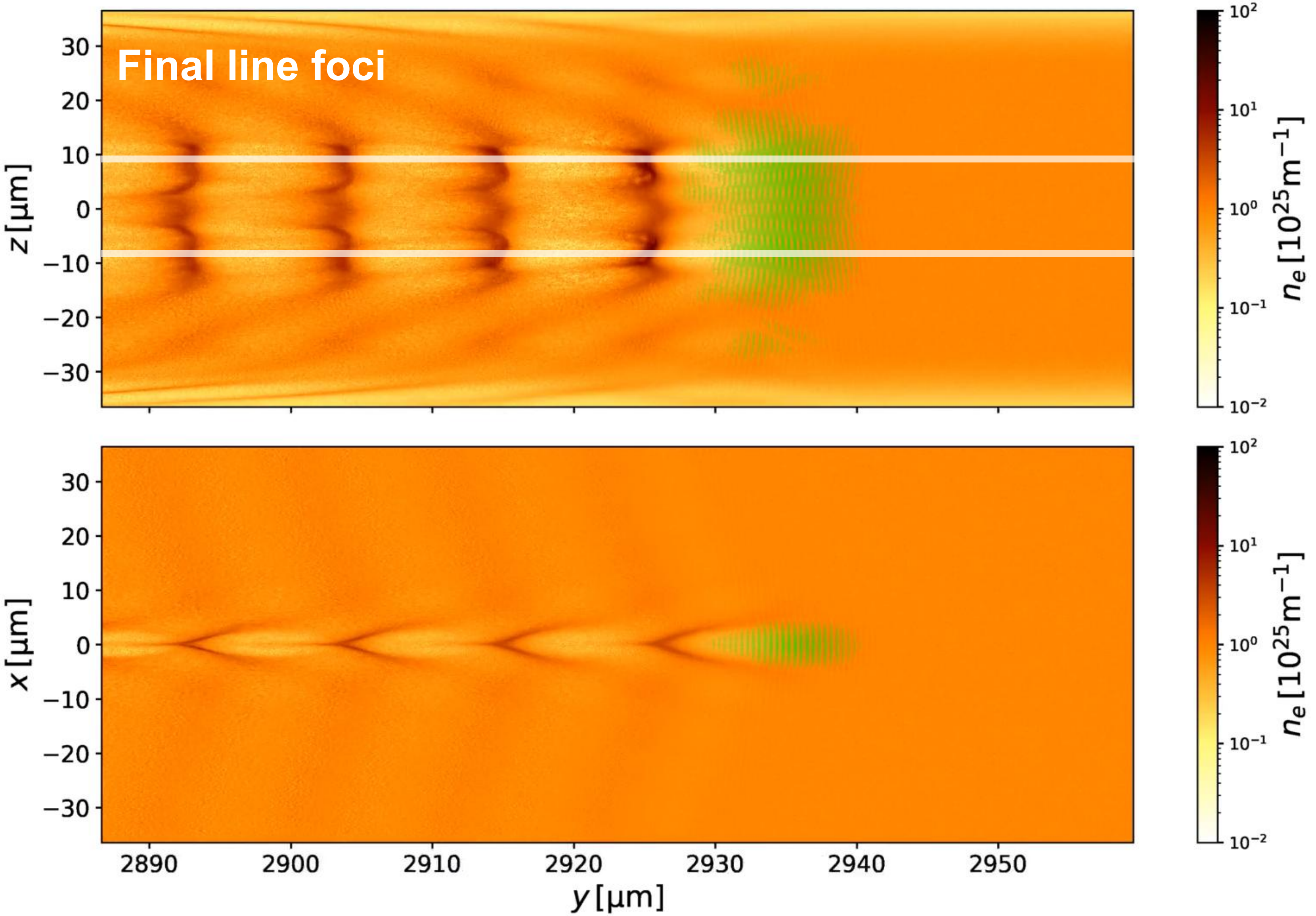


- Field reaches steady-state in accelerating field after 0.75 mm and remains constant far beyond LWFA dephasing and depletion lengths.
- Some reflections from boundarie still exist → Need to further reduce PML reflections.

$L_{LWFA,\ dephasing}(n_e = 10^{19}\ cm^{-3}, a_0 = 2.0) \sim 680\mu m$
$L_{LWFA,\ depletion}(n_e = 10^{19}\ cm^{-3}, a_0 = 2.0) \sim 1330\mu m$



Transverse plasma dynamics shifts TWEAC lateral line foci



- The plasma self-focusing dynamics shifts the TWEAC laser foci.
- This can be precompensated by shifting the initial cylindrical line focus.
- Here, the focal lines have been shifted too much.
- Requires further investigation.

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.
- Non-axialsymmetric lateral in- and output coupling maintains quasi-stationary accelerator dynamics.
- Simulating TWEAC beyond 10 GeV requires exascale computing resources.

Energy-efficient, low-angle ($\Phi = 5°$) TWEAC at high plasma densities (10^{19} cm^{-3})

- Demonstrated stationary acceleration conditions for small-angle TWEAC scenarios beyond dephasing and depletion length.
- For low-incidence angle setups: A new TWEAC laser model, supporting strong focus geometries, enables modeling narrow TWEAC acceleration cavities < 20μm in width.
- Transition to steady-state conditions < 0.7mm.
- Nonlinear TWEAC wakefields support 200 GeV/m.