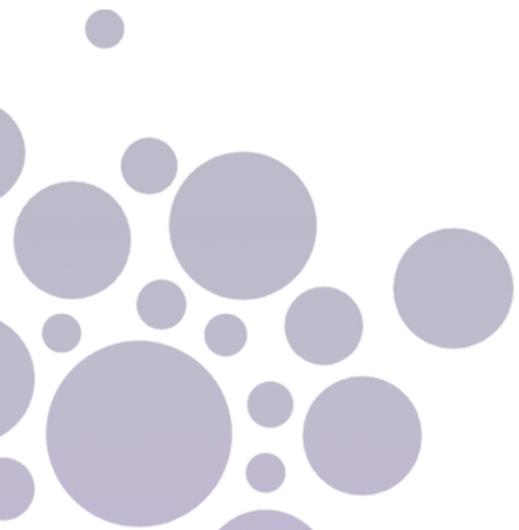


# Challenges in LWFA staging for 10 TeV Wakefield Colliders

F. Massimo

ALEGRO WORKSHOP 2025, SLAC, 5 March 2025



# Inputs from the 10 TeV Wakefield Collider Design Study WGs

- (●) WG LWFA Linac meeting:

<https://indico.slac.stanford.edu/event/9619/>

- (●) WG Laser Driver Kickoff meeting:

<https://indico.slac.stanford.edu/event/9588/>

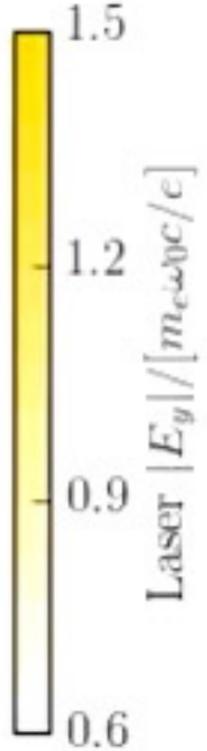
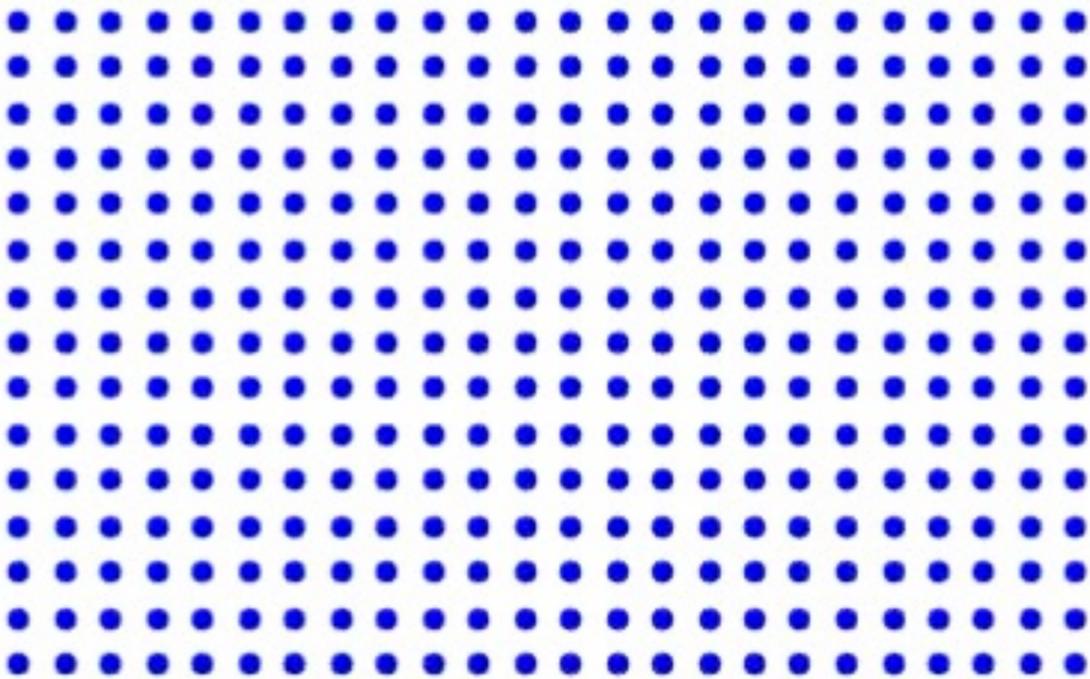
# Outline

- Why Staging?
- Sources and acceleration of electron beams
- Interfaces
- Plasma components and Laser Driver
- Simulations

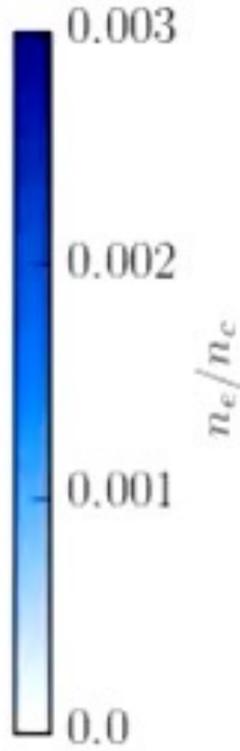
# Outline

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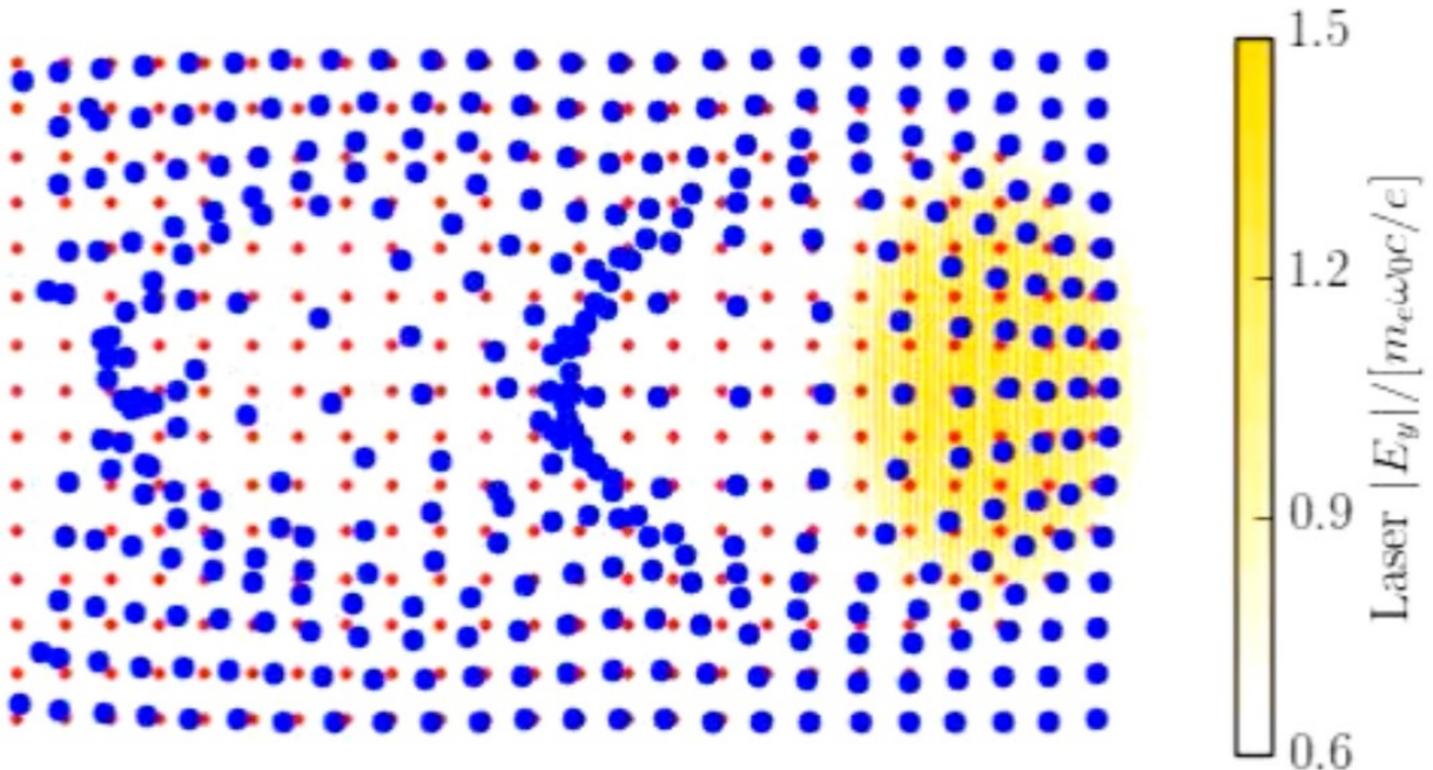
# Quick introduction to Laser Wakefield Acceleration(LWFA)



Electrons ● Immobile Ions ●  $M_i \gg m_e$

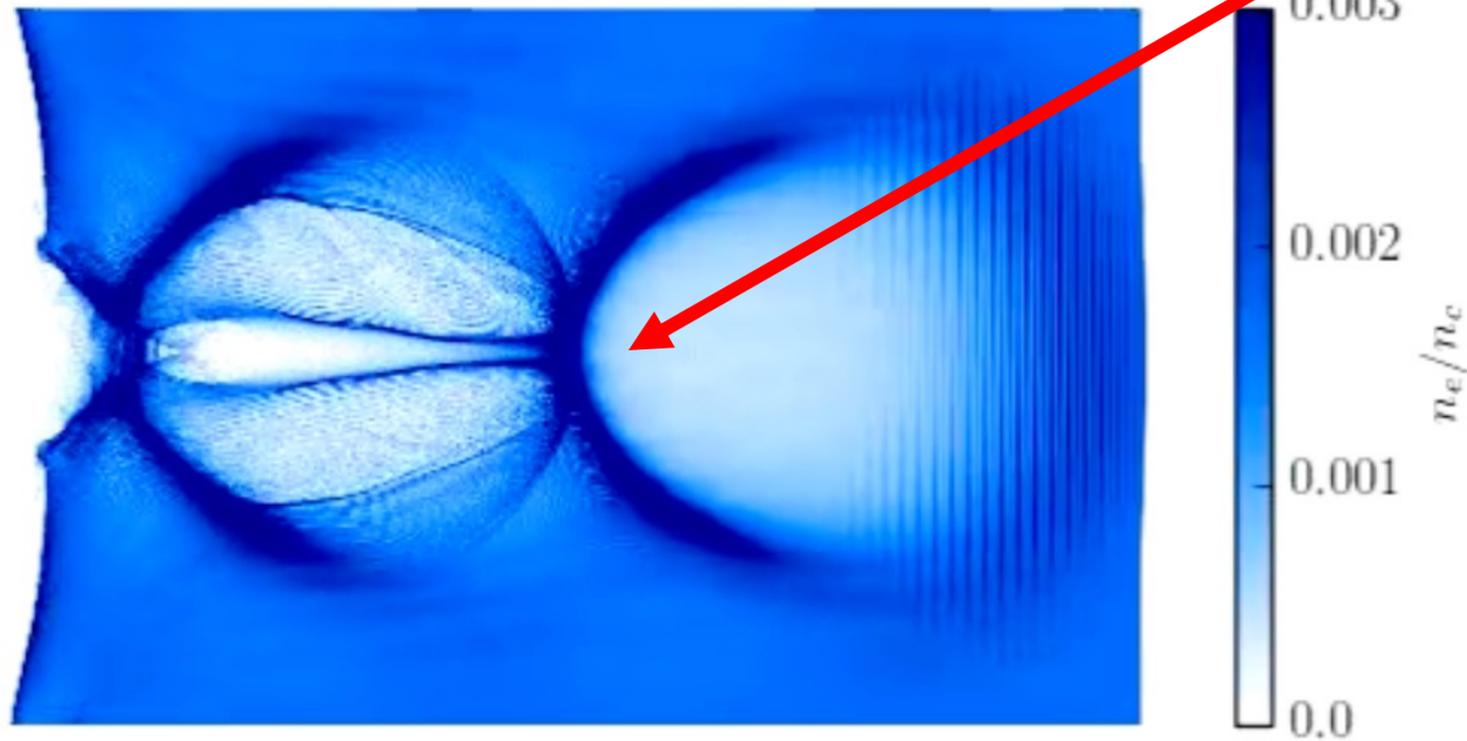


# Quick introduction to Laser Wakefield Acceleration(LWFA)



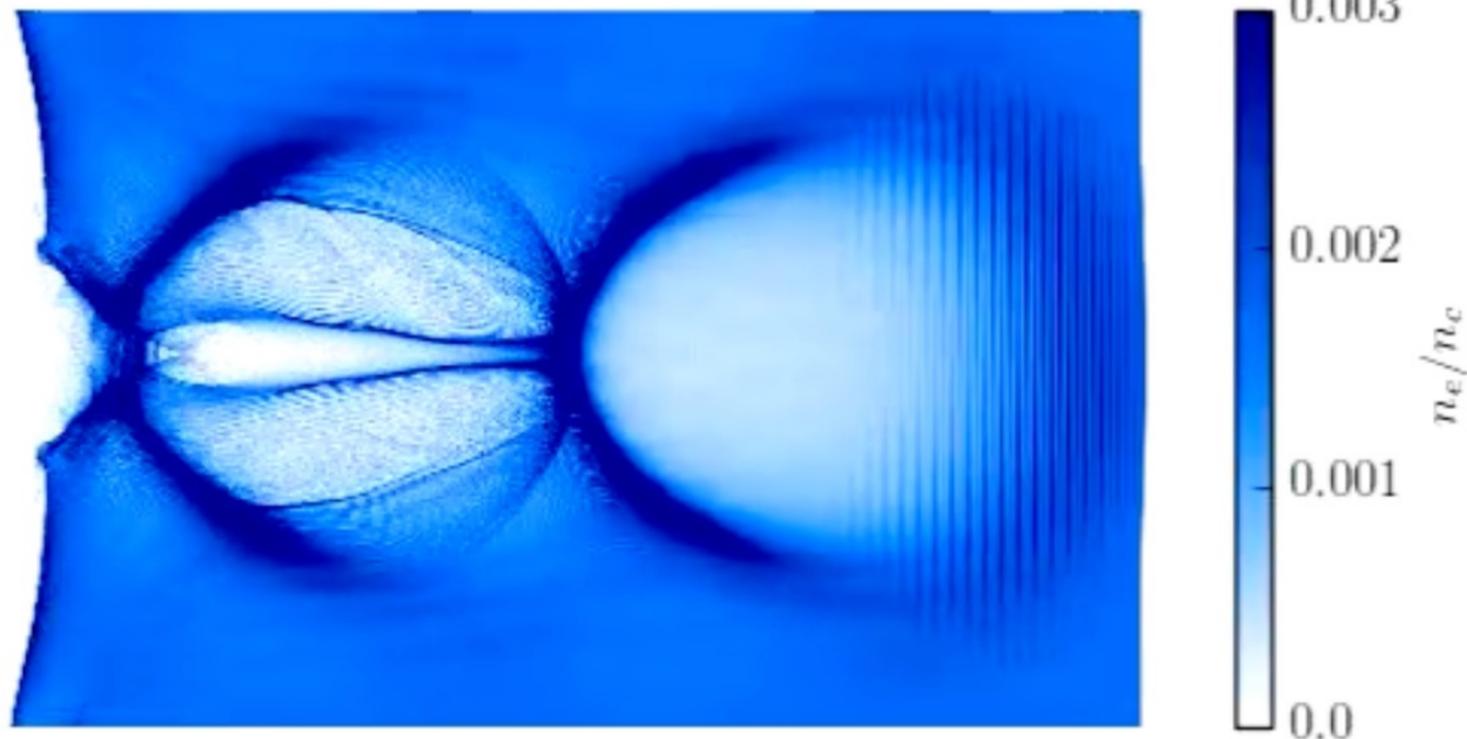
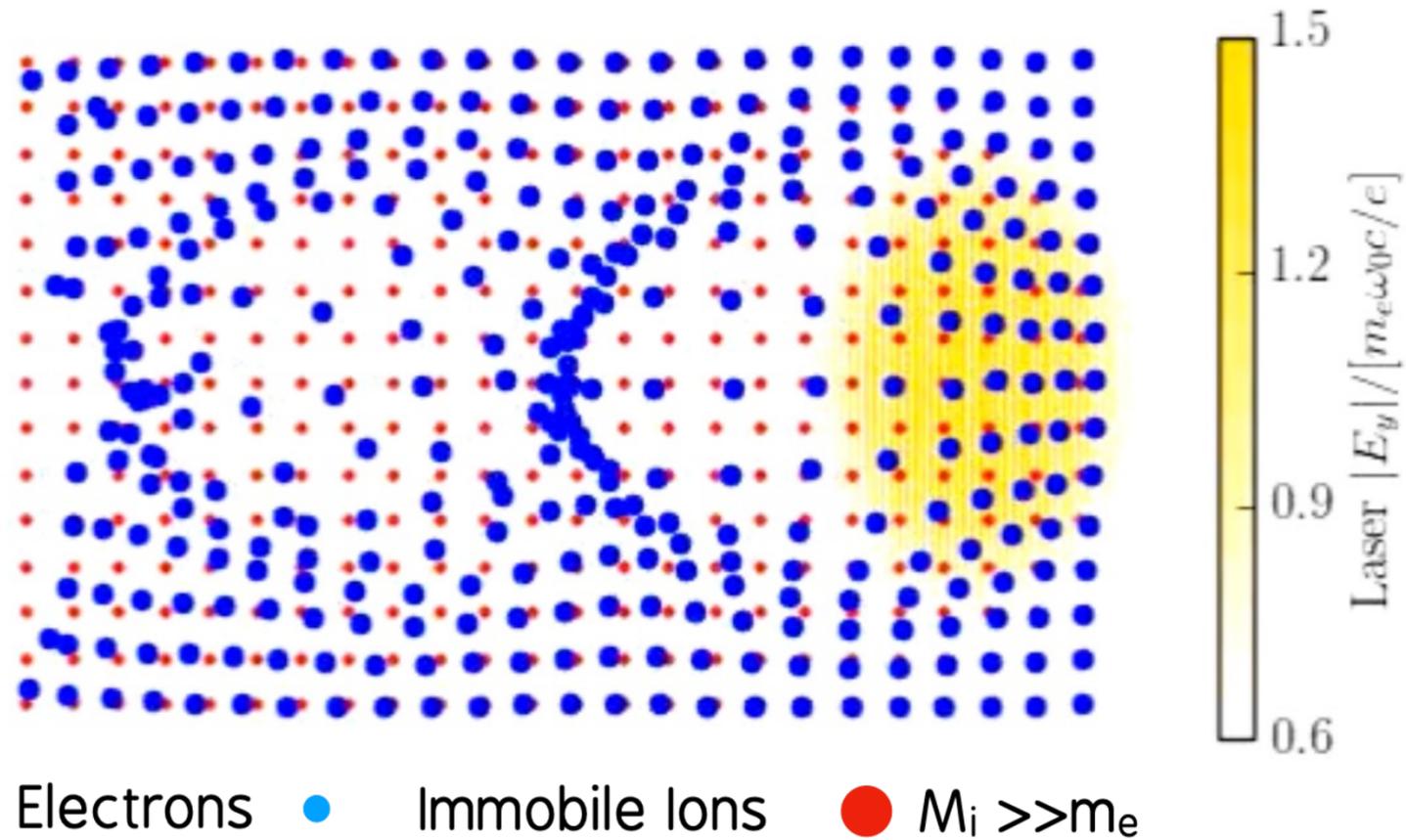
Electrons ● Immobile Ions ●  $M_i \gg m_e$

Relativistic electron beams injected **here** can be accelerated and focused



Positron acceleration is more challenging!

# Quick introduction to Laser Wakefield Acceleration(LWFA)



## Advantages:

Compact acceleration mechanism

## 3 Main LWFA Design Challenges:

- Do not spoil the electron beam quality, just enough to keep it usable for your application (stability is most welcome)
- Accelerate it until you reach your target energy (10 TeV for this design study)
- Keep it globally smaller and more efficient than a conventional accelerator

# So why do we need multiple plasma stages?

## Main physical limits to energy gain in LWFA:

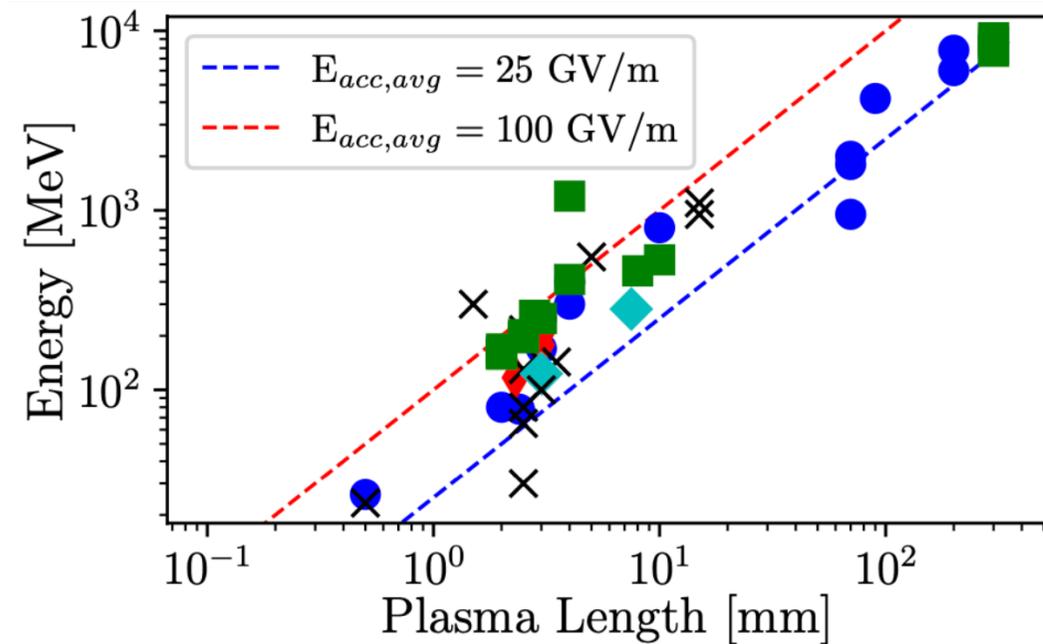
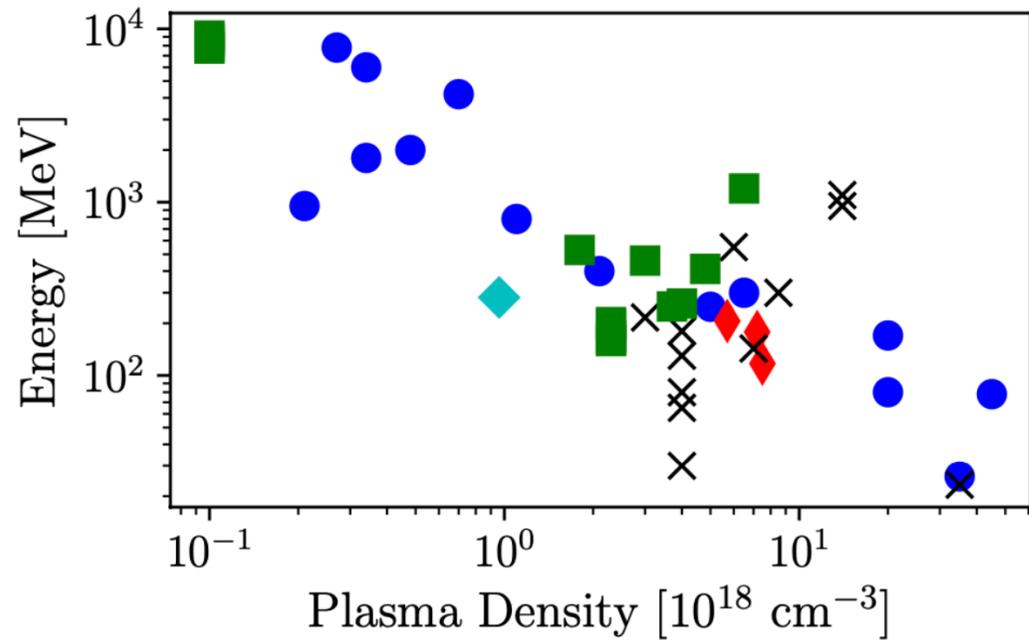
- Laser diffraction length → use laser guiding
- Laser energy depletion length → working near to this length is bad for beam quality
- Electron dephasing length → This is the real limit in cases for high beam quality

## Reason inferred from literature:

The best combinations of laser-plasma parameters for electron injection in plasma waves are not the best ones to accelerate it to high energies

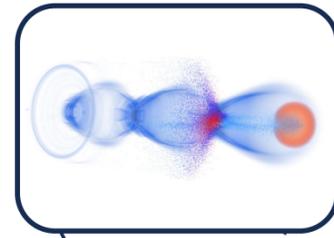
→ **Separate injection and acceleration stages**

# Example of 2 stage electron Laser Wakefield Accelerator

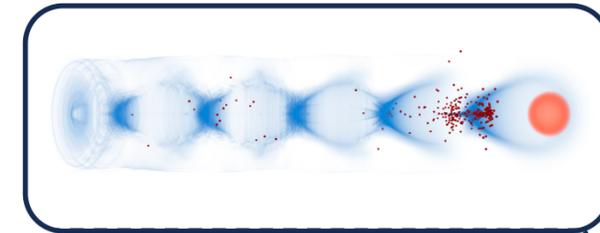


(Probably containing at least one plasma mirror and one plasma lens)

Laser pulse #1



Laser pulse #2



Interface between plasma stages

Plasma stage #1  
~ a few mm

Plasma stage #2  
~ 1-10 cm

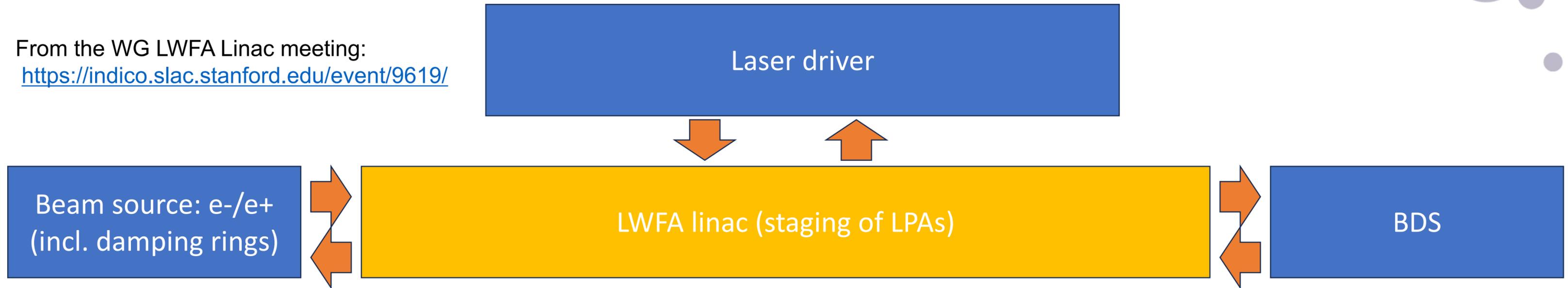
Propagation direction

**Note:**

the first LWFA stage may be substituted with a conventional photoinjector

# Scope of LWFA linac WG (and synergies with other WGs)

From the WG LWFA Linac meeting:  
<https://indico.slac.stanford.edu/event/9619/>



## LWFA linac WG:

- Accelerate “acceptable electron and positron beams” from the beam source to the BDS in a compact and cost-effective manner  
“acceptable beams” → determined as compromise between source, BDS, laser driver, and linac capabilities
- Identify key challenges (e.g., quality-preserving staging, positrons, etc.)
- Perform reviews of different technologies (i.e., what LWFA regime?)
- Develop metrics\* (i.e., how well does a given technology perform?)
  - Evaluate maturity of technology
  - Maximize acceptable particles delivered to BDS / Power consumption
  - Minimize linac footprint
  - .....

\* Same as metrics for PWFA linac

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# Electron sources from LWFA: Simultaneous optimization of multiple parameters

- >100 pC
- <1 % energy spread
- Energy > ?
- Emittance <~ 0.1 - 1 mmrad?
- Requirement on shape, e.g. flat beams?
- Requirement on current profile for beam loading?

## Should we use a LWFA e- source or an externally injected beam?

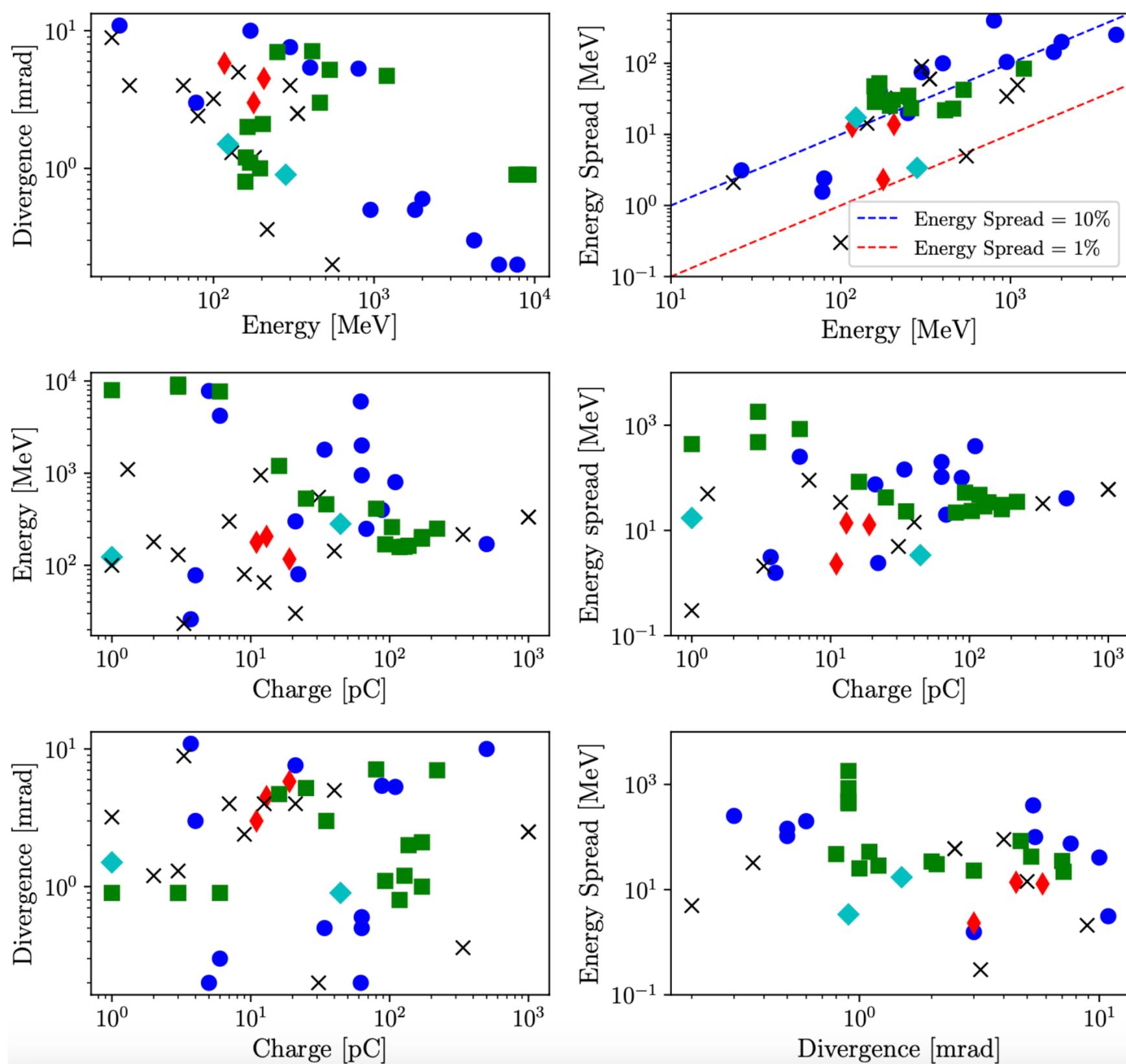


Figure 1.8: Correlations between the beam parameters extracted from selected publications from the literature. The different markers denote different injection techniques: (●) self-injection [29–31, 34–40]; (◆) colliding pulse injection [41, 42]; (×) tailored-density injection (including down-ramp injection and shock injection) [34, 43–49]; (■) ionization Injection [38, 50–54]; (◆) ionization Injection assisted by tailored-density [55, 56]. Please note that the definition of the electron beam

# A self-guided stage operating in the bubble regime providing high-gradient, high-charge, and high-efficiency acceleration has been designed

Schroeder et al.,  
JINST (2022)

Laser:  $U=50$  J,  $\lambda_0=1.0$   $\mu\text{m}$ ,  $a_0=4.5$ ,  $T_0=80$  fs,  $w_0=36$   $\mu\text{m}$   
Plasma:  $n_0=3.4 \times 10^{17}$   $\text{cm}^{-3}$ , stage length = 3.1 cm, linear taper (+74%)

$\Delta W_{\text{bunch}} = 3.08$  GeV (100 GV/m)  
 $Q_{\text{bunch}} = 1.3$  nC –  $L_{\text{bunch}} = 9.3$   $\mu\text{m}$  –  $I_{\text{bunch}} = 49$  kA  
Energy spread = 0.1%

Energy considerations:

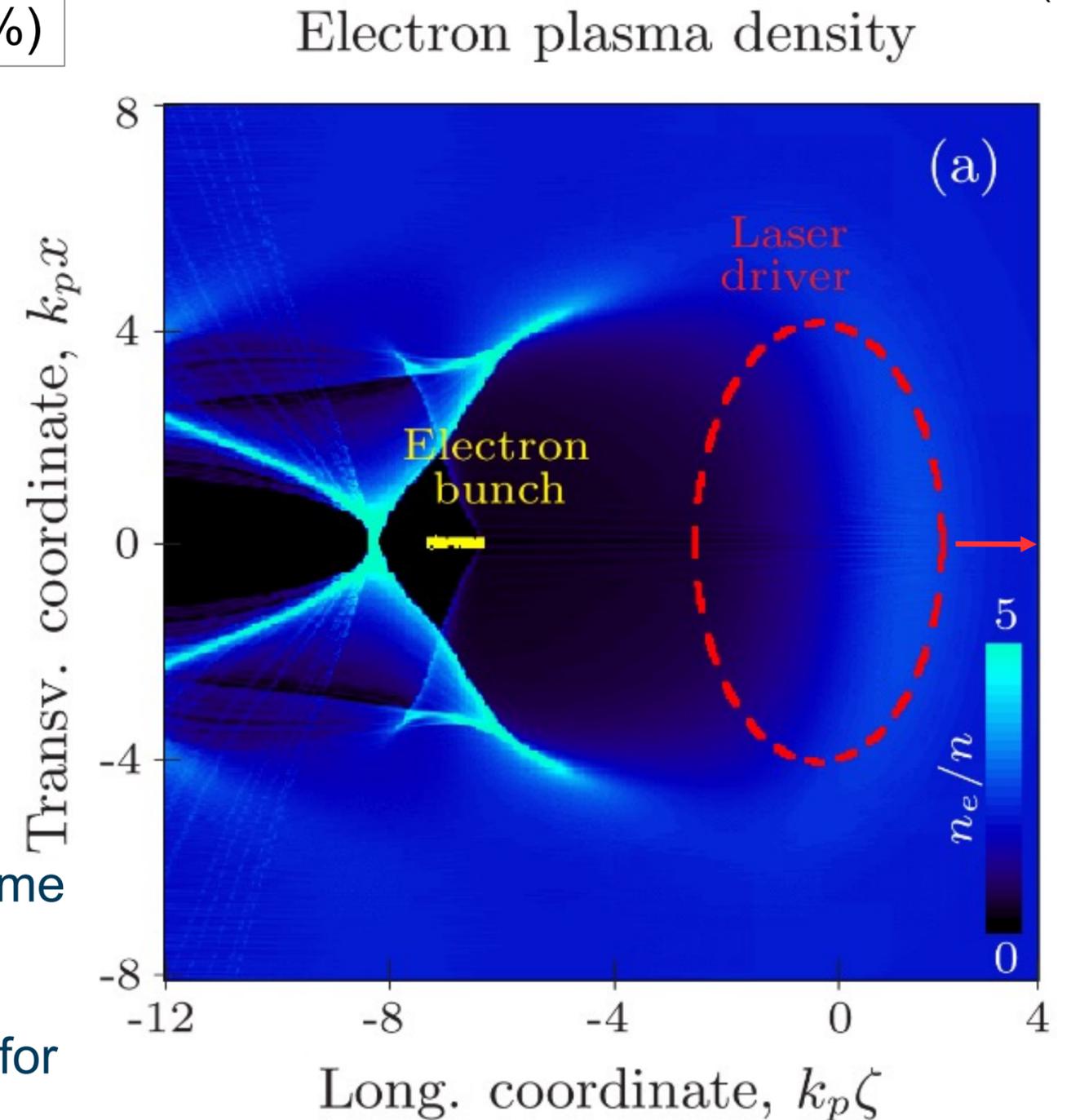
- Wake-to-bunch energy transfer = 40%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic

→ ~320 LPA stages/TeV

→ Not suitable for positron acceleration (different acceleration scheme required for positron arm, e.g., Diederichs et al., PRAB 2019)

→ Strong focusing yields small bunch size (~nm @ ~ TeV energies for collider-relevant emittances):

**challenging for inter-stage transport and alignment!**



# Example of LWFA stage operating in the quasi-linear regime providing high-gradient, high-charge, and high-efficiency

Schroeder et al.,  
NIMA (2016)

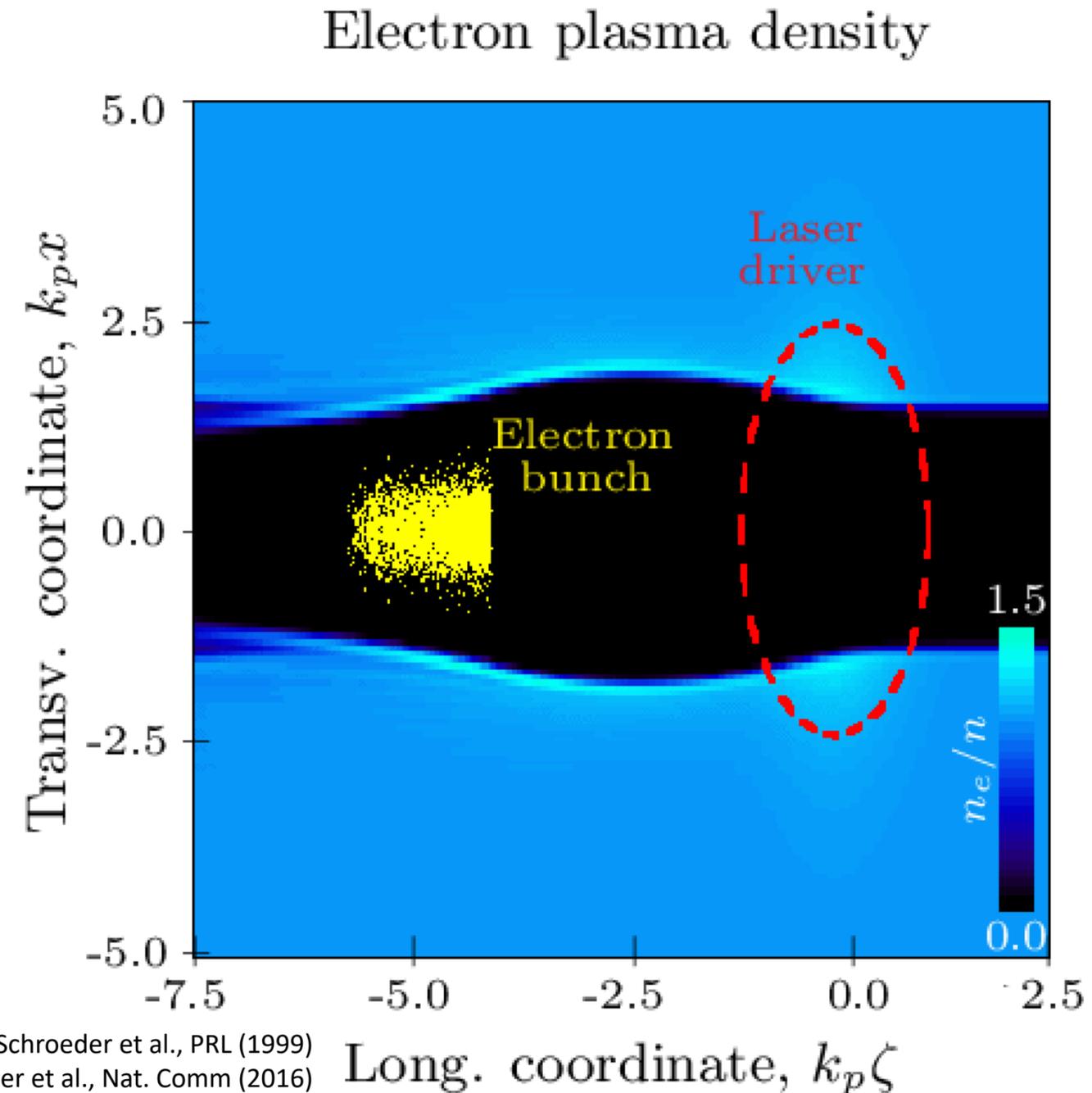
Laser:  $U=8.9$  J,  $\lambda_0=1.0$   $\mu\text{m}$ ,  $a_0=1.8$ ,  $T_0=73$  fs,  $w_0=41$   $\mu\text{m}$

Plasma (hollow channel):  $n_0=0.96 \times 10^{17}$   $\text{cm}^{-3}$ ,  $R_c=24$   $\mu\text{m}$ , stage length = 78 cm w/ optimal taper

$\Delta W_{\text{bunch}} = 5.05$  GeV (6.5 GV/m)  
 $Q_{\text{bunch}} = 0.24$  nC –  $L_{\text{bunch}} = 30$   $\mu\text{m}$  –  $I_{\text{bunch}} = 5$  kA  
 Energy spread = 0.8%

Energy considerations:

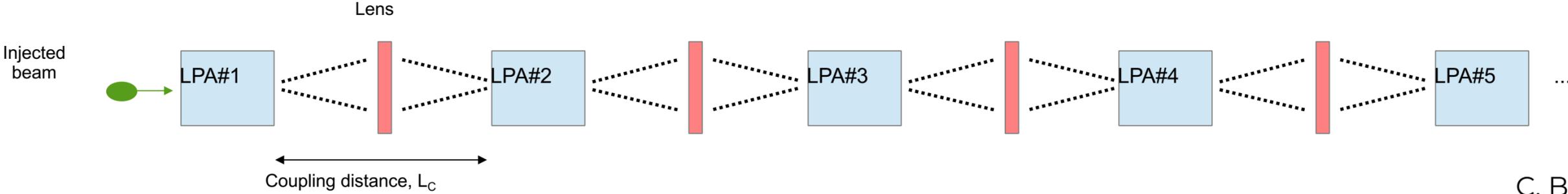
- Wake-to-bunch energy transfer = 68%
- Laser driver depletion = 20% → remaining laser driver energy could be returned to the grid with photovoltaic
- ~200 LPA stages/TeV + suitable for positron acceleration
- Negligible emittance growth from Coulomb scattering and no energy spread from synchrotron radiation
- Unstable w/o strong focusing: stabilization based on structured channel under investigation
- Hollow-channel allows for large (~ $\mu\text{m}$ -scale) beam size: **relaxed constraints on inter-stage transport and alignment!**



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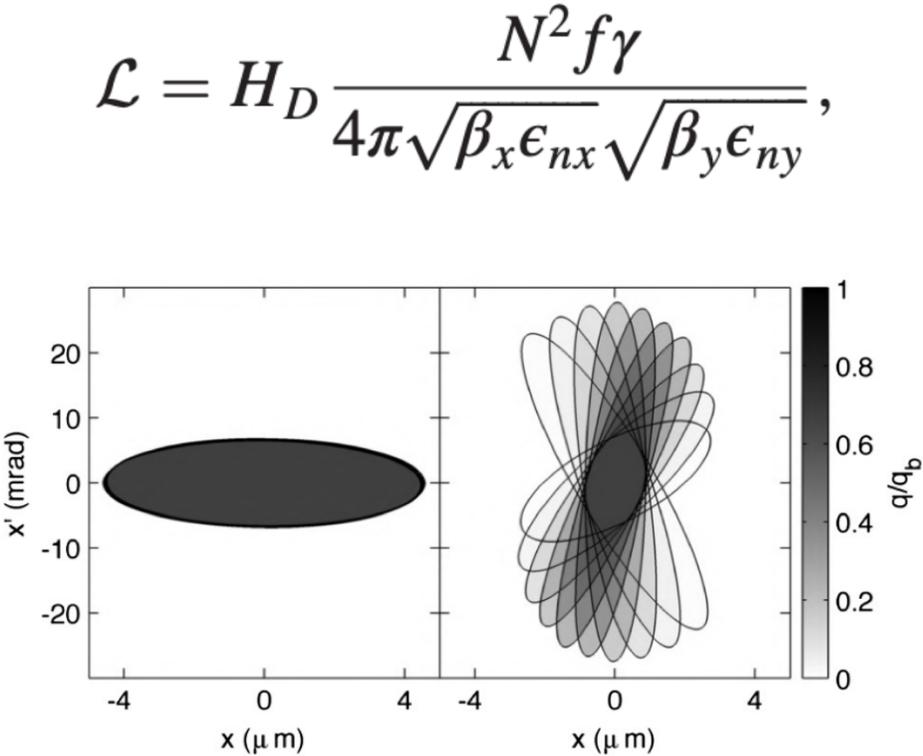
# Challenge: emittance growth due to chromaticity



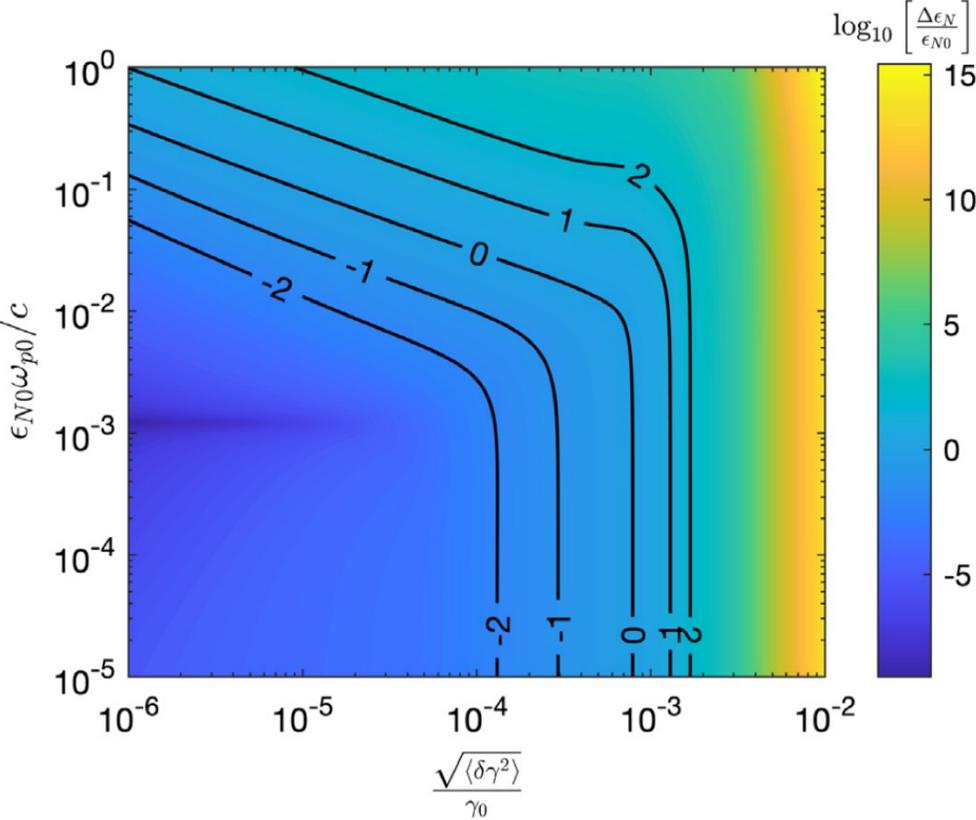
$$\Delta \epsilon \simeq \left( \frac{\epsilon_0}{\sigma_0} \right)^2 \frac{\sigma_\gamma}{\gamma_0} \frac{s}{\gamma_0}$$

C. Benedetti, WG LWFA Linac meeting:

<https://indico.slac.stanford.edu/event/9619/>

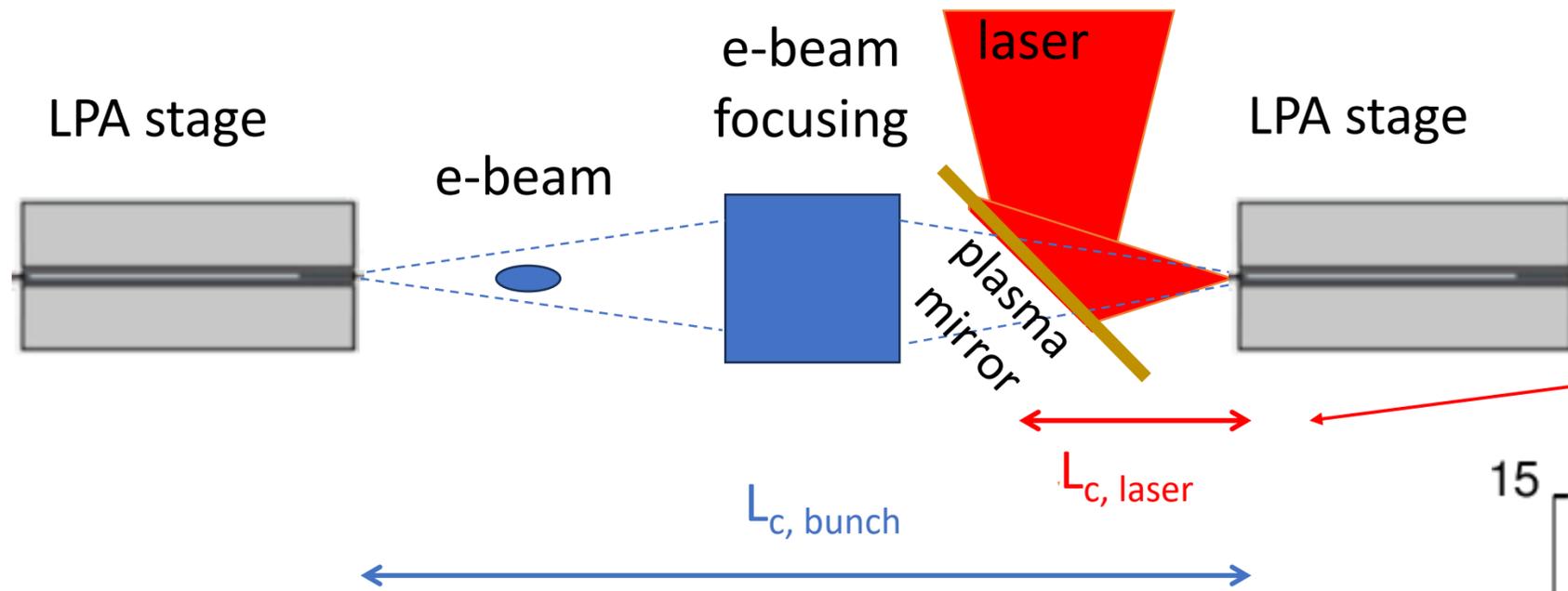


C. Lindstrøm, PRAB (2021)



A. G. R. Thomas and D. Seipt, PRAB (2022)

# Minimum coupling distance between stages determined by refocusing of tightly-focused bunch (not laser in-coupling)

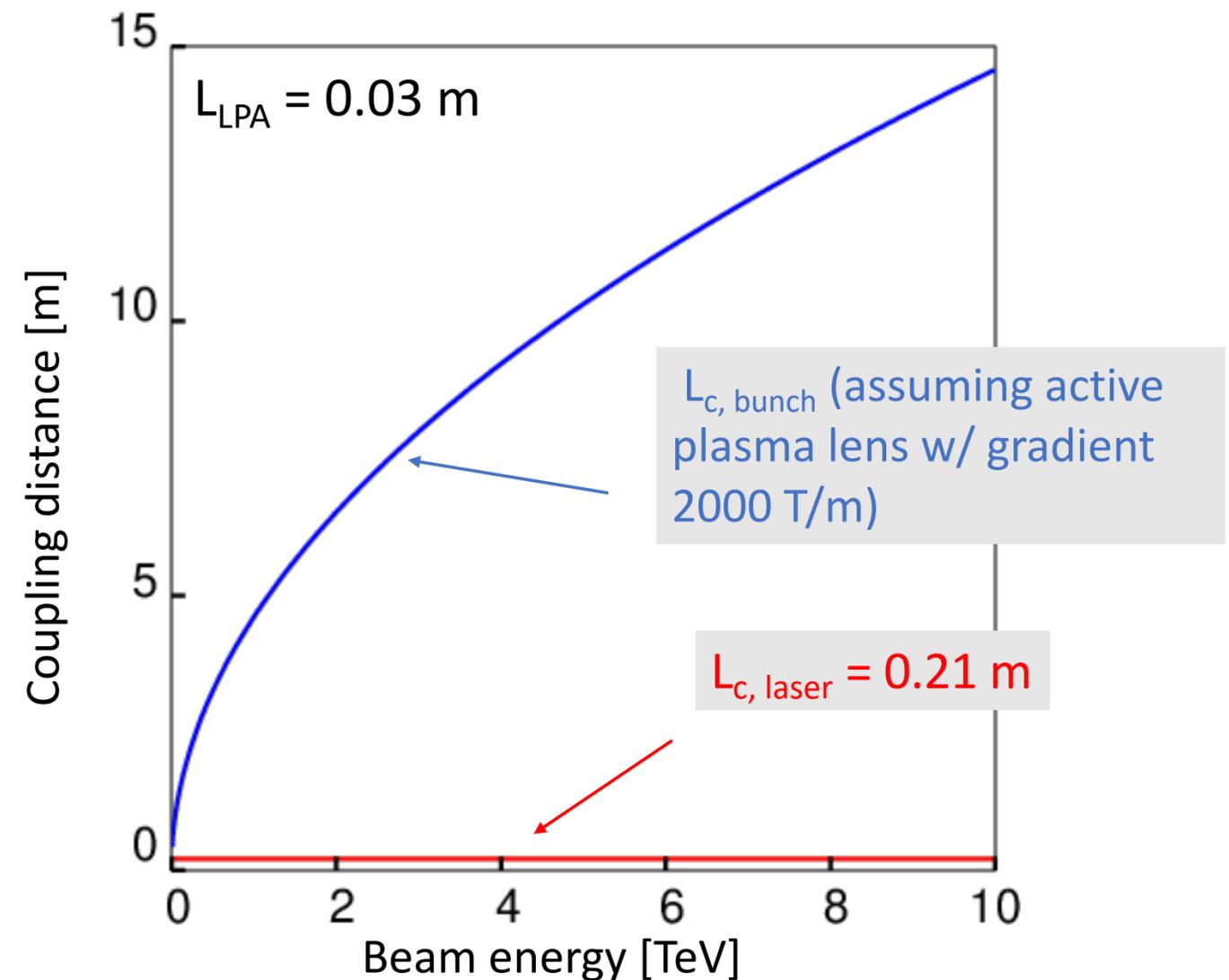


Determined by laser intensity  
@ plasma mirror ( $I_{pm} \sim 10^{16} \text{ W/cm}^2$ )

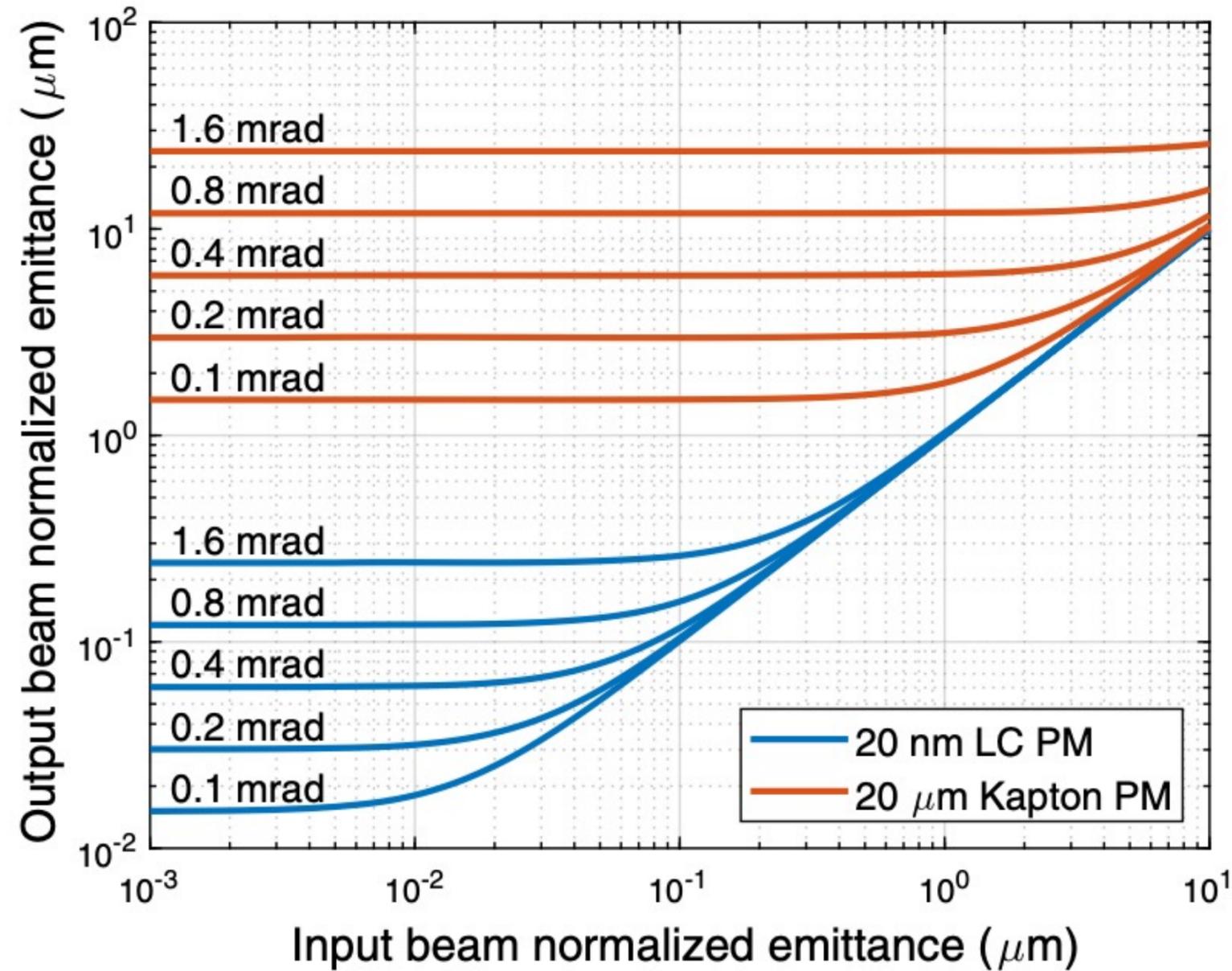
Determined by focusing gradient ( $\sim$  fixed to its max value) and beam energy

$$\rightarrow L_{c, \text{ bunch}} \sim \gamma^{1/2}$$

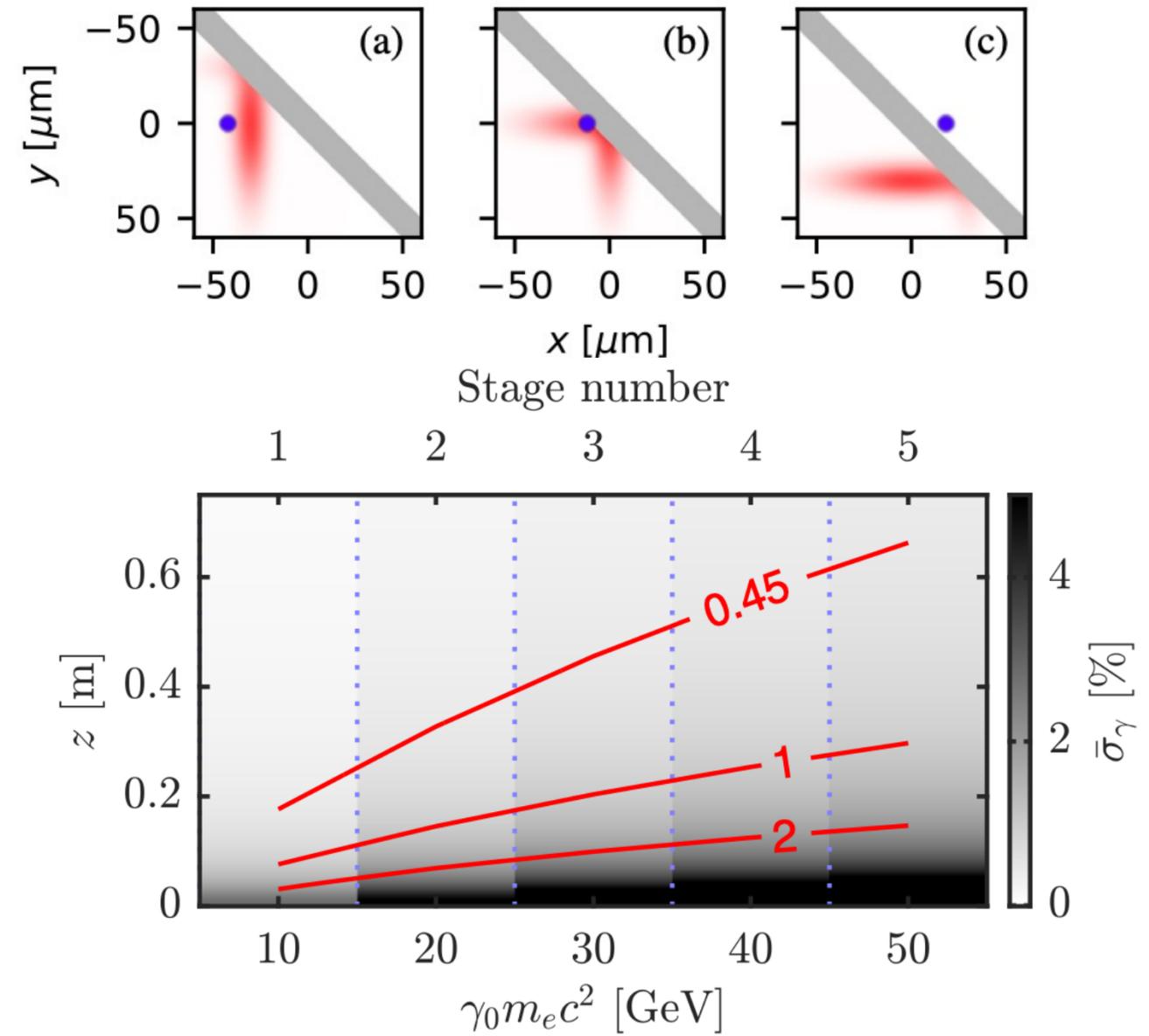
- Average gradient decreases with energy (LPA stages are further and further apart)
- Focusing optics always needed for tightly focused bunches (ballistic transport possible above  $>44 \text{ TeV}$ )



# Plasma mirrors (and the reflected laser) affect the beam quality



A. Zingale et al, PRAB (2021)  
 N. B. Reid, J. Appl. Phys. (1991)



M. J. V. Streeter, Z. Najmudin, PRAB (2020)

# Outline

- Why Staging?
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# Plasma component challenges (a few)

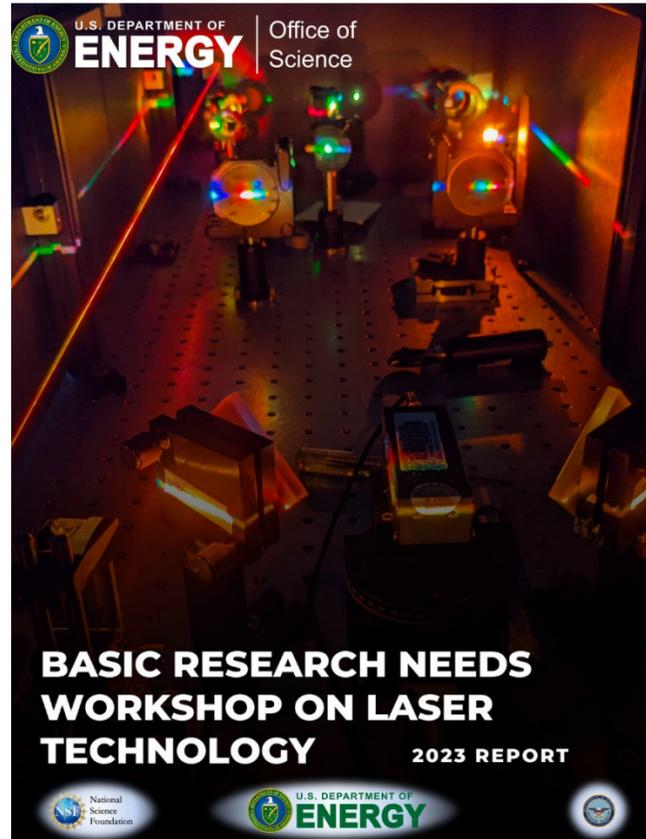
- **Neutral gas gas targets (e.g. gas jets, gas cells...)**
  - Functioning at high repetition rate
  - Extending their resistance to Joule-level lasers
  - Stabilizing gas density profiles (requires further development of diagnostics)
  - Recovery of gas for sustainability
- **Guiding components (e.g. waveguides, HOFI)**
  - increased laser stability
  - improved plasma density tailoring (requires further development of diagnostics)
  - further improvements in electron beam quality
- **Plasma mirrors**
  - scalability to high-repetition rates
  - Optimization of their geometry and positioning
  - vacuum integration considerations
  - deleterious effects on the transmitted electron beams

From EuPRAXIA WP 10 and collaborators,  
*Technical Status Report on Plasma Components  
and Systems in the context of EuPRAXIA*  
<https://arxiv.org/abs/2412.16910>



# Laser Driver requirements

## Basic Research Need Workshop on Laser Technology, Report 2023



|                                | Type I: High-repetition-rate laser | Type II: High-average-power laser | Type III: Few-cycle laser | Type IV: Ultrahigh intensity laser   |
|--------------------------------|------------------------------------|-----------------------------------|---------------------------|--------------------------------------|
| Pulse peak power               | > 1 kW                             | 10 – 300 TW                       | 1 – 10 TW                 | 10 – 100 PW                          |
| Wavelength                     | 0.8 – 10 $\mu\text{m}$             | 0.5 – 10 $\mu\text{m}$            | 2 – 5 $\mu\text{m}$       | 0.8 – 2 $\mu\text{m}$                |
| Pulse Energy                   | NC                                 | 1 – 10 J                          | NC                        | 1 – 10 kJ                            |
| Pulse Length                   | NC                                 | 30 – 100 fs*                      | few-cycle                 | 30 – 300 fs                          |
| Repetition Rate                | 0.1 – 1 GHz                        | 1 – > 10 kHz                      | > 100 kHz                 | 0.1 – 10 Hz                          |
| Average Power                  | 10 – 100 W                         | 1 – > 100 kW                      | 50 – 500 W                | NC                                   |
| Energy Stability               | < 1%                               | < 1%                              | < 0.5%                    | 1%                                   |
| Beam Quality                   | Strehl > 0.95                      | Strehl > 0.95                     | Strehl > 0.95             | Strehl > 0.9                         |
| Wall-plug Efficiency           | NC                                 | > 10%                             | NC                        | NC                                   |
| Pre-pulse contrast             | NC                                 | > $10^5$                          | NC                        | > $10^{12}$<br>@ $10^{21}$ intensity |
| Time window for pre-pulse      | NC                                 | ns-ps                             | NC                        | ns-ps                                |
| Phase stability, if CEP locked | < 100 mrad                         | Optional,<br>< 300 mrad           | < 100 mrad                | NC                                   |
| Pointing stability             | NC                                 | < 0.1 $\mu\text{rad}$             | NC                        | NC                                   |
| Bandwidth                      | NC                                 | near FTL                          | NC                        | NC                                   |

\* Pulse length applies to 1–2-micron wavelengths, with scaled durations for other wavelengths.

Table 1. Target performance for the laser types discussed in the priority research directions. Common

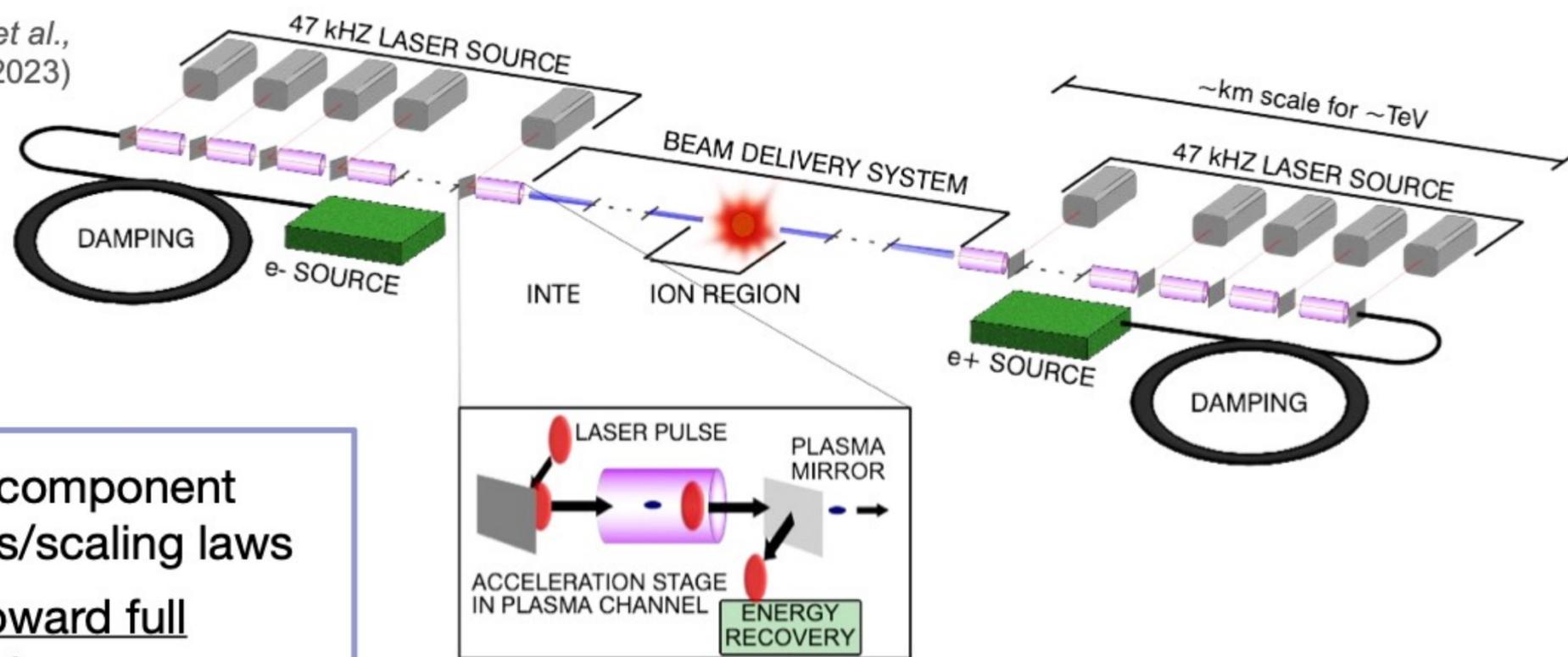
**Note:**  
Collider requirements may be more demanding

# Conceptual physics considerations determine parameter ranges

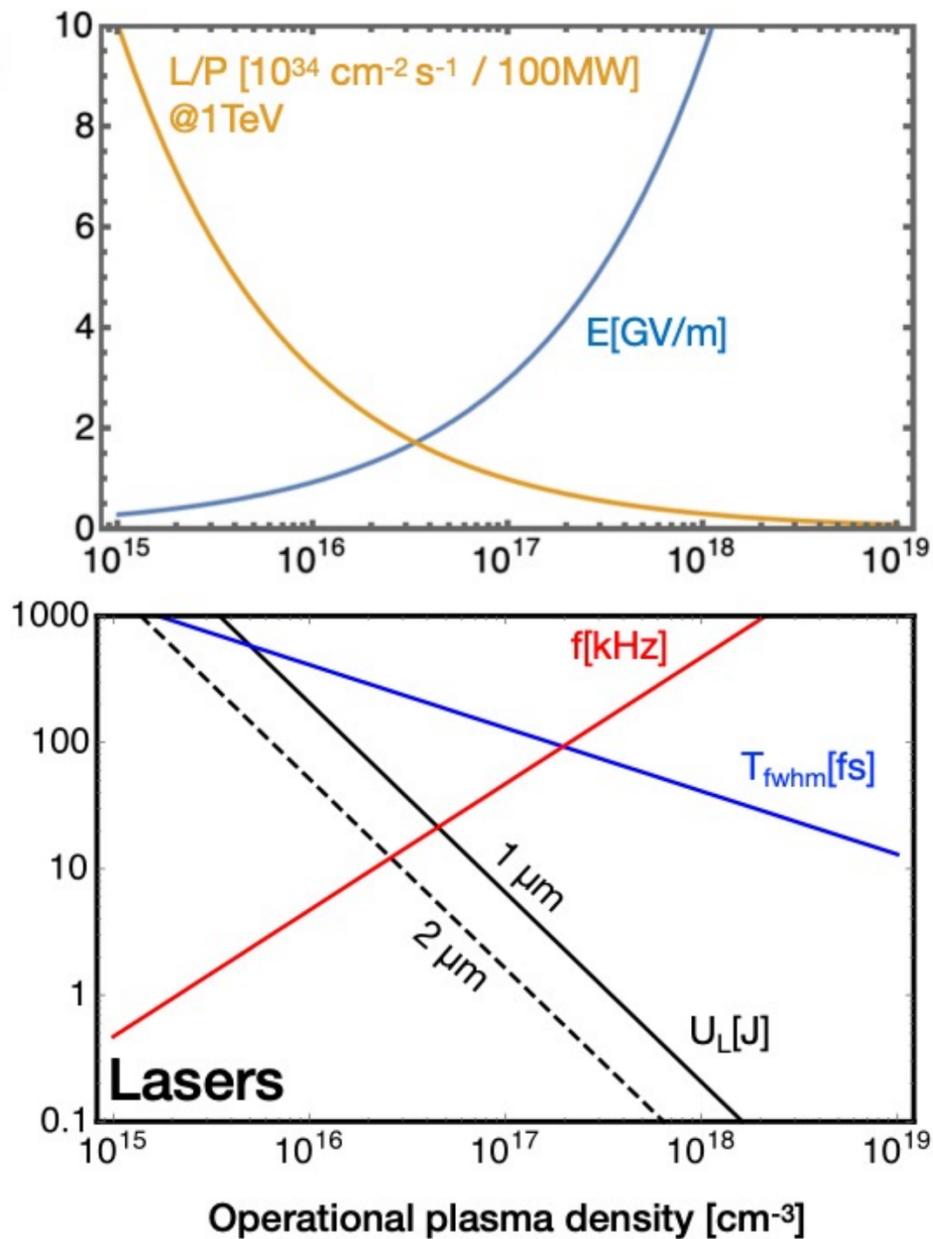
## Basic design choices driven by system optimization

- Minimizing linac length (gradient  $> \text{GV/m}$ )
  - Maximizing **energy efficiency** (luminosity/power)
  - Plasma density sets bunch charge (also limited by Beamstrahlung),  
luminosity requires **repetition rate**
- } Restricts **plasma density range**,  
energy gain per stage  $\rightarrow$  **staging**

C.B. Schroeder *et al.*,  
JINST 18 T06001 (2023)



- Based on component simulations/scaling laws
- Working toward full self-consistency



## Conceptual collider parameter sets derived during Snowmass

T. Barklow *et al.*, JINST 18 P09022 (2023);  
C.B. Schroeder *et al.*, JINST 18 T06001 (2023)

# Capability gap in laser driver technology exists

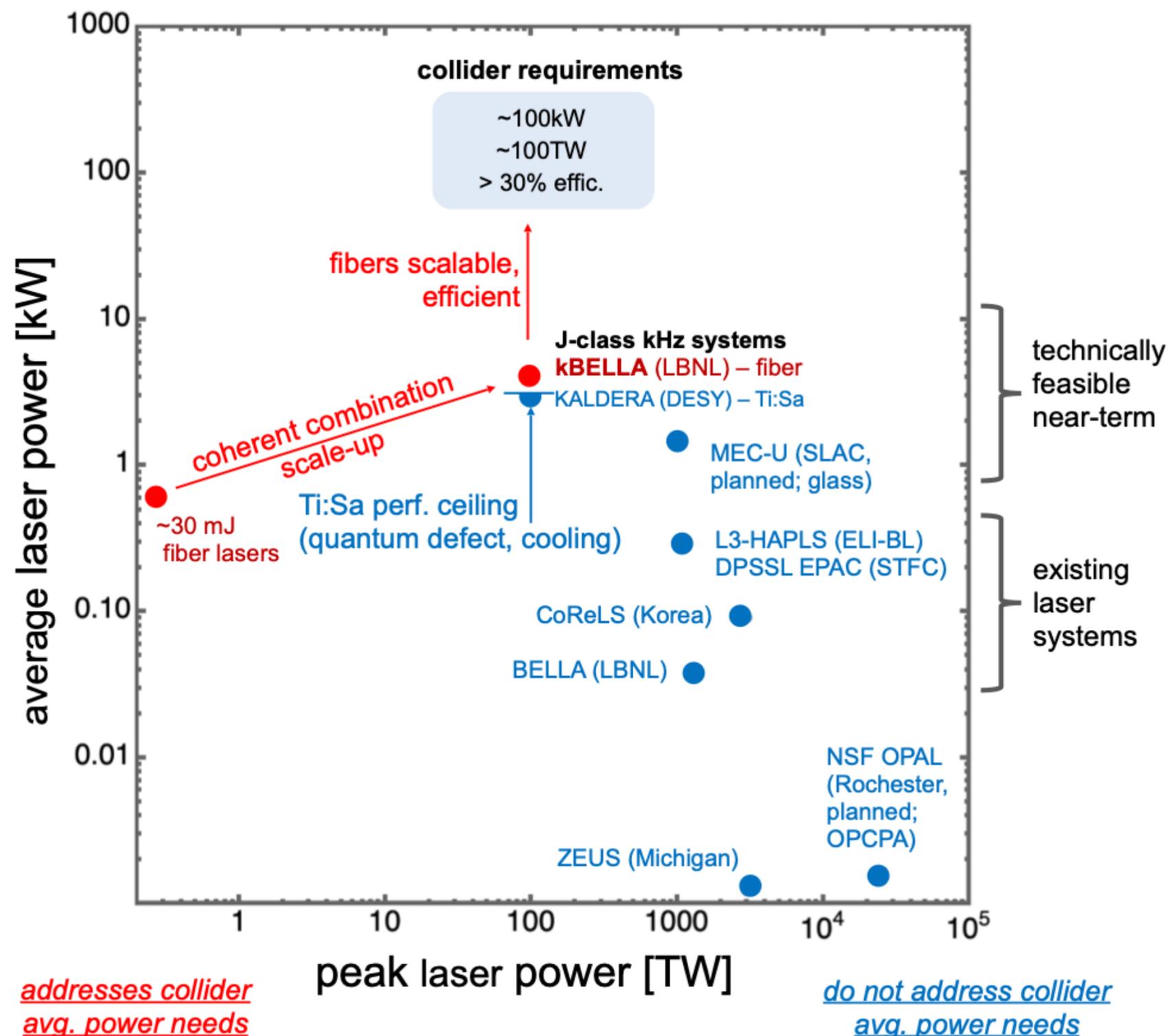
## Novel laser technology needed to fulfill collider demands

in repetition rate (Hz  $\rightarrow$  ~10s kHz), efficiency (0.1%  $\rightarrow$  10s %)

Promising emerging laser architectures

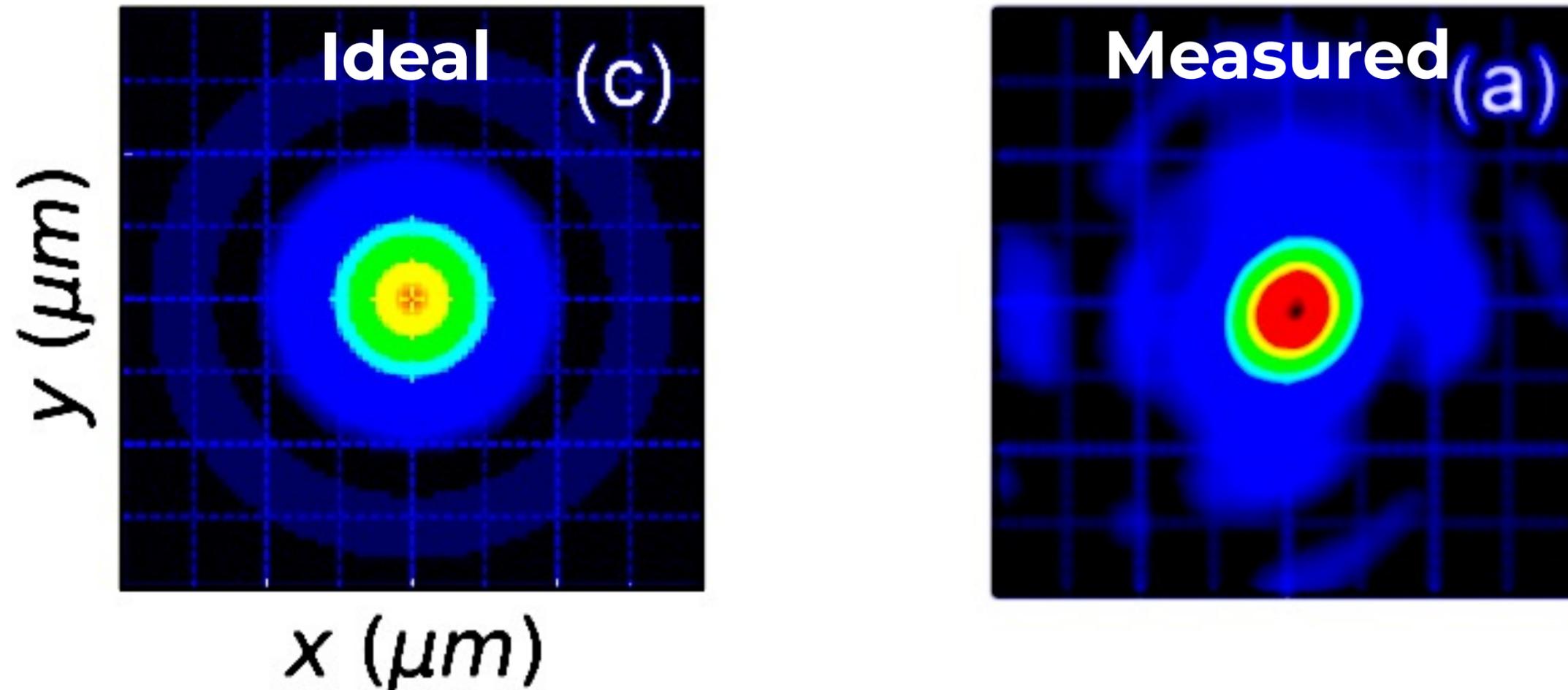
- Cryo-cooled **Yb:YAG** ( $\lambda = 1 \mu\text{m}$ ), R&D at CSU
- **Tm:YLF** ( $\lambda = 1.9 \mu\text{m}$ ), R&D at LLNL
- **Coherent combination of fiber lasers** ( $\lambda = 1 \mu\text{m}$ ), R&D at Michigan, LBNL, Jena, École Polytechnique

**Example: kBELLA** addresses the driver rate and efficiency gap



# High-intensity laser pulse for LWFA are asymmetric

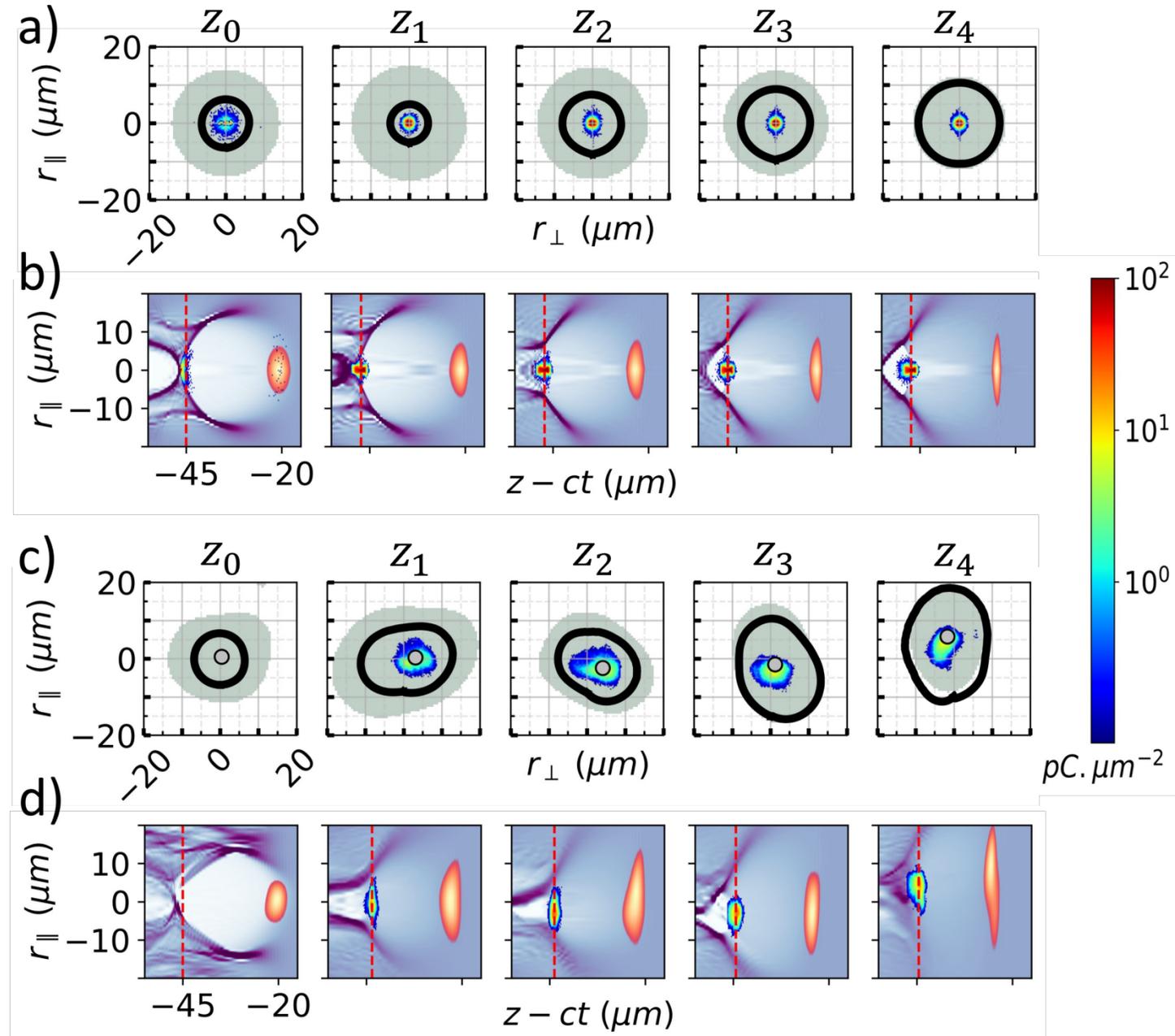
Laser fluence on transverse planes  
(no info on the space-temporal couplings)



I. Moulanier et al.,  
J. Opt. Soc. Am. B 40(9), 2450-2461 (2023))

# Plasma waves and accelerated electrons follow the evolution of the reconstructed asymmetric laser pulse

**Gaussian laser pulse**  
**Reconstructed laser pulse**



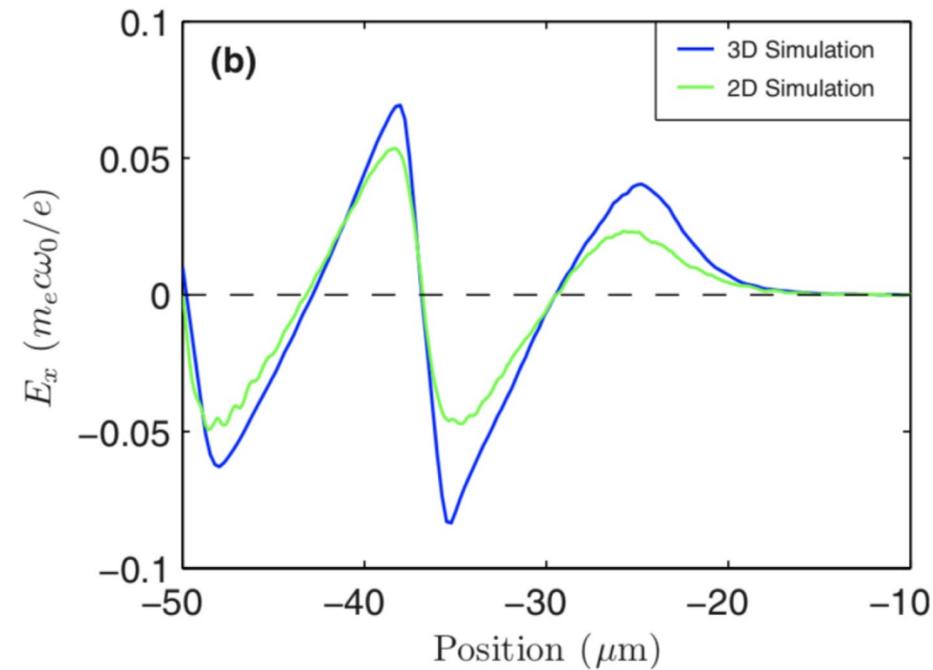
I. Moulanier et al.,  
 Journal of Physics Conf. Series,  
 Proceedings of the 6<sup>th</sup> EAAC (2024)

# Outline

- Why Staging?
- Sources and acceleration of electron beams
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- **Simulations**

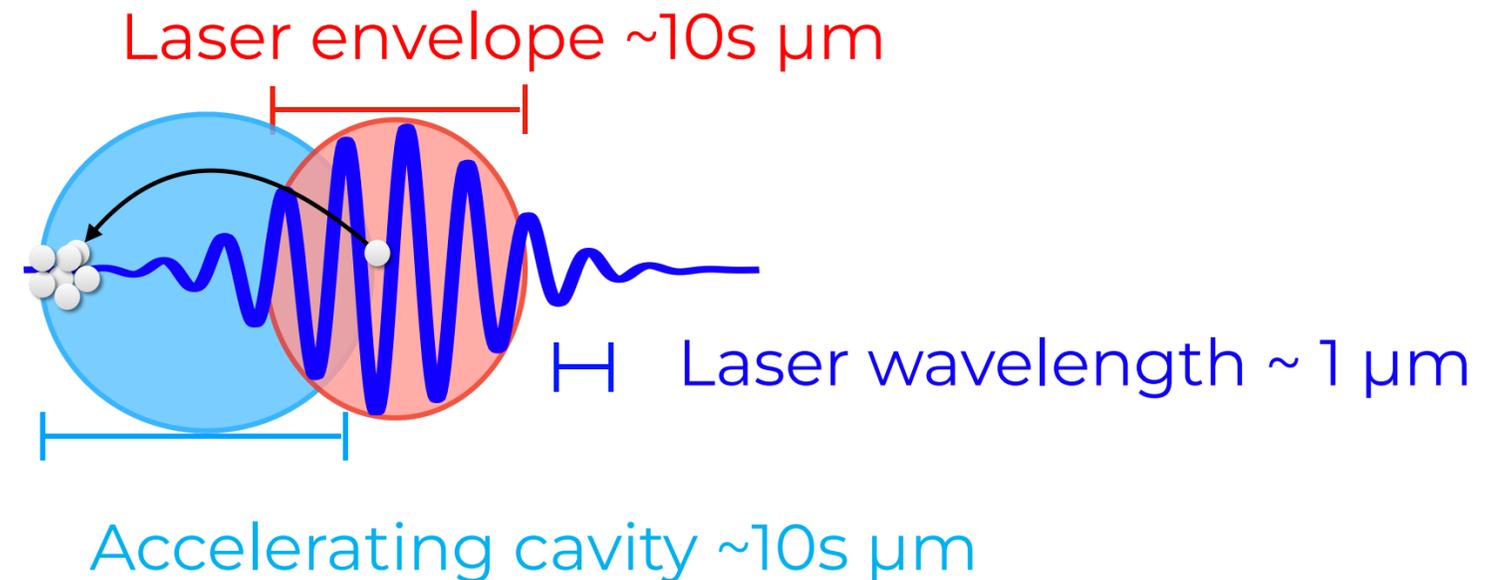
# LWFA Simulations: why are they resource-consuming?

- **“Curse of dimensionality”**: 3D-like accuracy is needed



X. Davoine et al., Phys. Plasmas 15, 113102 (2008)

- **Minimum/Maximum scale disparity**:  
Laser wavelength  $\sim 1 \mu\text{m}$   
Plasma stage Length  $\sim 10\text{s mm, } 10\text{s cm, } 1 \text{ m}$



## “Problem size reduction” techniques:

Cylindrical geometry with azimuthal Fourier decomposition, Quasi-static approximation, time-averaged ponderomotive approximation, Lorentz boosted frame technique, hybrid fluid/kinetic models

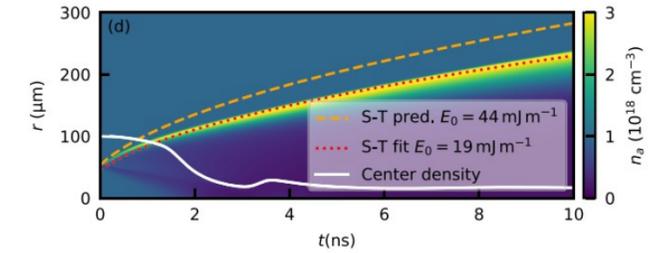
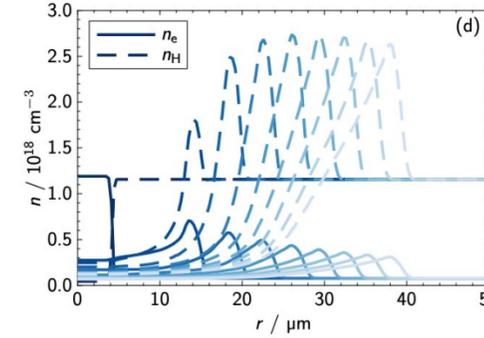
**Take-home message #1 for LWFA simulations:** check results with different codes and models

**Take-home message #2 for LWFA simulations:** in a LWFA collider, even “reduced” simulations will be expensive

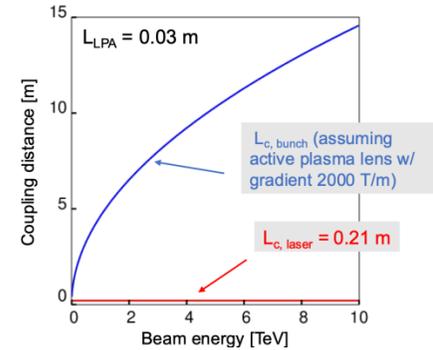
See also J. Vieira’s talk at ALEGRO 2023: <https://indico.cern.ch/event/1193719/contributions/5201954/>

# The LWFA part is not the only one we need to simulate!

- Plasma channel formation for laser guiding

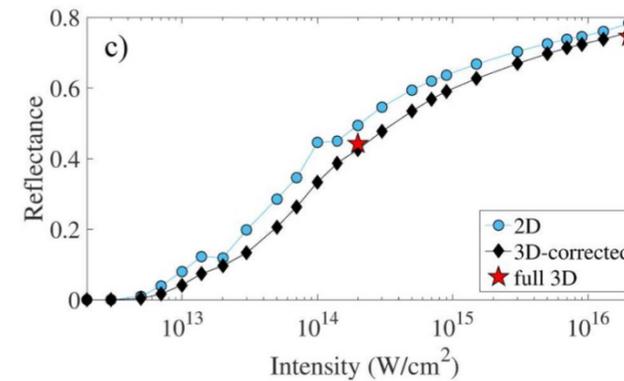


- Plasma lenses

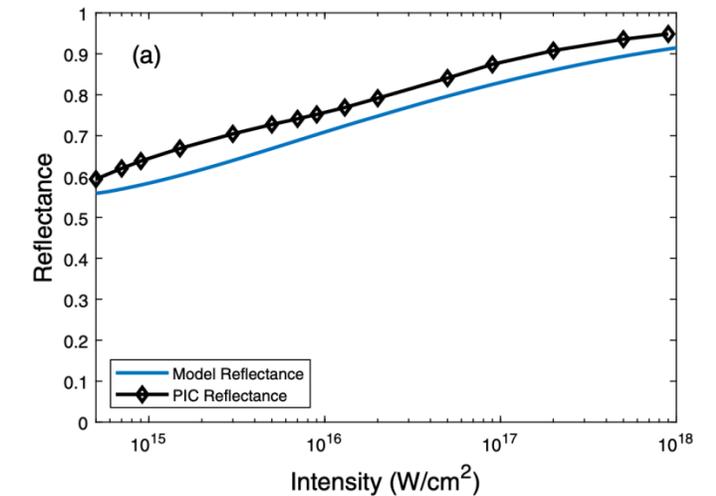


C. Benedetti, WG LWFA Linac Kickoff meeting

- Plasma mirrors (reflectivity, passage of electron beams, reflected laser-electron beam interaction at high energy, ...)



G. E. Cochran, Phys. Plasmas 2019

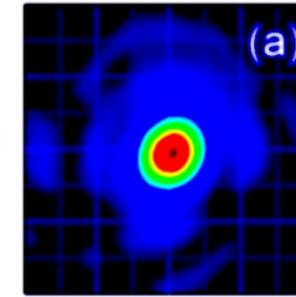


A. Zingale, PRAB 2021

- Energy dissipation and recovery

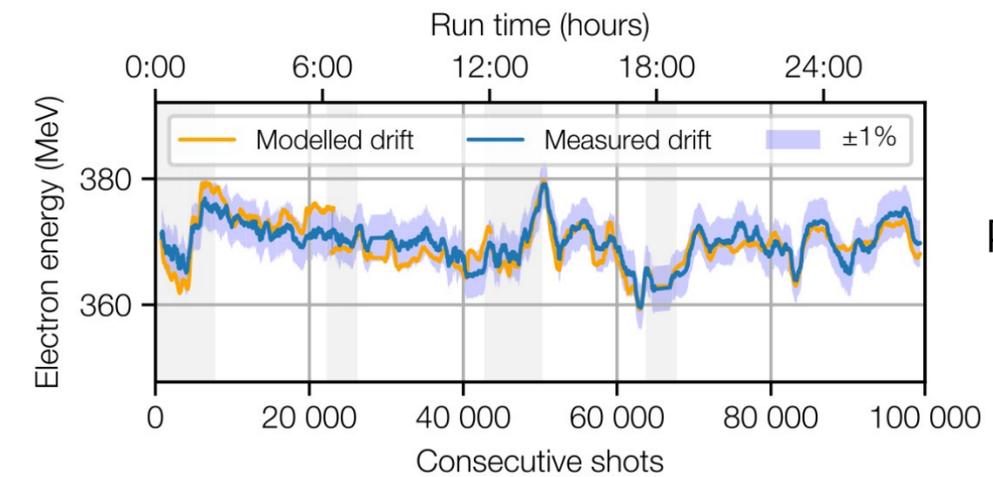
# Simulation of tolerances (not only for the LWFA part!)

- Asymmetric laser pulses? → need for laser field reconstruction



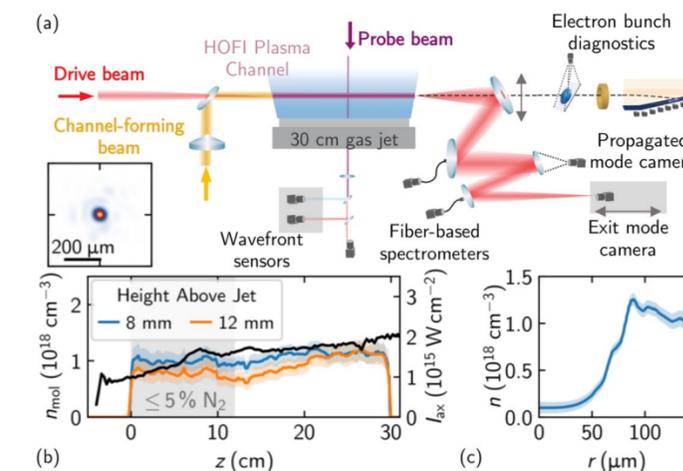
I. Moulanier et al.,  
JOSA B 2024

- Laser pointing instability, drifts in the laser parameters



A. Maier et al.,  
Phys. Rev. X 2020

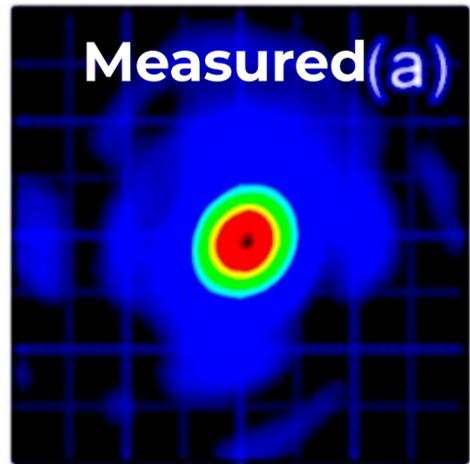
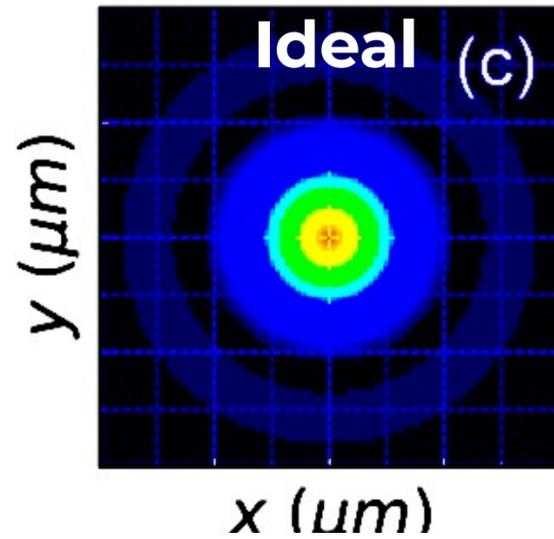
- High accuracy measurements of plasma density



A. Picksley et al.,  
Phys. Rev. Letter 2024

# Case study: LWFA simulations with laser pulses reconstructed from measurements yield more « realistic » results

Laser fluence on transverse planes  
(no info on the space-temporal couplings)



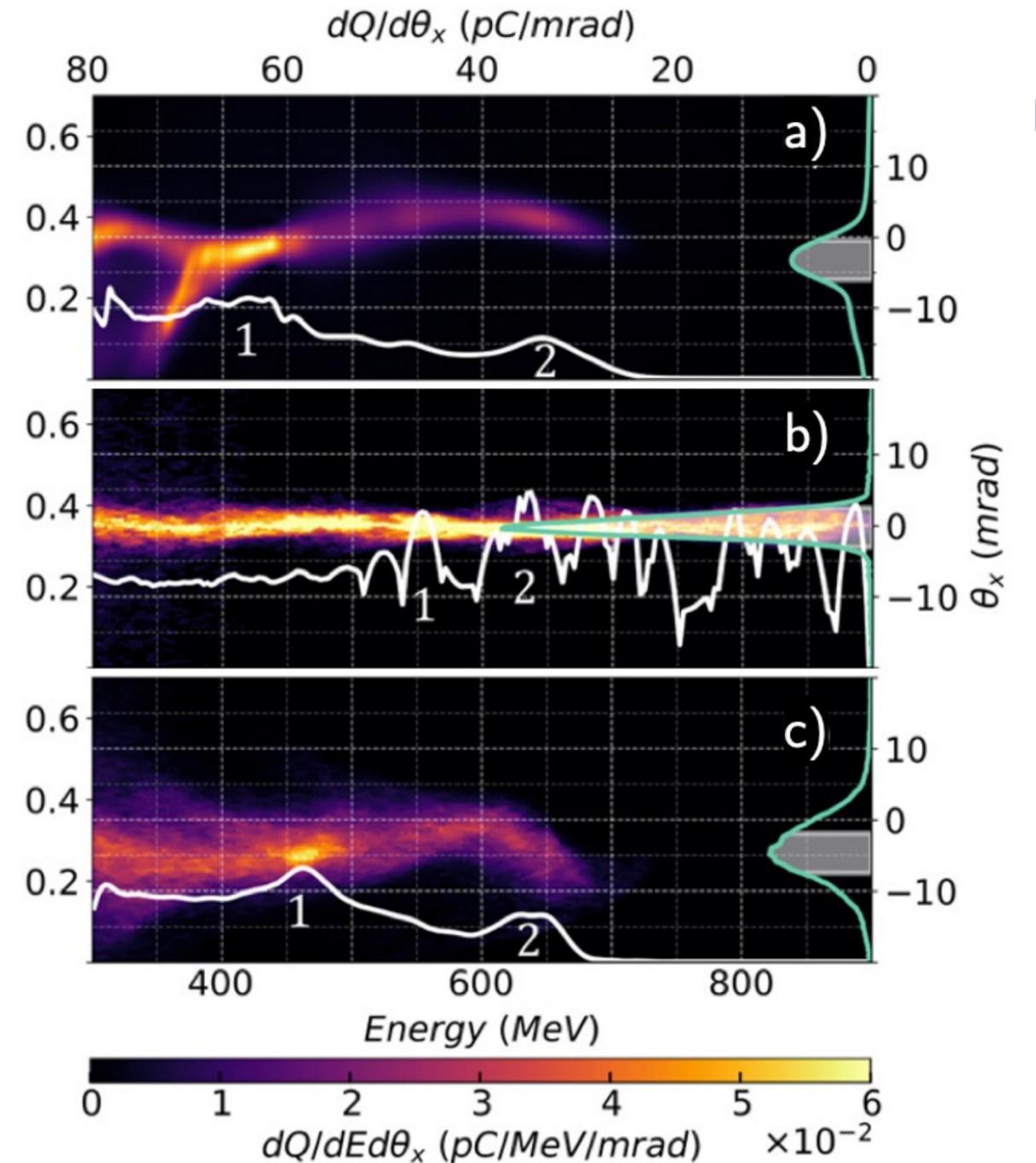
Measured  
Electron spectrum

Simulation with  
Gaussian laser

Simulation with  
reconstructed laser

I. Moulanier et al.,  
Physics of Plasmas 2023

I. Moulanier et al.,  
J. Opt. Soc. Am. B 40(9), 2450-2461 (2023))



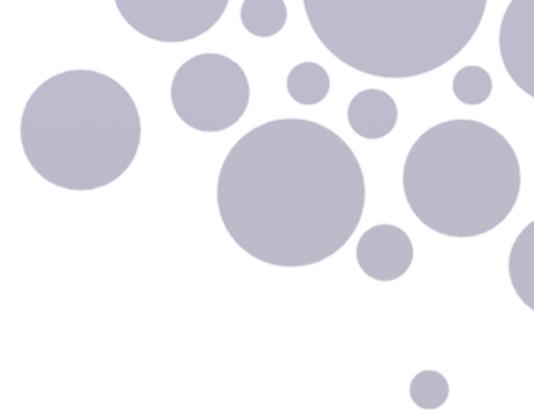
# Conclusions

- LWFA staging is unavoidable if we hope to reach 10 TeV
- Electron beam sources, beam delivery system, laser driver, staging, interfaces and simulation related activities will need to work closely for this design
- Technological developments and fundamental R&D will be required for all the accelerator components

# Recap of some LWFA linac challenges to be considered [and potential solutions (some requiring significant R&D)]

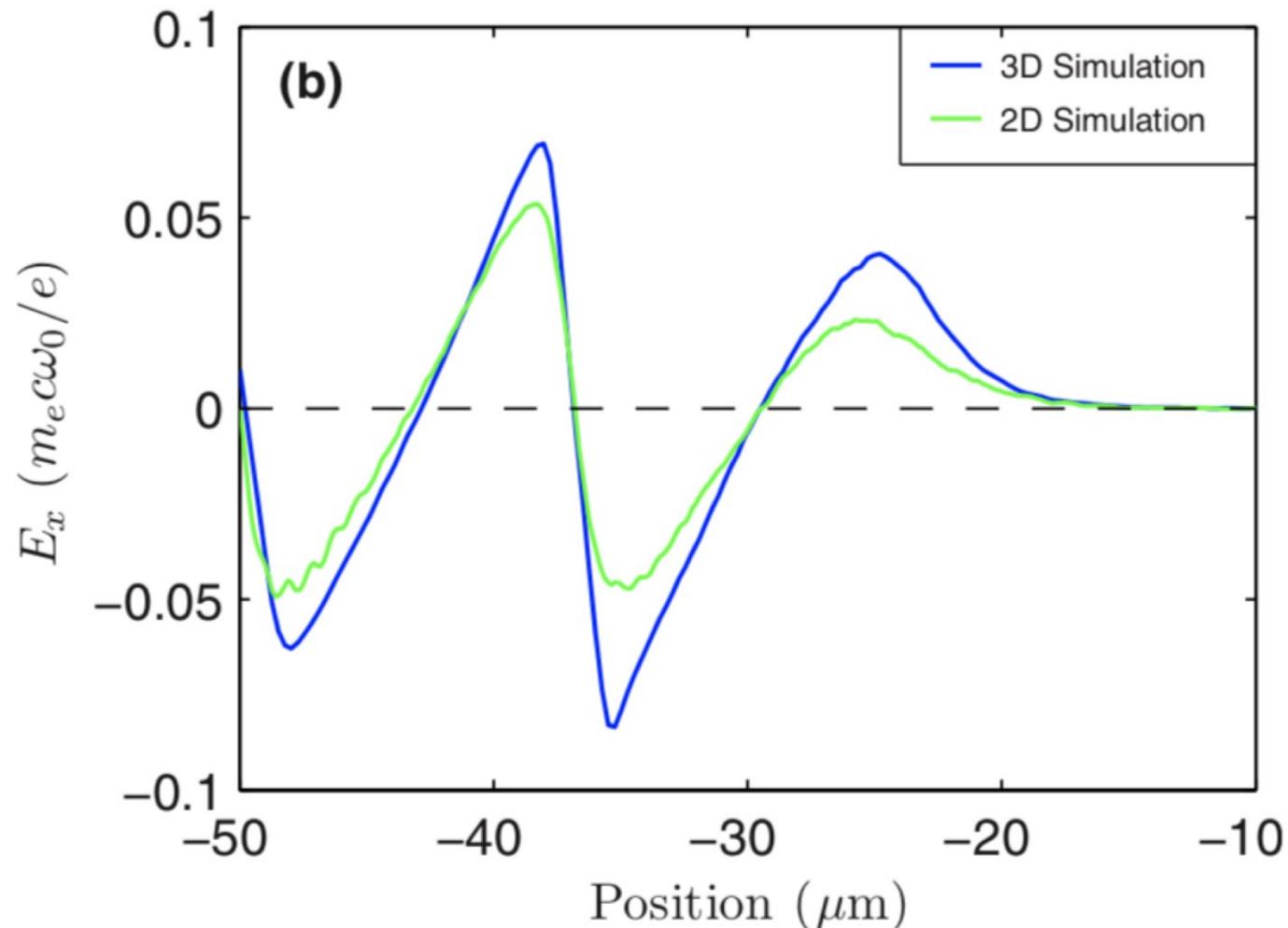
- **Laser diffraction**
  - Self-guiding in nonlinear regime
  - Guiding in pre-formed plasma channel
- **Laser-particle beam dephasing**
  - Plasma tapering
- **Laser depletion w/ high gradient**
  - Staging with compact driver in-coupling
- **Positron acceleration**
  - Use plasma columns/filaments
  - Use hollow channels
- **High laser-to-beam efficiency (w/ no energy spread growth)**
  - Shaped particle beams
  - Laser energy recovery
- **Heating of plasma**
  - Use an “energy recovery” pulse
- **High-average laser power**
  - Fiber laser combining
- **Scattering in plasma**
  - Strong plasma focusing
  - Use (near-)hollow channels
- **Emittance growth via ion motion**
  - Use (near-)hollow channel
  - Adiabatic, slice-by-slice, matching
- **Emittance mixing due to resonances**
  - Use hollow channel and round particle beams
- **Beamstrahlung mitigation**
  - Short bunches
- **Transverse beam instabilities**
  - Detune betatron freq. (e.g., ion motion or energy spread)
  - Stagger tuning
- **Alignment tolerances:**
  - Control beam size
- **Preserving beam quality in plasma mirror**
  - Use thin plasma mirror w/ hole
- **Control plasma channel properties**
  - Use OFI technique
- **Quality-preserving staging**
  - Use achromatic transport for beams
  - Use hollow channels
- **Increase efficiency**
  - Use energy recovery
- **Beam polarization**
- **Beam-deflected laser interaction**
  - Use properly shaped plasma mirror
  - Acceleration in later plasma period
- .....

# Additional slides



# LWFA simulations require considerable resources

2D cartesian simulations:  
Not accurate enough



X. Davoine et al., Phys. Plasmas 15, 113102 (2008)

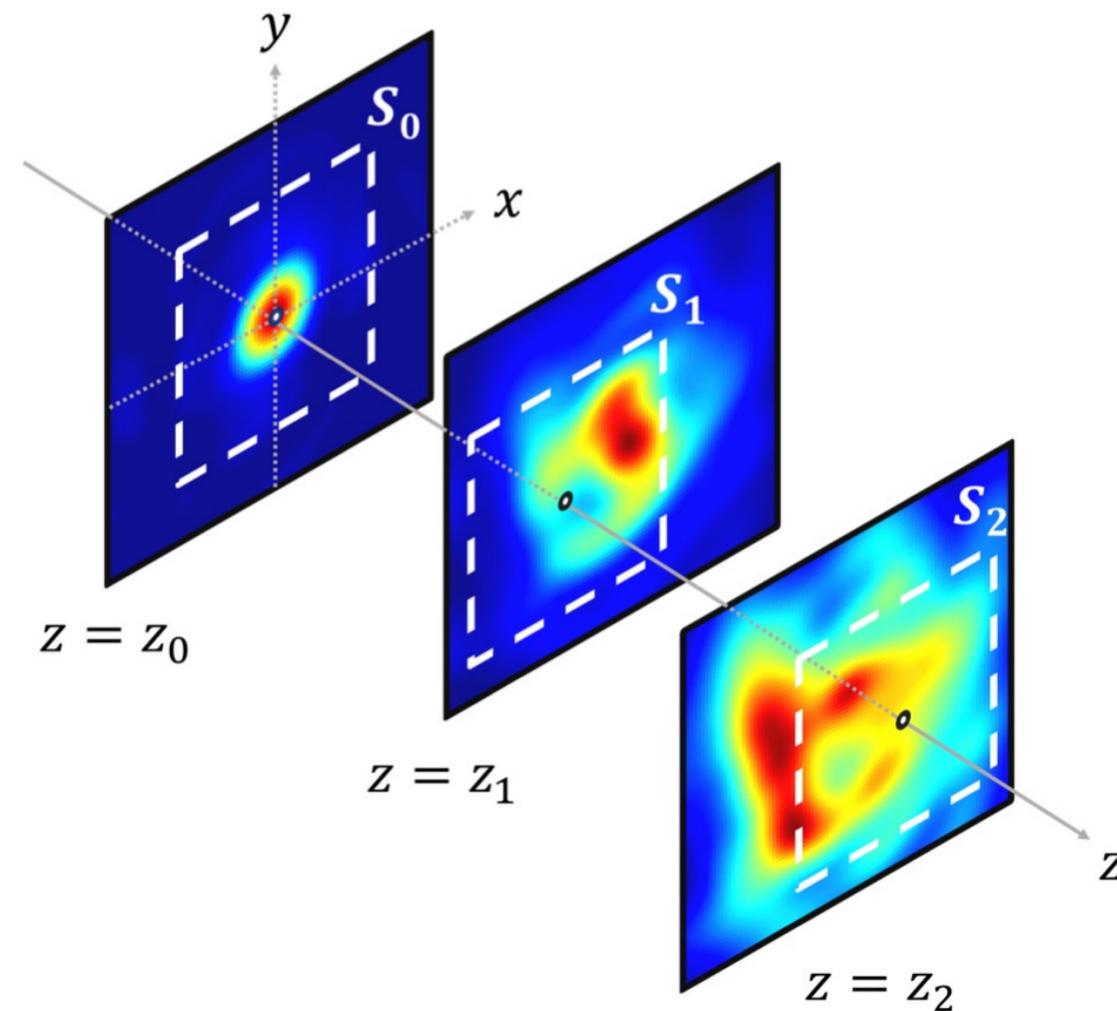
Example of 3D simulation scale  
with “classic” electromagnetic PIC loop  
and “classic” numerical schemes

- Laser wavelength  $\lambda_0 = 0.8 \mu m$  ->  $0.016 \mu m$ ,  $\Delta x = 0.016 \mu m$ ,  $c\Delta t = 0.99\Delta x$
- Laser duration: 30 fs -> Window size  $L_x = 40 \mu m = 2500 * \Delta x$
- $w_0 = 12 \mu m$  ->  $\Delta y = \Delta z = 0.5 \mu m$ , Window size  $L_y = L_z = 125 \mu m = 192 * \Delta y$
- Acceleration length = **1 mm**  $\sim 60000 c * \Delta t$
- 8 macro-particles per cell ->  $\sim 2500 * 250 * 250 * 8 =$   
 **$10^9$  macro-particles, pushed for 60k timesteps!**

**Smallest scale  
to sample**

**Largest scale to simulate  
(Note: current LWFA  
studies require several  
mm, up to 10s of cm, or  
even m)**

# Novel Gerchberg-Saxton Algorithm with Mode Decomposition (GSA-MD) to reconstruct laser field from measured fluence images



Fluence ( $\sim$  [field amplitude]<sup>2</sup>) data measured at transverse planes is used to reconstruct the laser phase (and field)

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