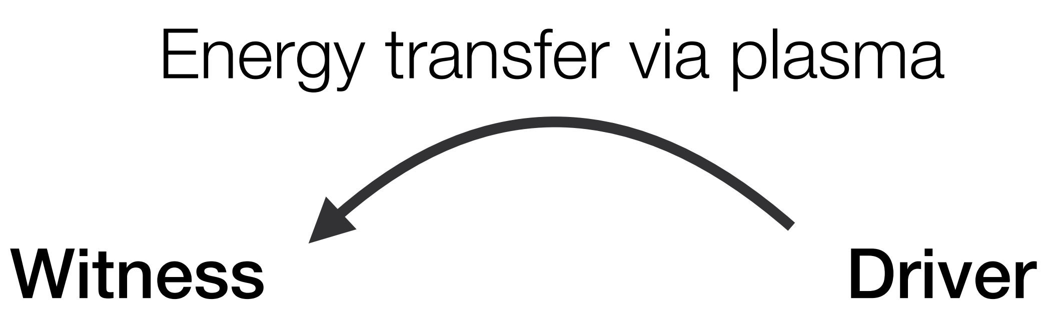
New Concepts for Energy Frontier Colliders: Plasma Wakefield Acceleration

Jens Osterhoff

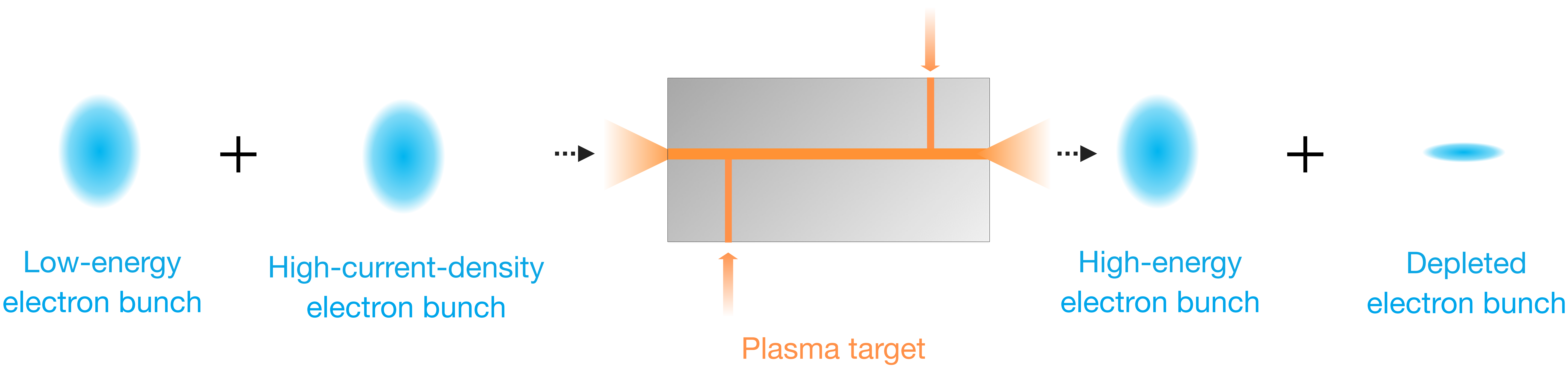
FLASHForward ▸▸ | Research Group for Plasma Wakefield Accelerators FLA-PWA

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Plasma wakefield acceleration in a nutshell



Plasma is ionized matter
- > cannot easily be destroyed any further
- > can sustain extreme electric field



Beam → plasma wakefield acceleration (PWFA)
Laser → laser wakefield acceleration (LWFA)

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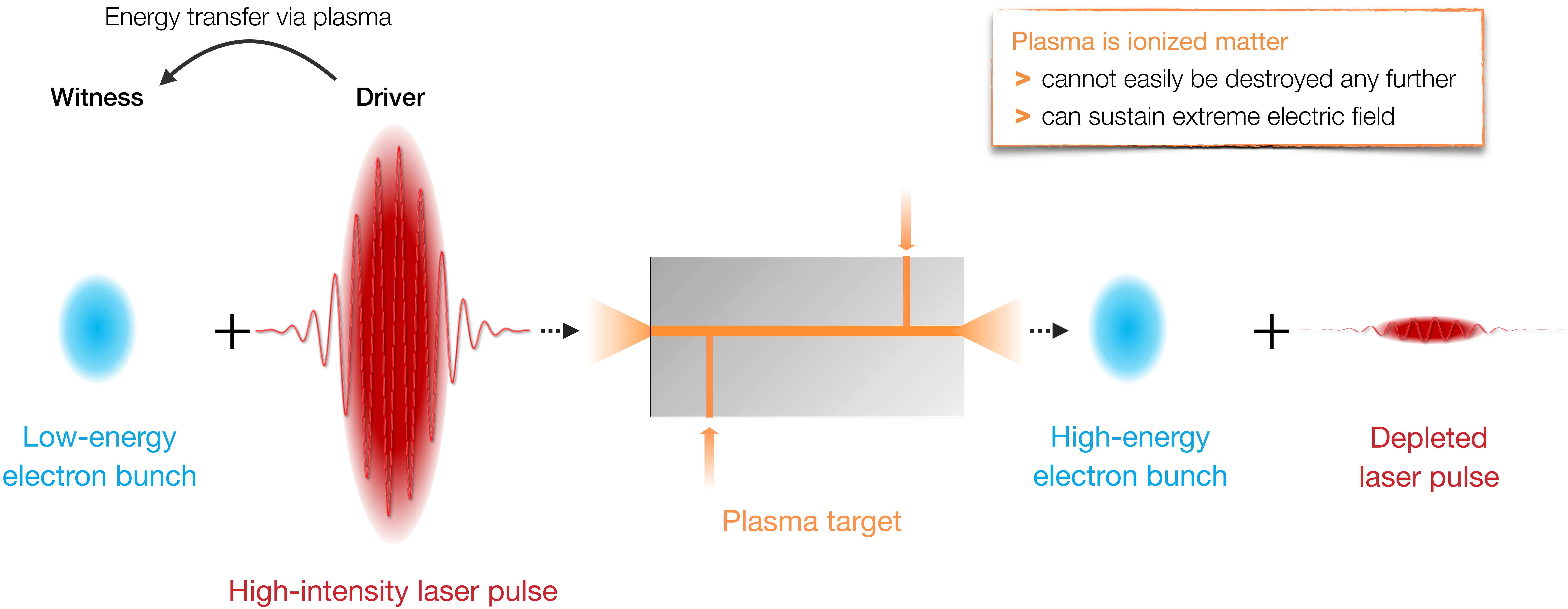

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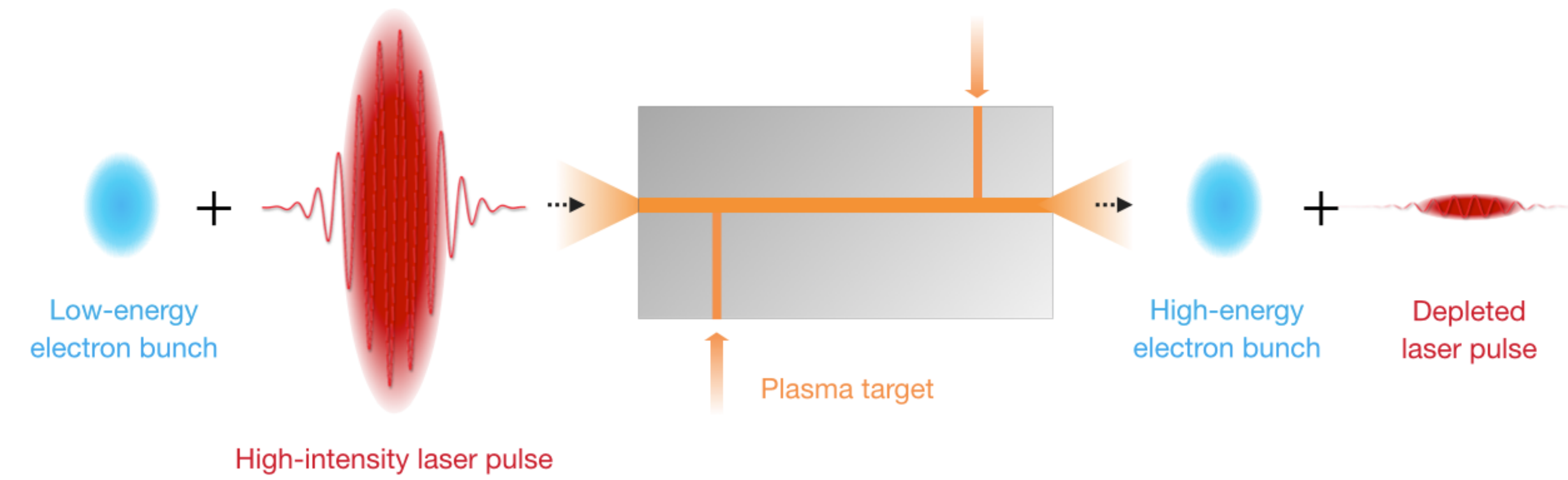
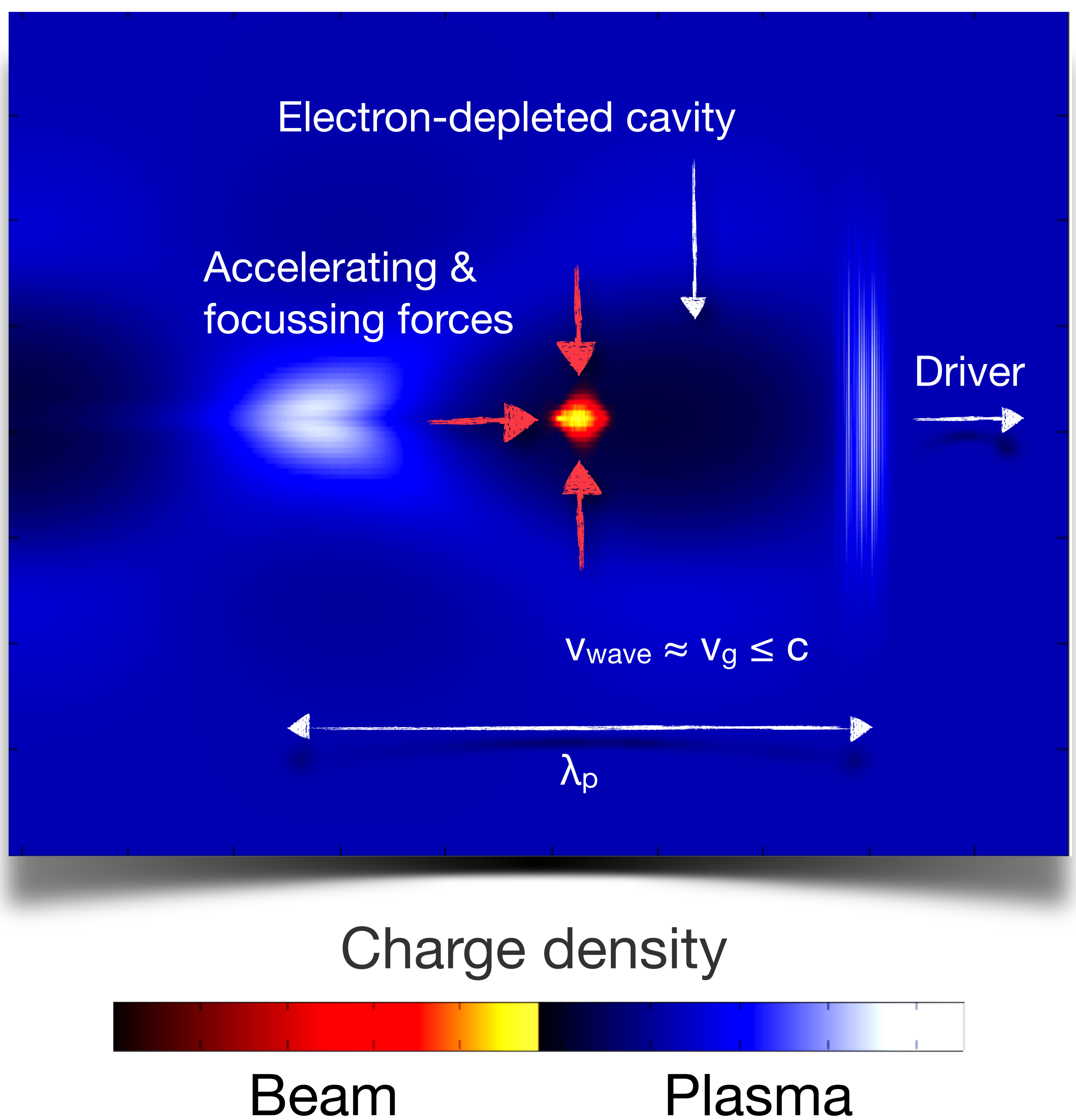




Electric field strength

$$E \approx \frac{mc\omega_p}{e} \approx (96\ \mathrm{V/m}) \sqrt{n_e[\mathrm{cm}^{-3}]}$$

e.g. $E \approx 100$ GV/m (for $n_e \approx 10^{18}$ cm^{-3})

GeV energy gain over cm

→ W.P. Leemans *et al.*, Nature Physics 2, 696 (2006)

Structure size

$$\lambda_p \approx \frac{2\pi c}{\omega_p} \approx (33\ \mathrm{km}) \sqrt{n_e^{-1}[\mathrm{cm}^{-3}]}$$

e.g. $\lambda_p \approx 33$ µm (for $n_e \approx 10^{18}$ cm^{-3})

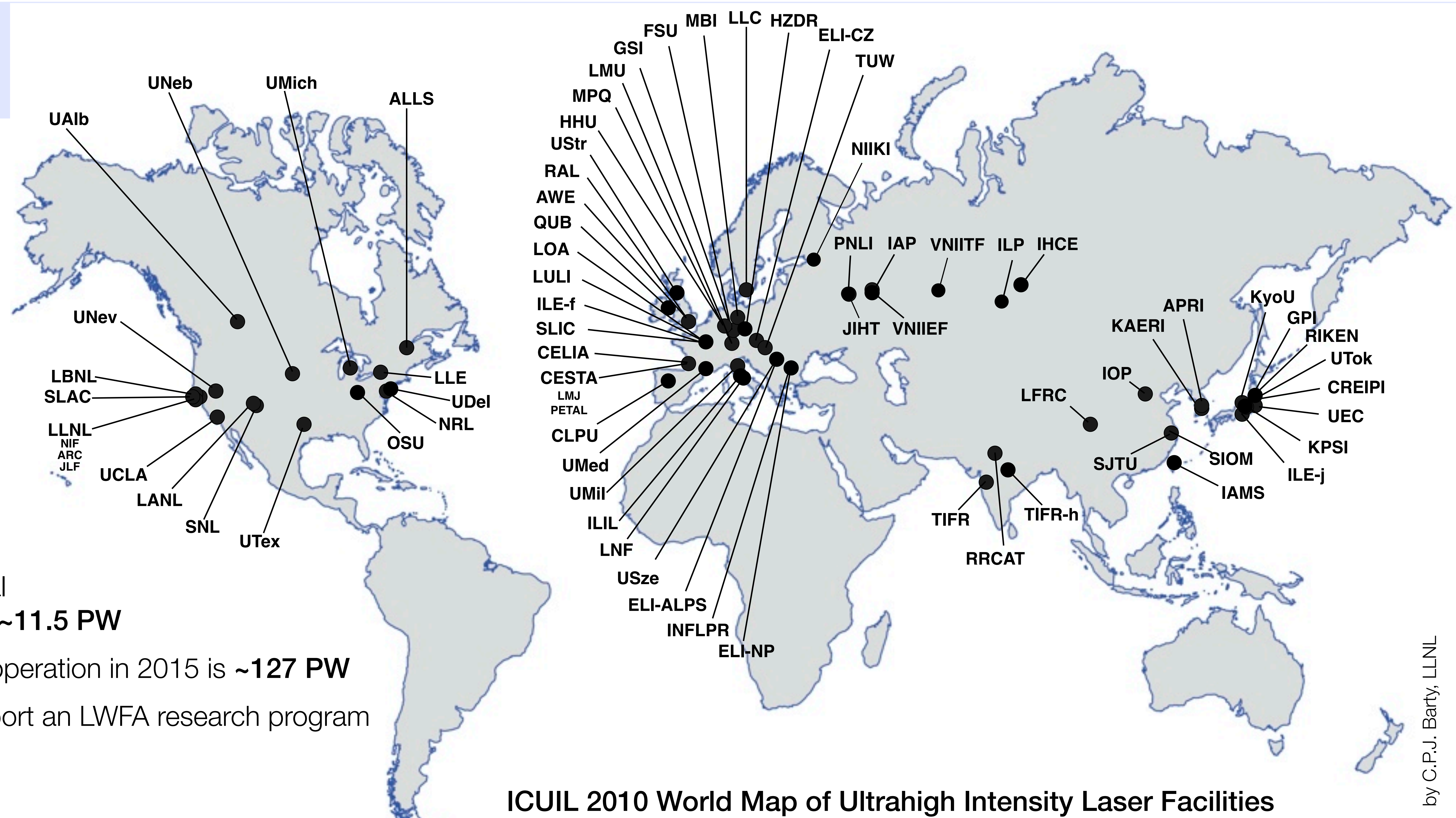
Bunch length in the µm range

→ O. Lundh *et al.*, Nature Physics 7, 219 (2011)

We are still in the inflation phase after the big bang of plasma accelerator science

Plasma wakefield community

is expanding



ICUIL 2010 World Map of Ultrahigh Intensity Laser Facilities

by C.P.J. Barty, LLNL

- Total peak power of operational high-intensity lasers in 2010 is **~11.5 PW**
- Expected total peak power in operation in 2015 is **~127 PW**
- Majority of these systems support an LWFA research program

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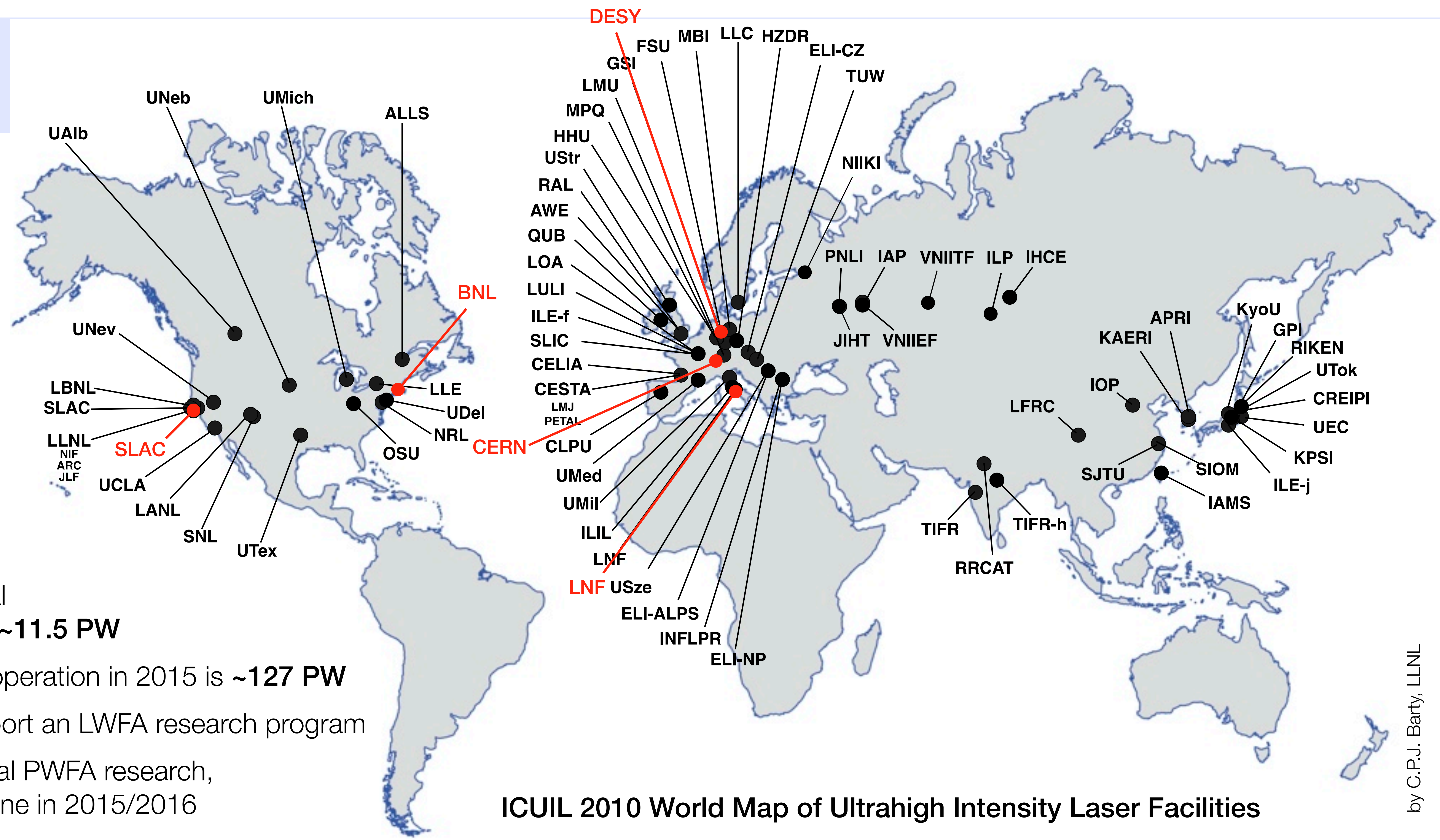

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- Majority of these systems support an LWFA research program
- Only two sites with experimental PWFA research, plus three labs to enter the scene in 2015/2016

Community objective is to make plasma technology applicable

Plasma wakefield community			
	Applications	*first photon sources, then HEP*	
	Main objective	*plasma-acceleration experiments*	now
		↓	
		first usable plasma-based accelerators	within a decade or two…
	Hope	*miniaturization entails a reduction in construction cost, proliferation of accelerators*	

General considerations for a plasma-based particle collider

- Overall average acceleration gradient must be significantly higher than for conventional machines
  - gradient of > 1 GV/m on average implies < 1 km/TeV

- Beams must feature sufficient luminosity and energy determined by physics

- Luminosity requires beam power

$$P_{beam} = \frac{4\pi\sigma_*^2}{N}\mathcal{L}\mathcal{E}_{cm}$$

- Technology must allow for sufficient efficiency

$$P_{wall} = \frac{P_{beam}}{\eta}$$

Excellent focussability
(low emittance and energy spread)

High charge

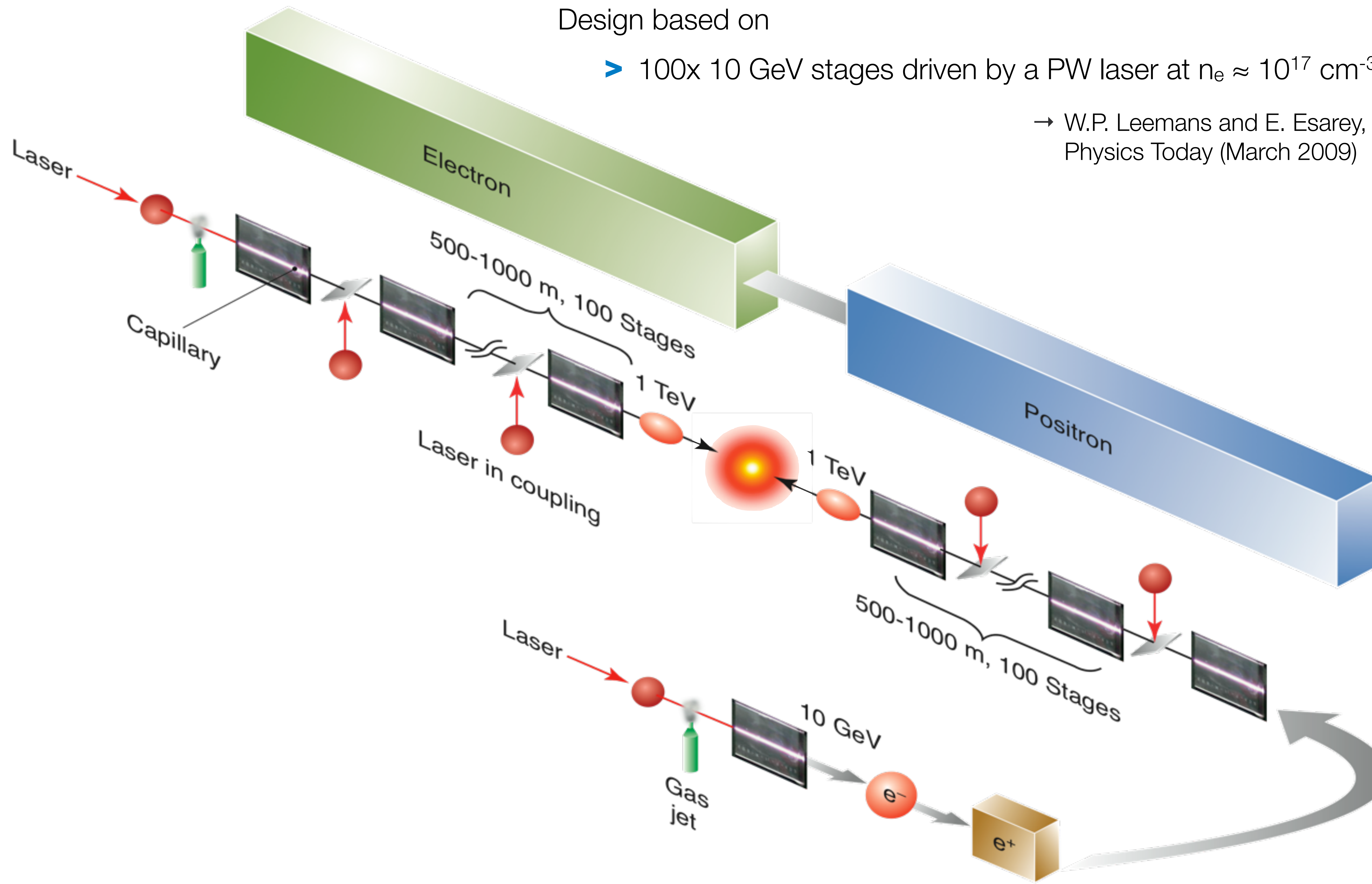
High wall-plug efficiency
(energy transfer to driver → to plasma → to witness)

Straw-man design of a TeV-class LWFA-based linear collider

Design based on

- 100x 10 GeV stages driven by a PW laser at $n_e \approx 10^{17}$ cm^{-3}

→ W.P. Leemans and E. Esarey, Physics Today (March 2009)



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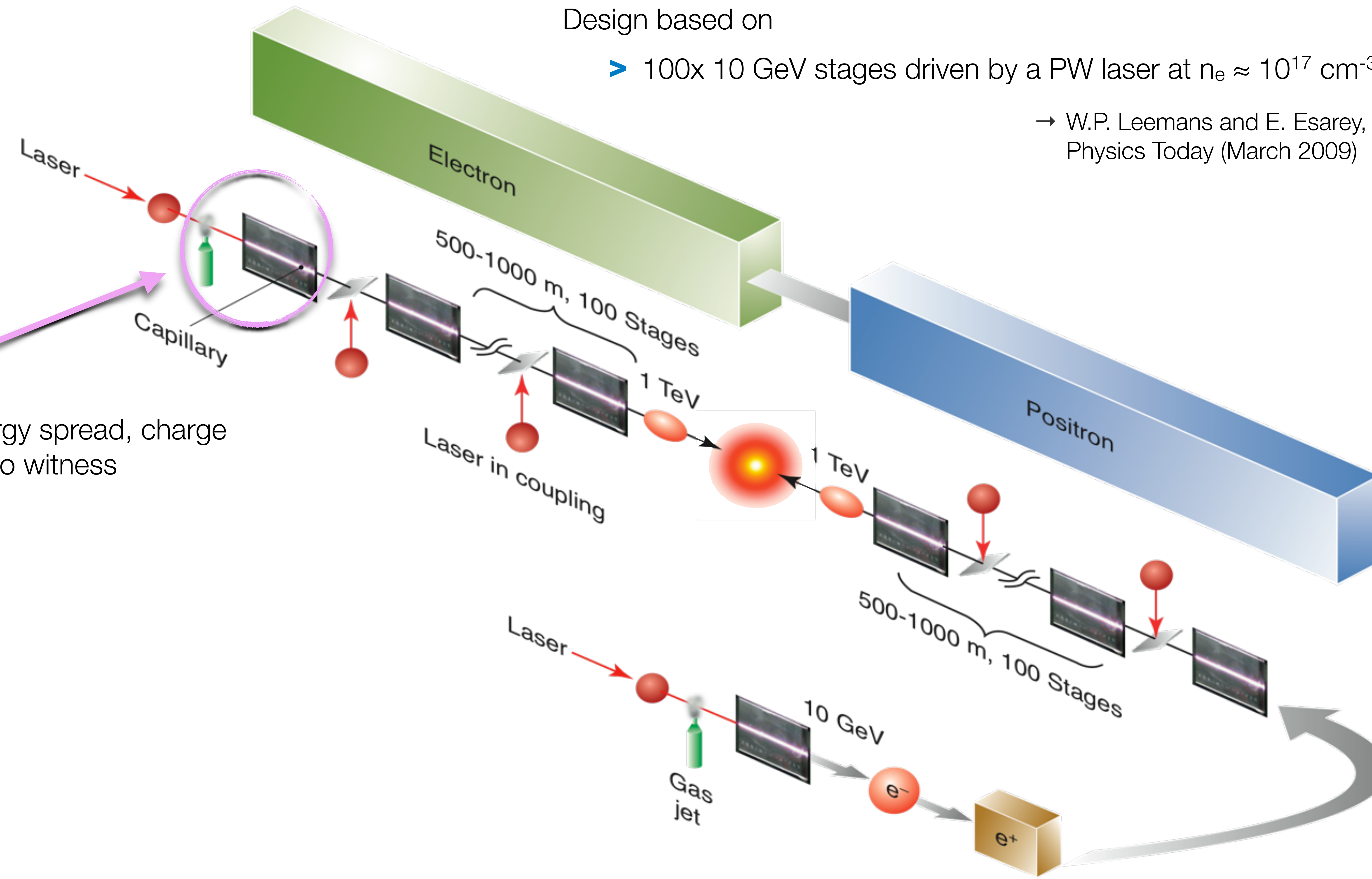
Challenges / required R&D



- Single acceleration module
  deliver consistent beam quality
  → emittance, energy, energy spread, charge
  efficient energy transfer of driver to witness

Coupling efficiency and energy spread require improvement beyond state-of-the-art

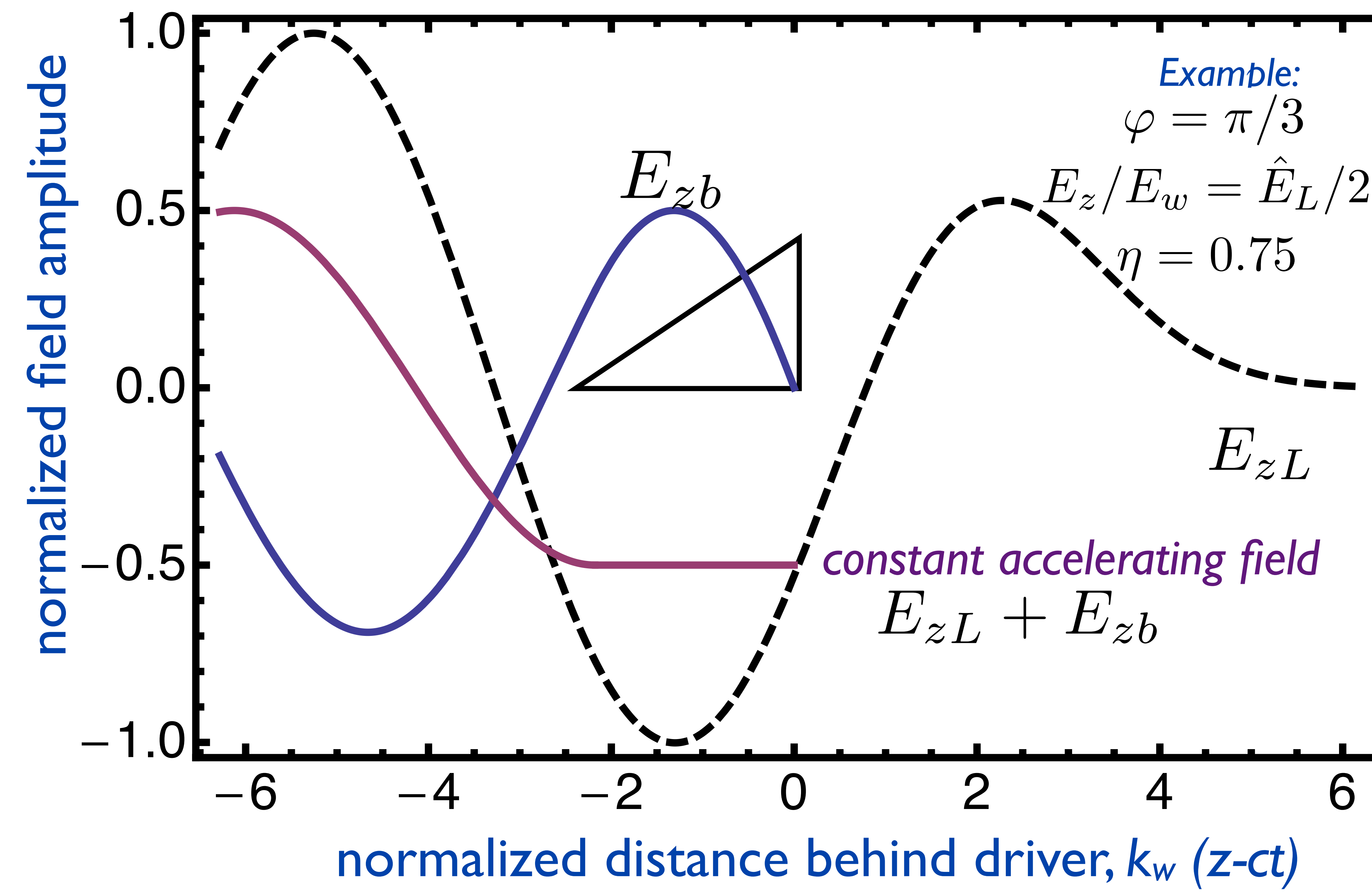
State-of-the-art for a single acceleration module

- Energy measured up to 4.25 GeV, up to 10 GeV expected
  → BELLA, LBNL, W.P. Leemans at NA-PAC 2013
- Transverse normalized emittance down to 0.1 µm
  → G.R. Plateau *et al.*, PRL 109, 064802 (2012). R. Weingartner *et al.*, PRSTAB 15, 111302 (2012)
- Energy spread ~1% level
- Charge ~100 pC
- Efficiency of energy transfer laser-to-beam ~1%

linked

solution: optimization by witness shaping, beam loading

→ idea by T. Katsouleas *et al.*, Particle Accelerators 22, 81 (1987)



by C.B. Schroeder, talk at AAC 2014

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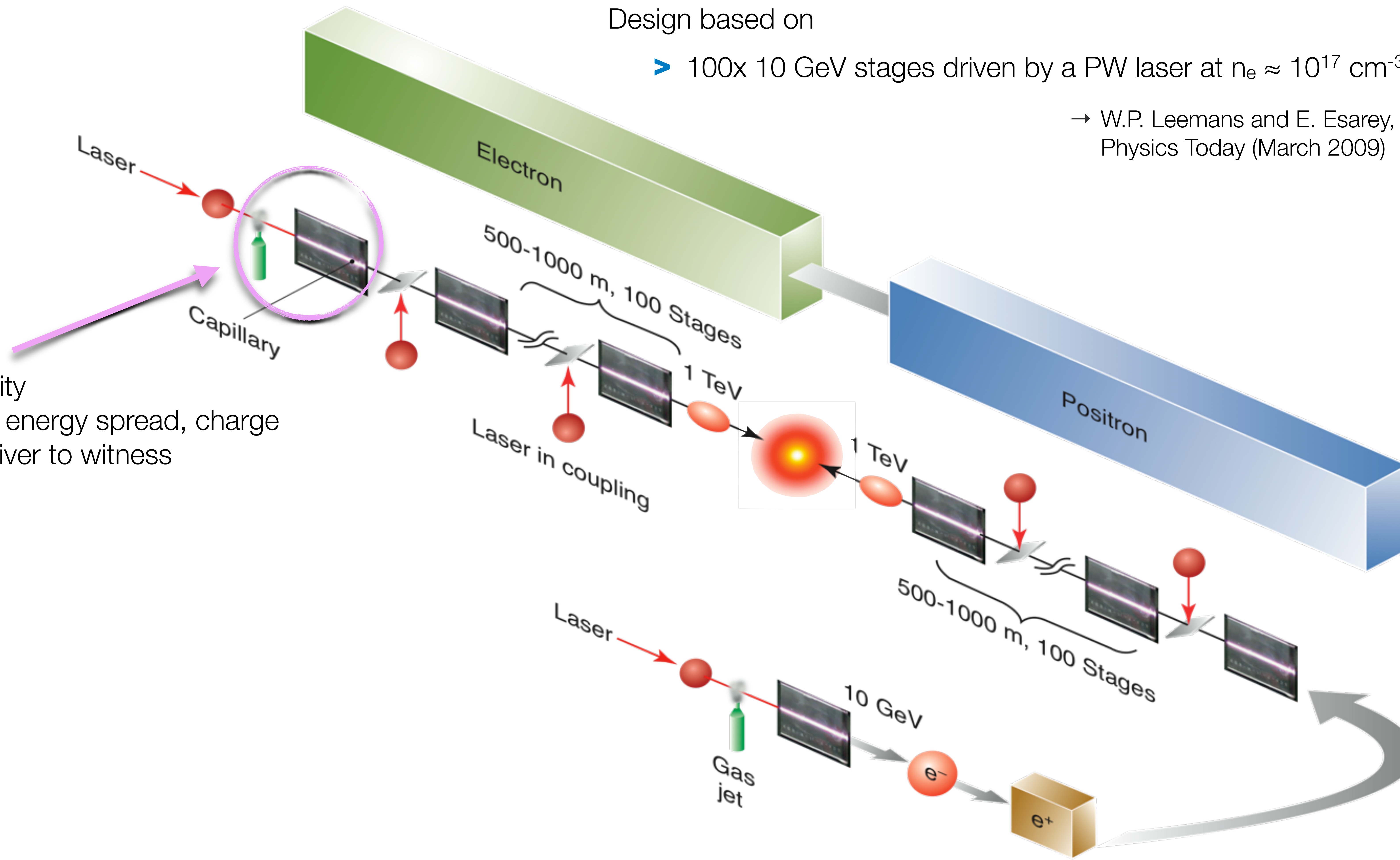

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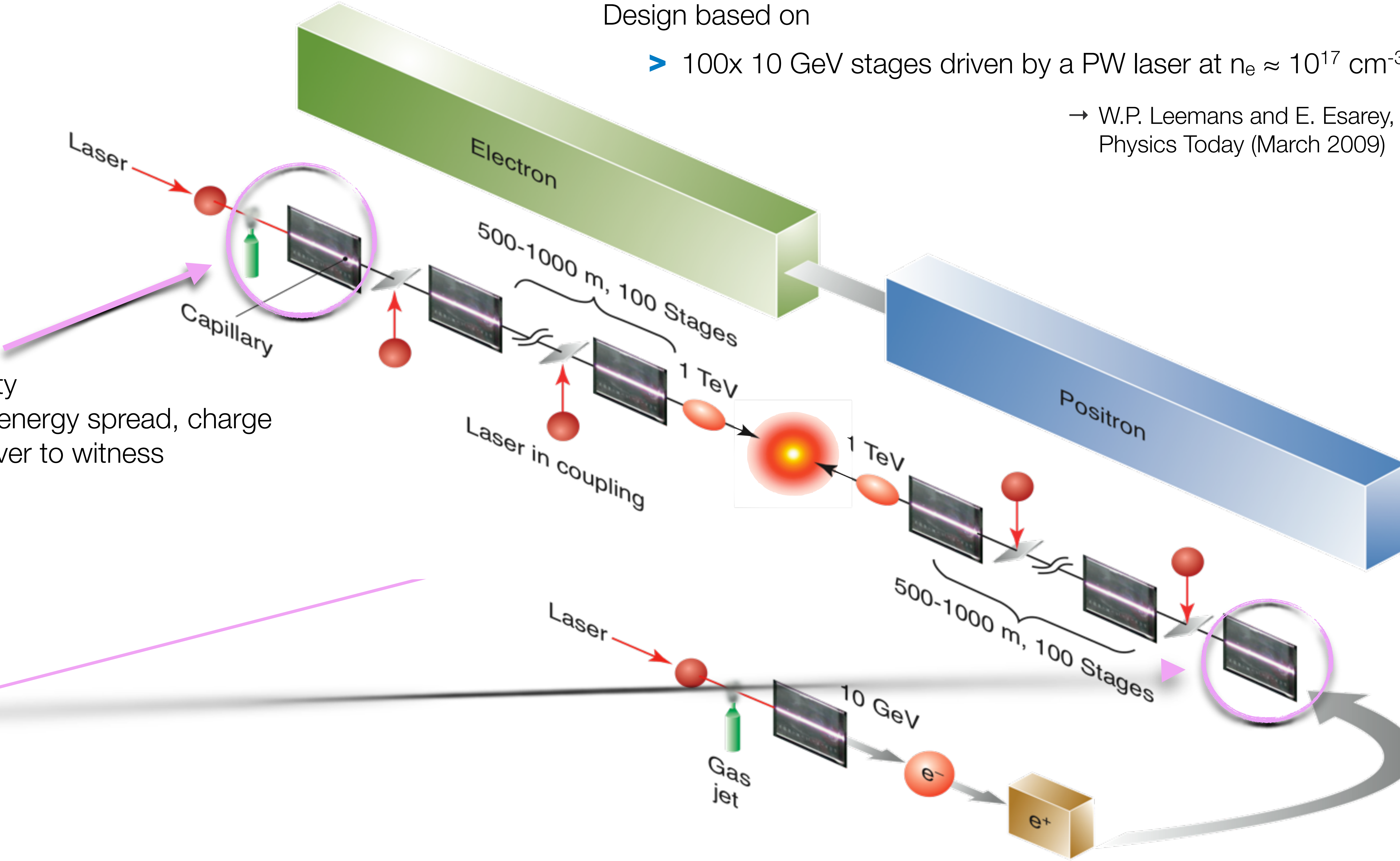
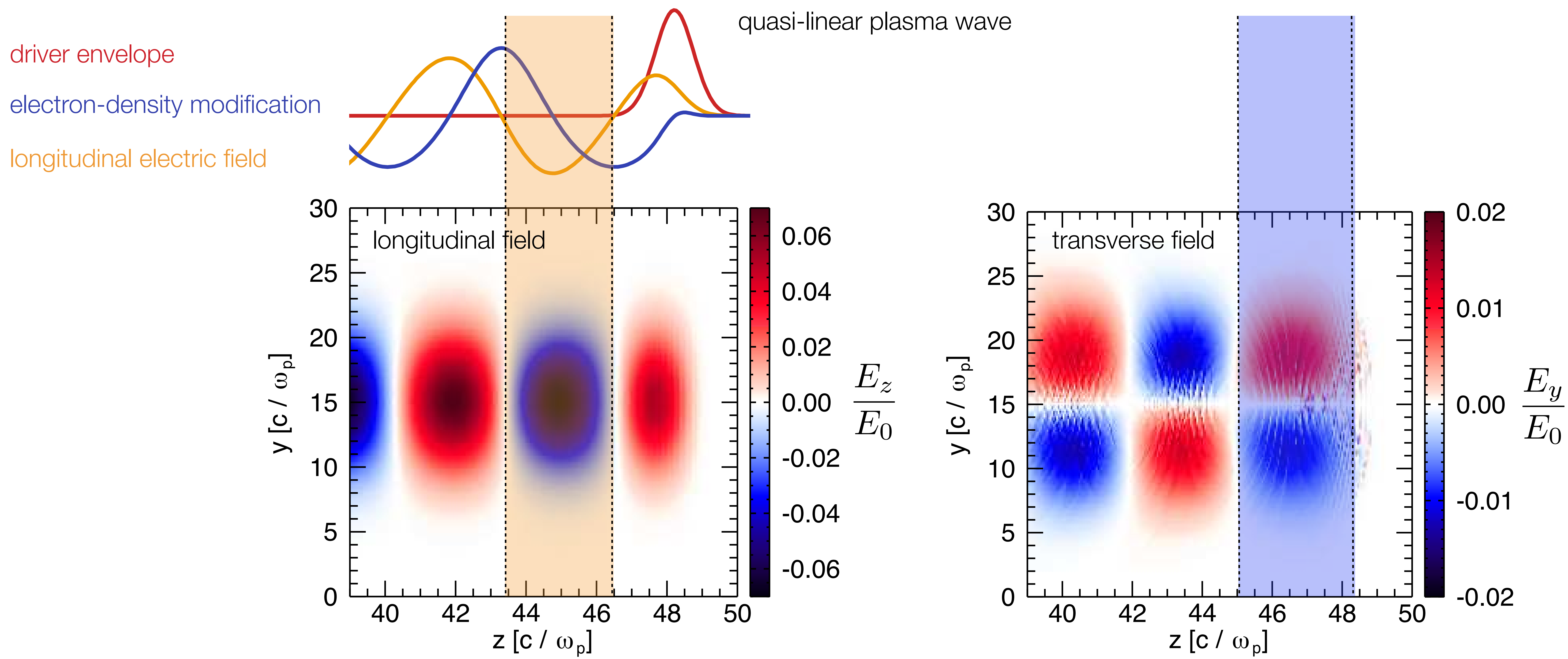
- Positron acceleration



Quasi-linear wakefields allow for positron acceleration



accelerating phase for e^-

focussing phase for e^-

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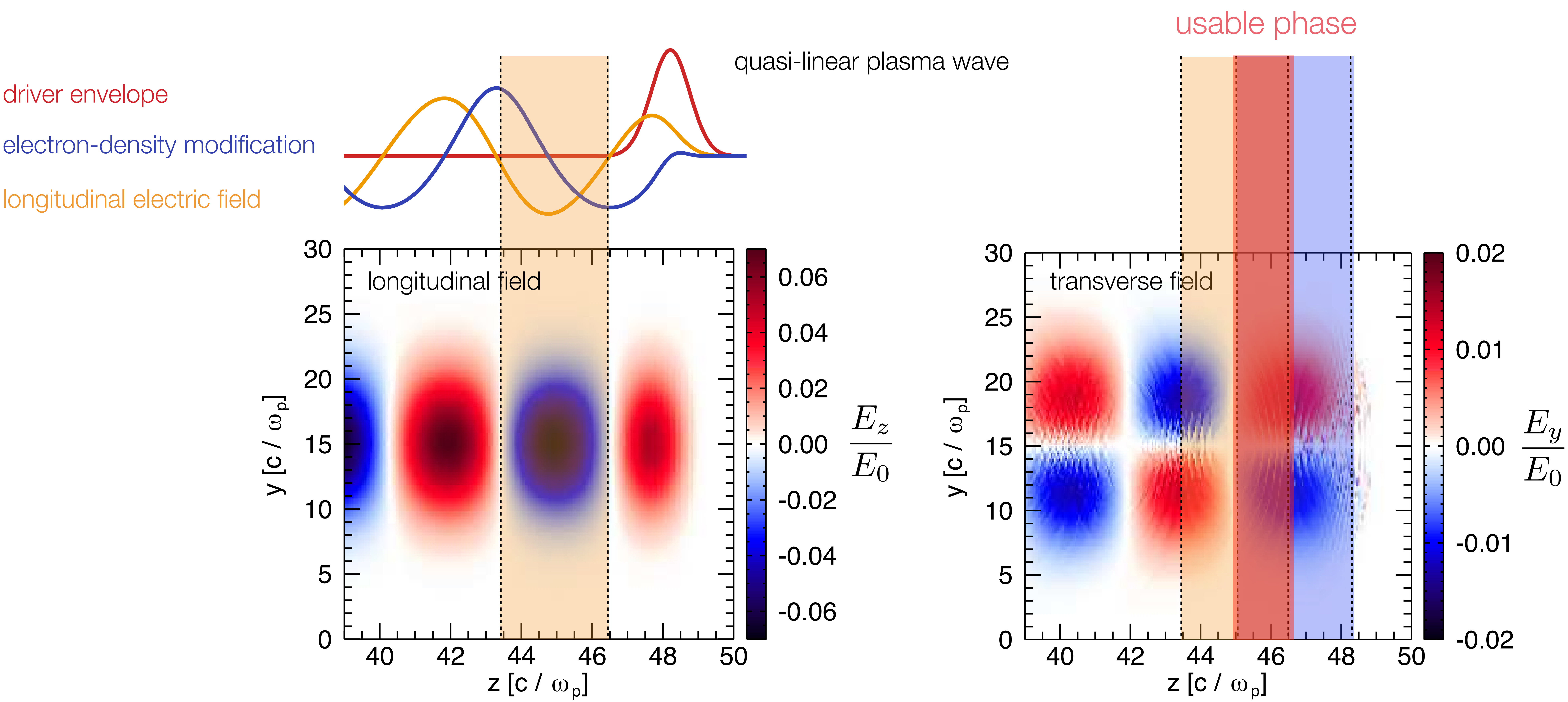
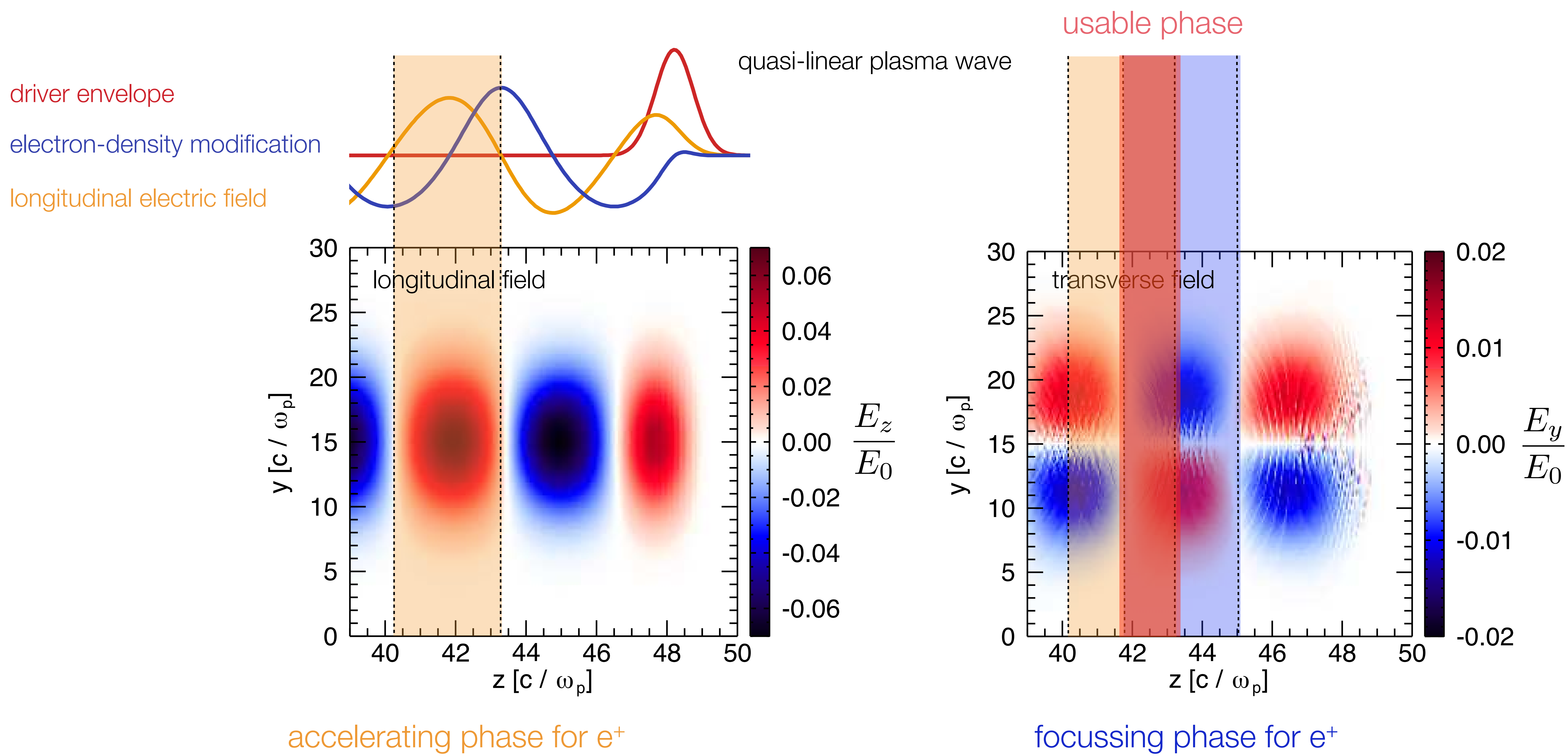


accelerating phase for e⁻

focussing phase for e⁻

Quasi-linear wakefields allow for positron acceleration



→ needs to be experimentally confirmed, no active research?

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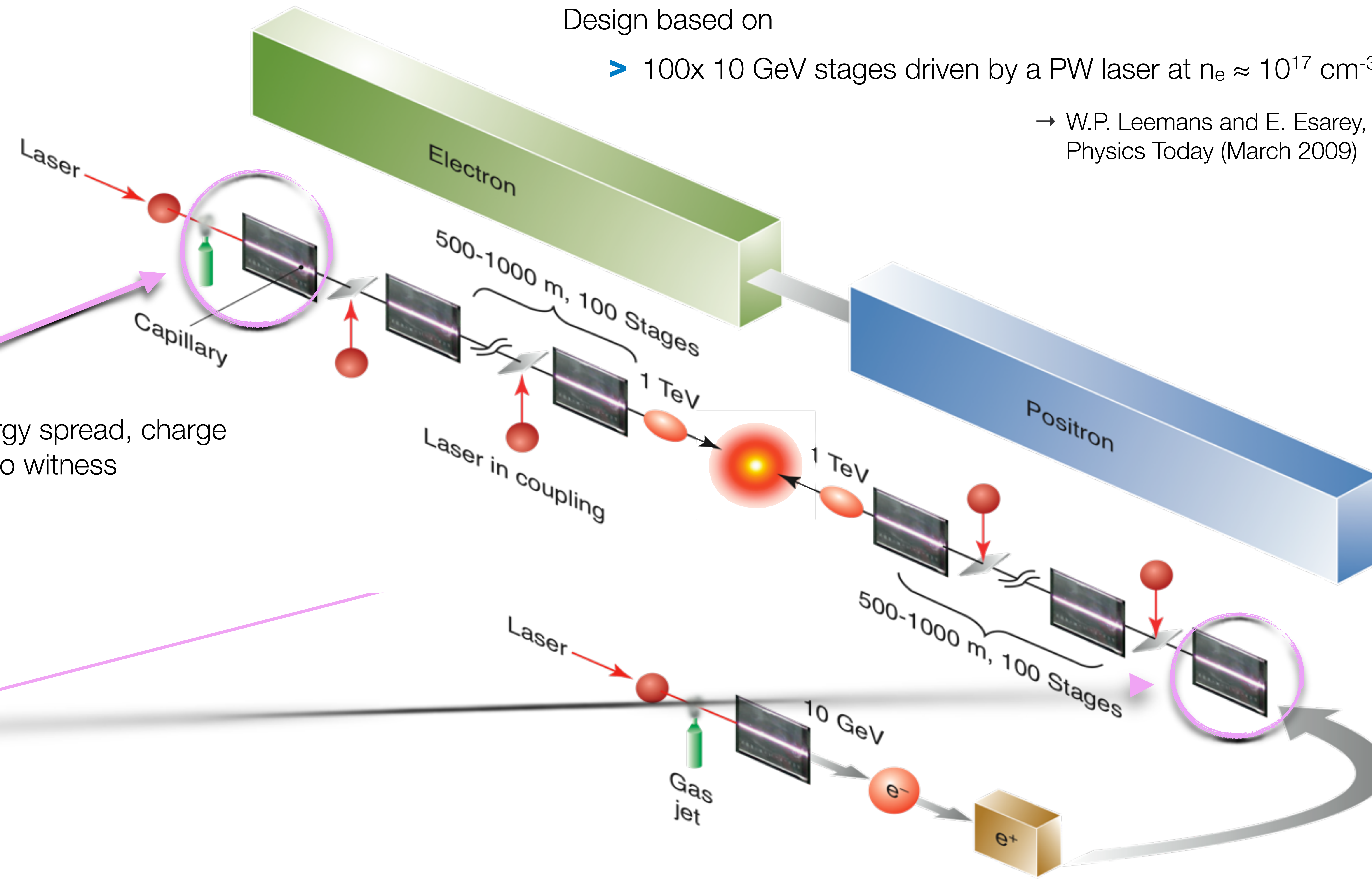

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- Coupling of two plasma stages
  laser in-coupling → accelerator length
  electron beam extraction and injection → beam quality preservation
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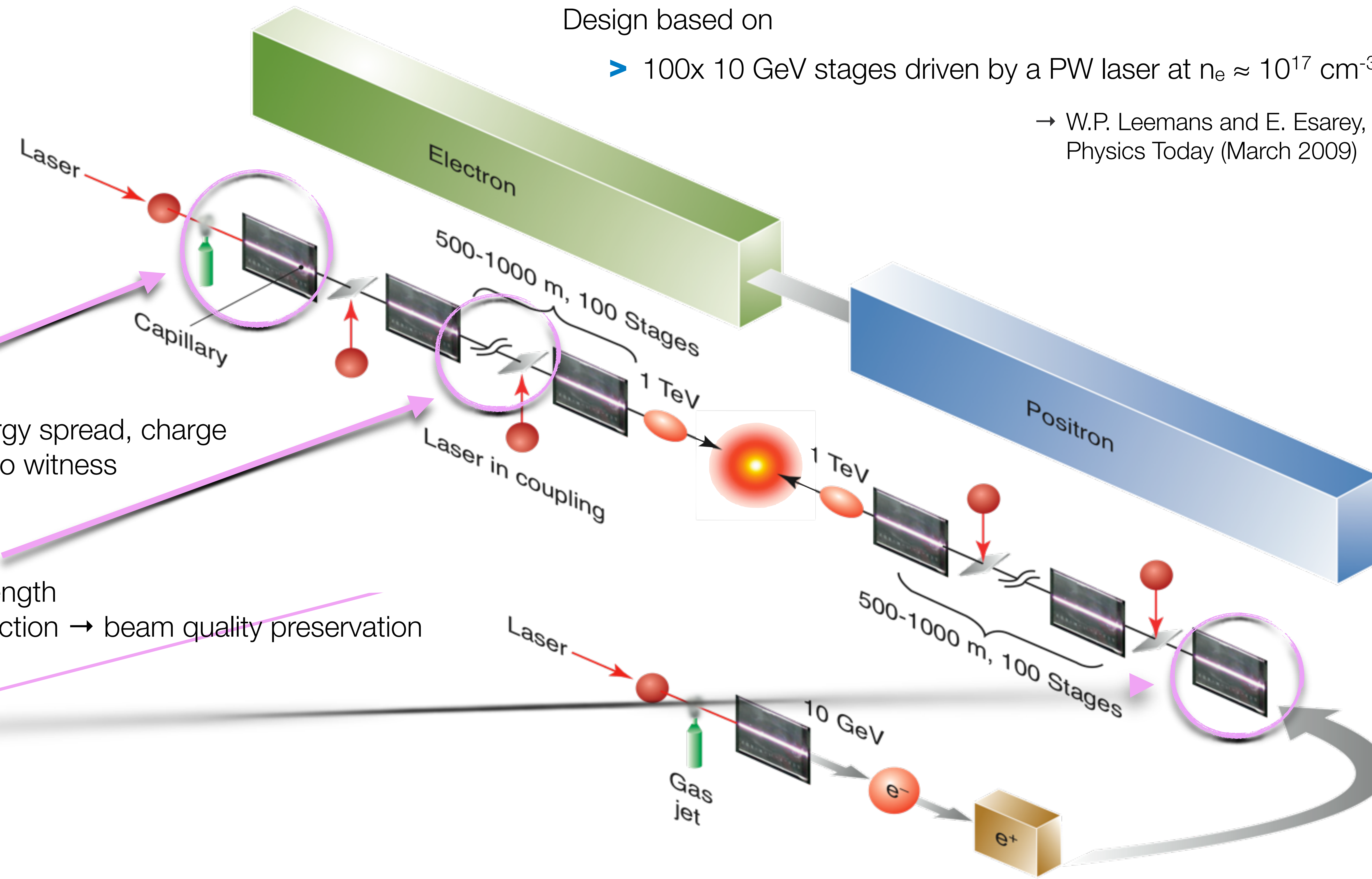
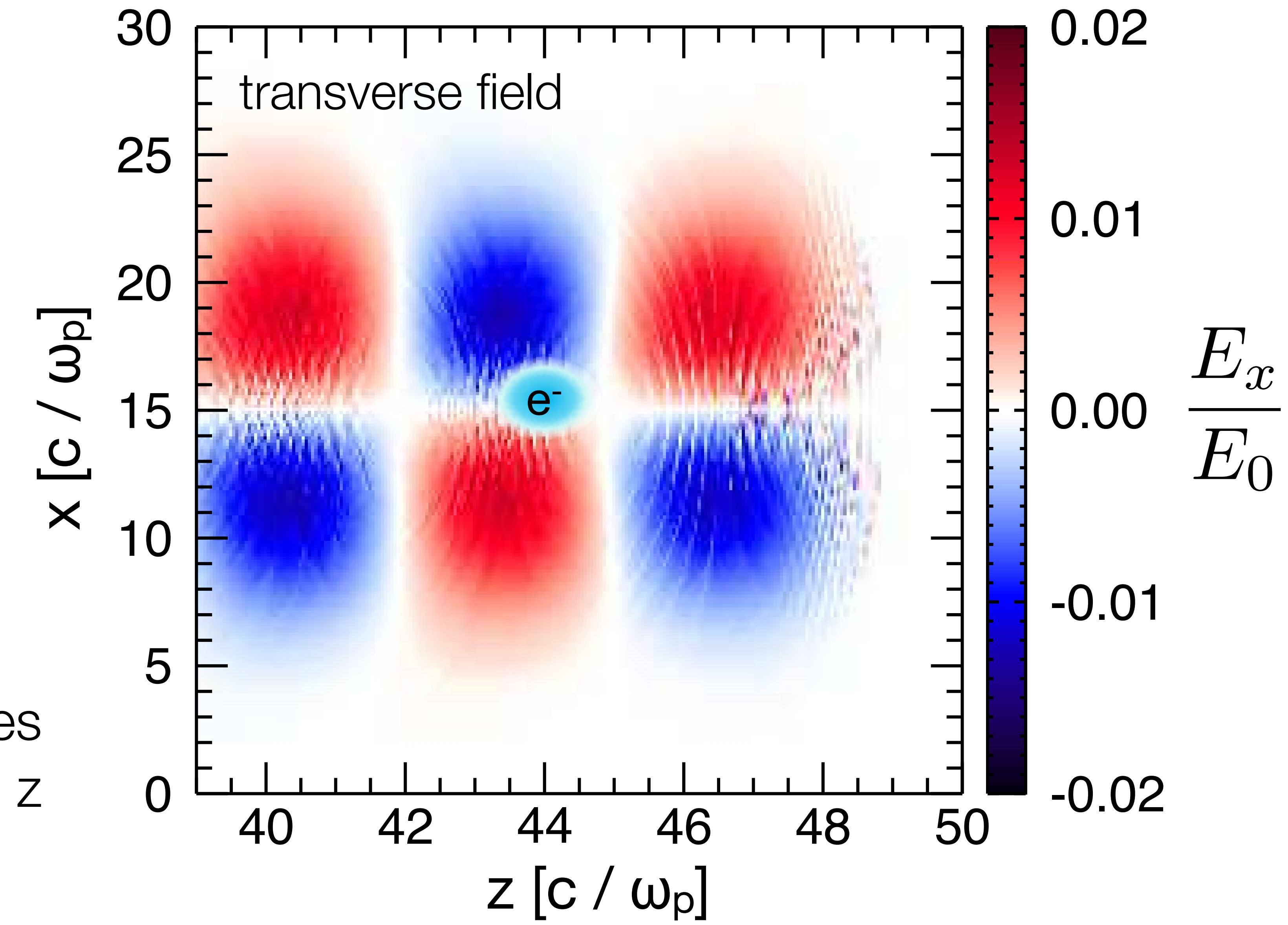


Coupling of plasma stages: preservation of beam emittance

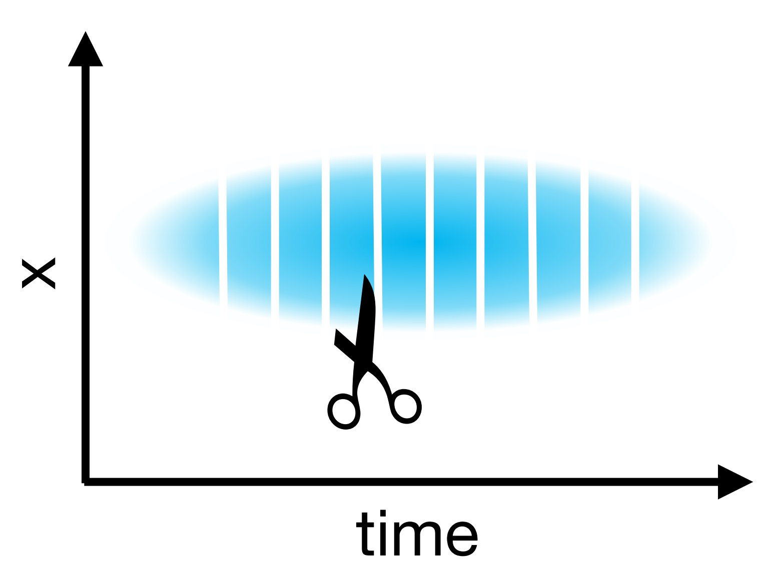
$$\epsilon = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

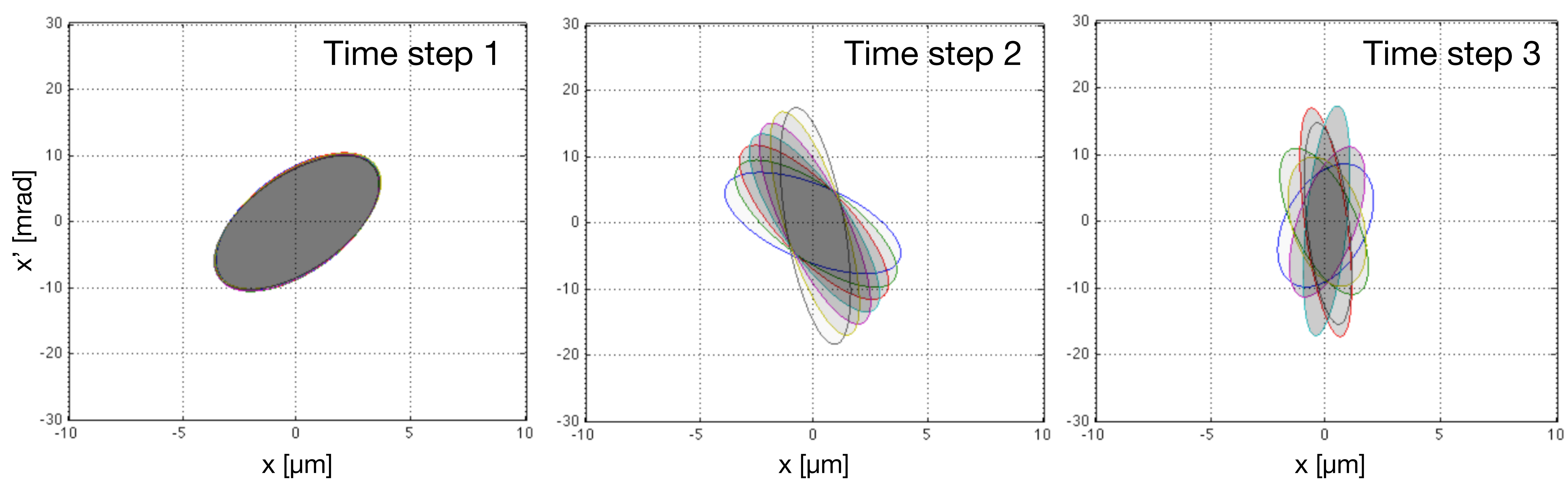
with $x' = p_x / p_z$

Beam focusing forces (in x) vary in plasmas in z



Slice rotation speeds vary along electron bunch





Coupling of plasma stages: beam matching required

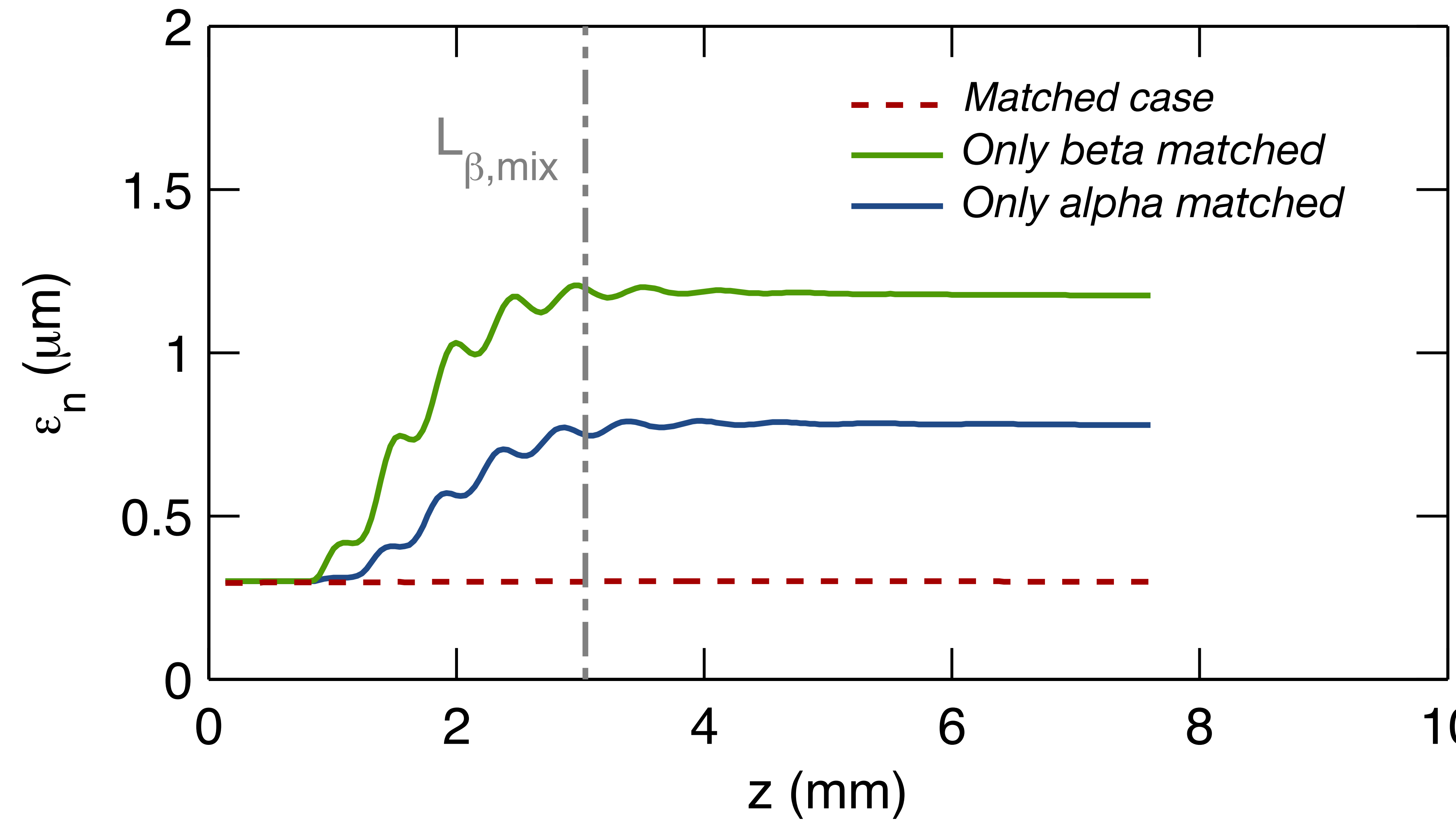
T. Mehrling *et al.*, Phys. Rev. STAB 15, 111303 (2012)

Total betatron phase mixing length

$$L_{\beta,\mathrm{mix}} \simeq \frac{\lambda_p}{a_0}\sqrt{\frac{8\pi\gamma_r}{k_p L_b}}$$

Matching conditions

$$\alpha_{match} = 0 \qquad \beta_{match} \simeq \frac{c}{\omega_\beta}$$



3D particle-in-cell (PIC) simulation

- Significant phase mixing occurs up to ~TeV energies within acceleration length
  (with plasma density 10^{17} cm^{-3}, quasi-linear wake, λ = 800 nm)
- Matching sections between stages require significant space with conventional technology ⟶ plasma optics to maintain average gradient?

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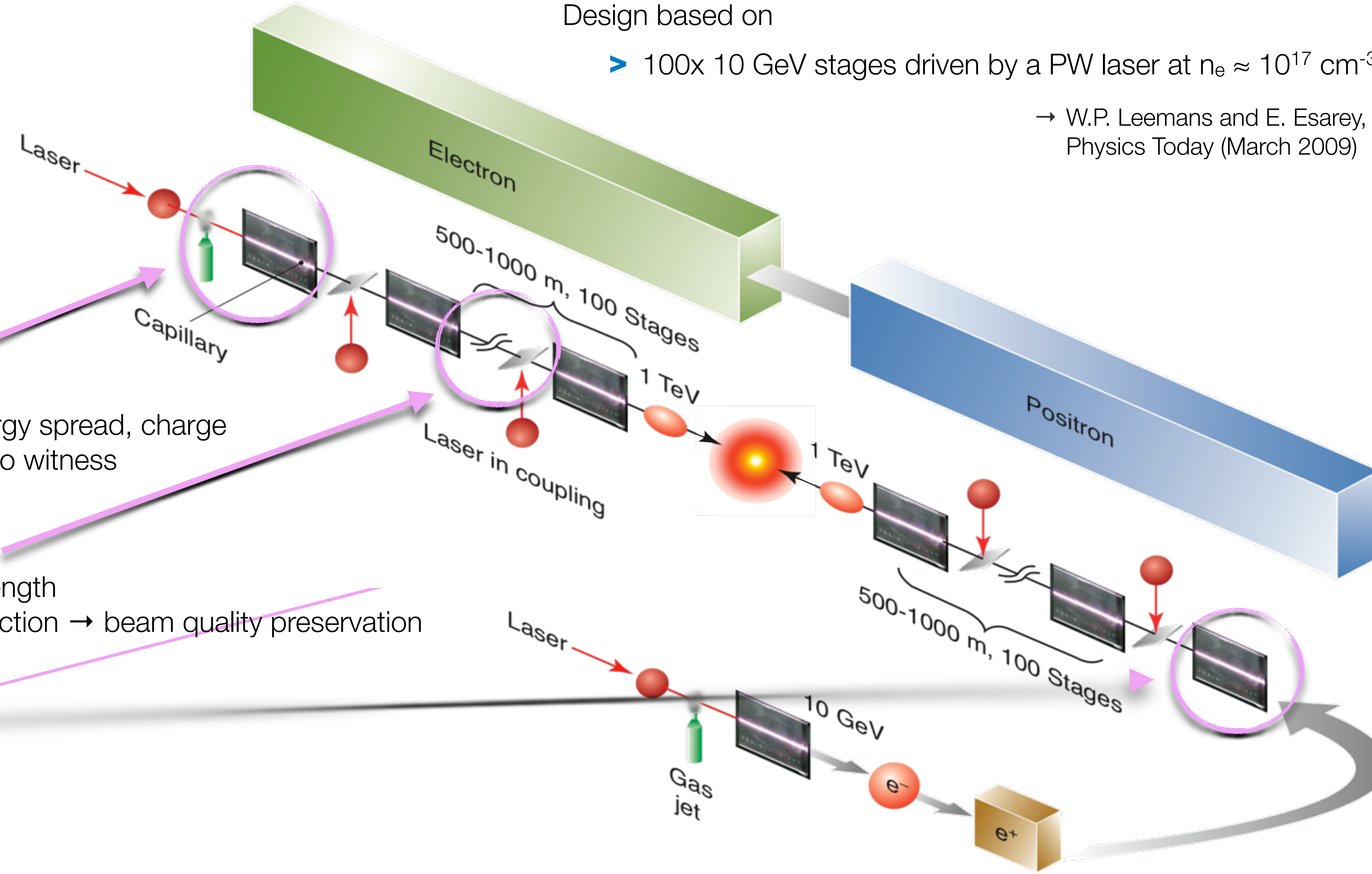

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Challenges / required R&D

- Laser system
  high peak power,
  high average power + efficiency
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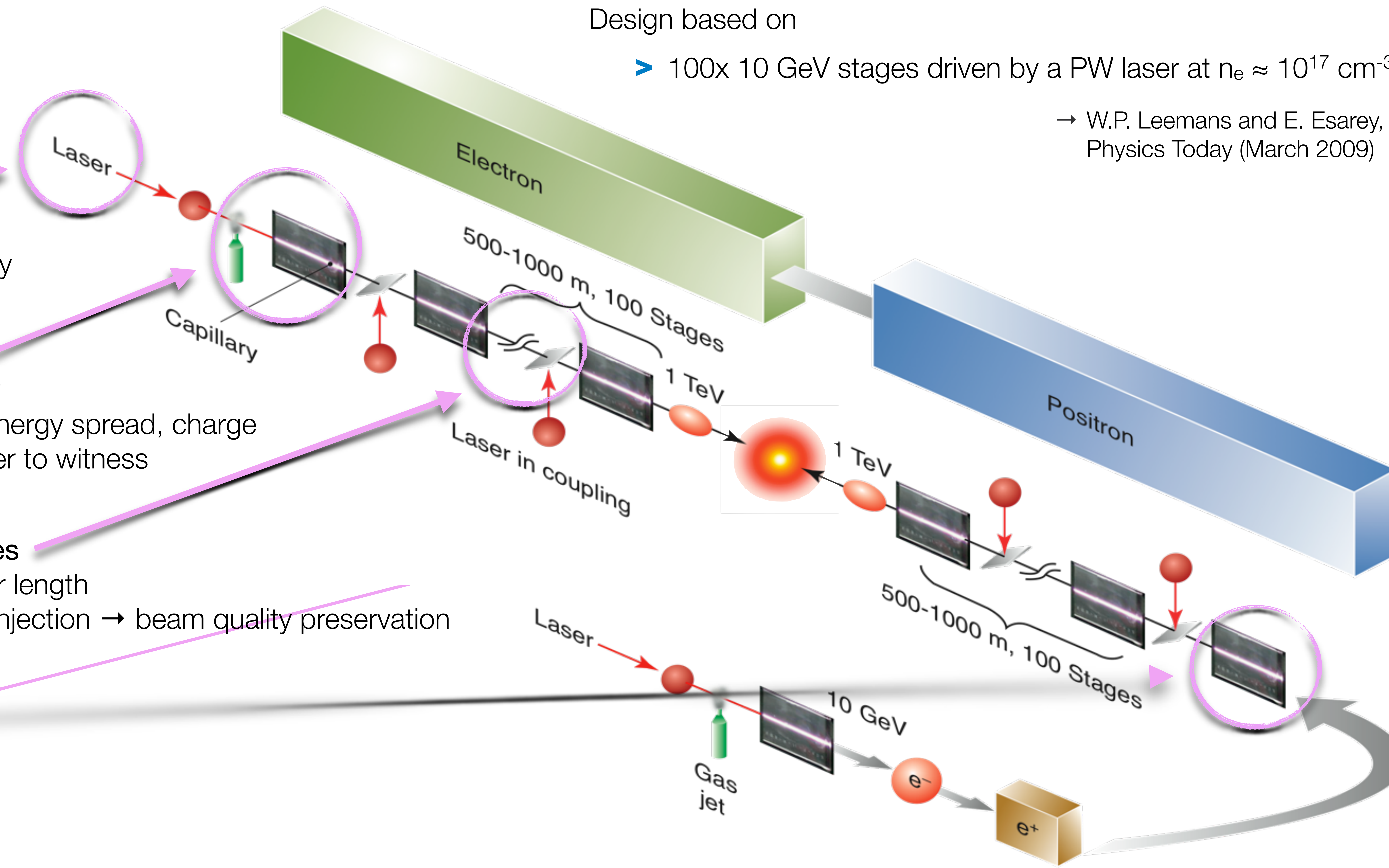

Efficiency and average-power requirements demand a quantum leap in laser technology

Required power per particle beam $P_b \approx 5$ MW
Maximum power from the grid $P_{AC} \approx 200$ MW

→ Need 5% wallplug efficiency

- Efficiency laser to plasma wave ~50%
- Efficiency plasma wave to beam ~30%

→ Expected laser-to-beam efficiency of 15%

→ Requires wallplug-to-laser efficiency of 33%

confer C.B. Schroeder *et al.*, Phys. Rev. STAB 13, 101301 (2010)

confer B. Shadwick *et al.*, Phys. Plasmas 16, 056704 (2009)

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With 10 GeV modules ×50 and total energy per beam ~300 J

→ 6 J energy gain per module

→ 40 J laser energy per module at ~17 kHz repetition rate

→ 680 kW average laser power required

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→ Current roadblock for LWFA colliders.

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confer C.

confer B.

from simu

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High-peak and high-average power, high-efficiency lasers based on fibers

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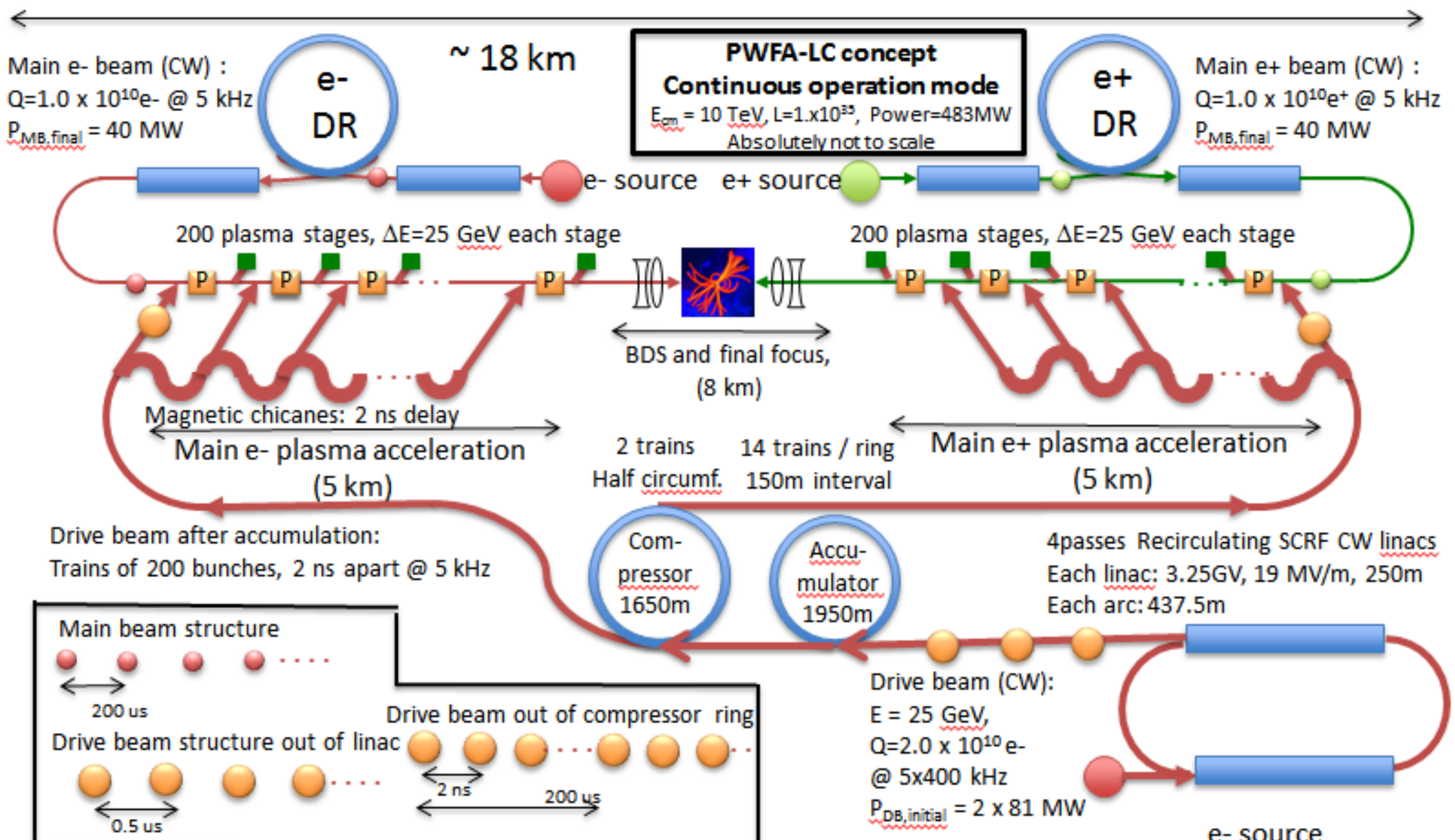
Concept for a 10 TeV PWFA-based linear collider



→ E. Adli *et al.*, SLAC-PUB-15426 (2013)

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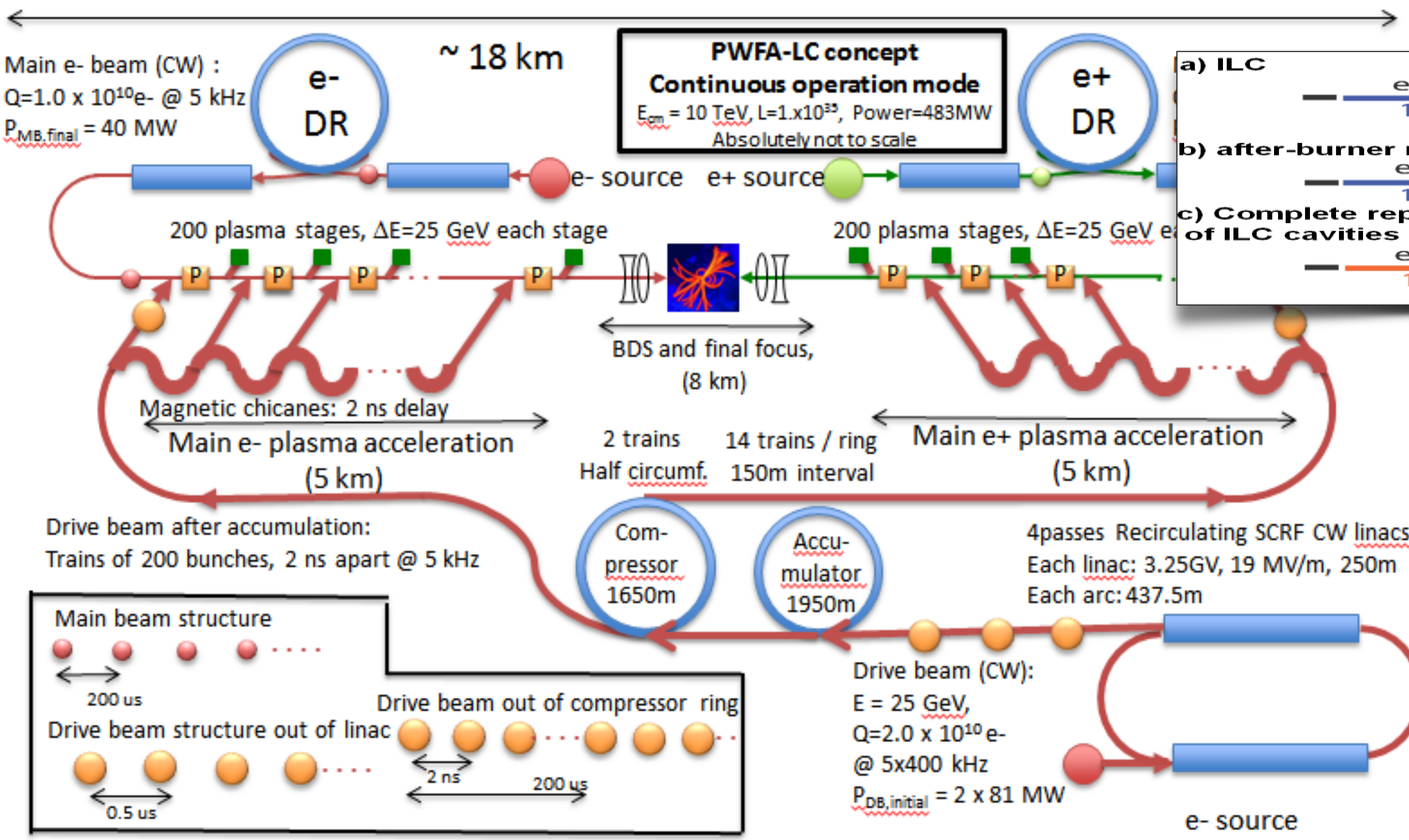
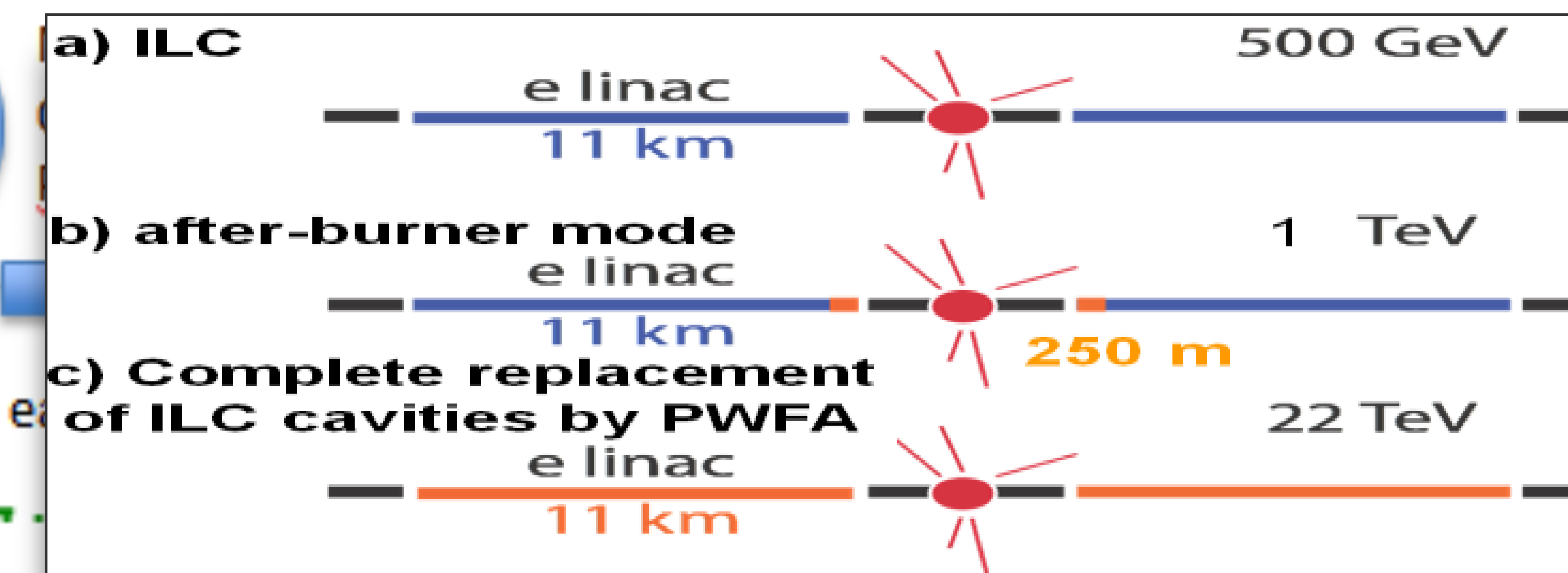


> Possibility of an ILC upgrade



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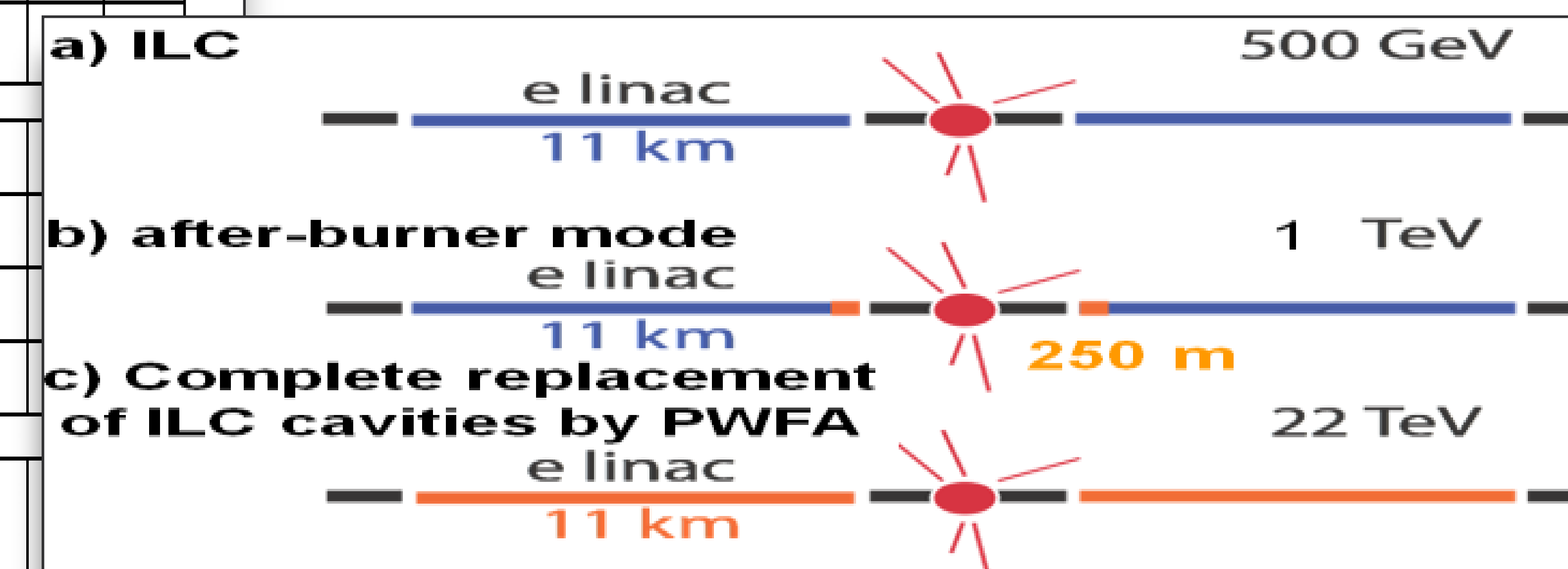

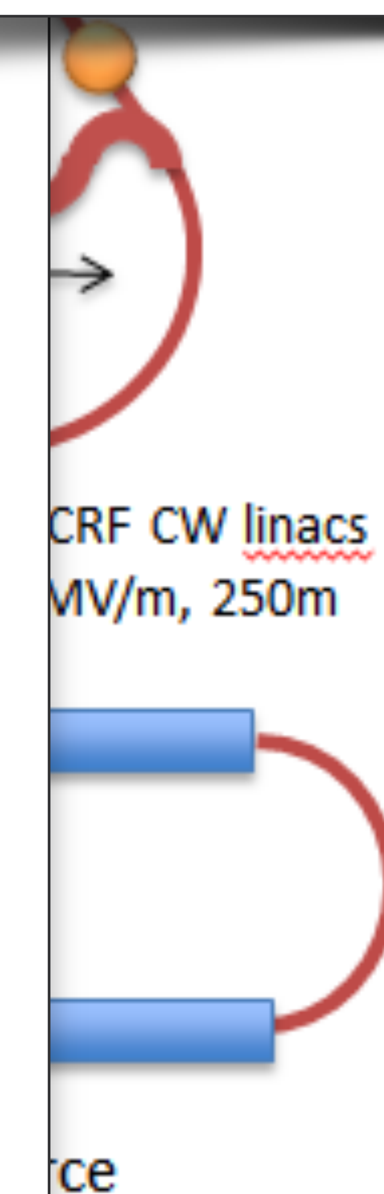

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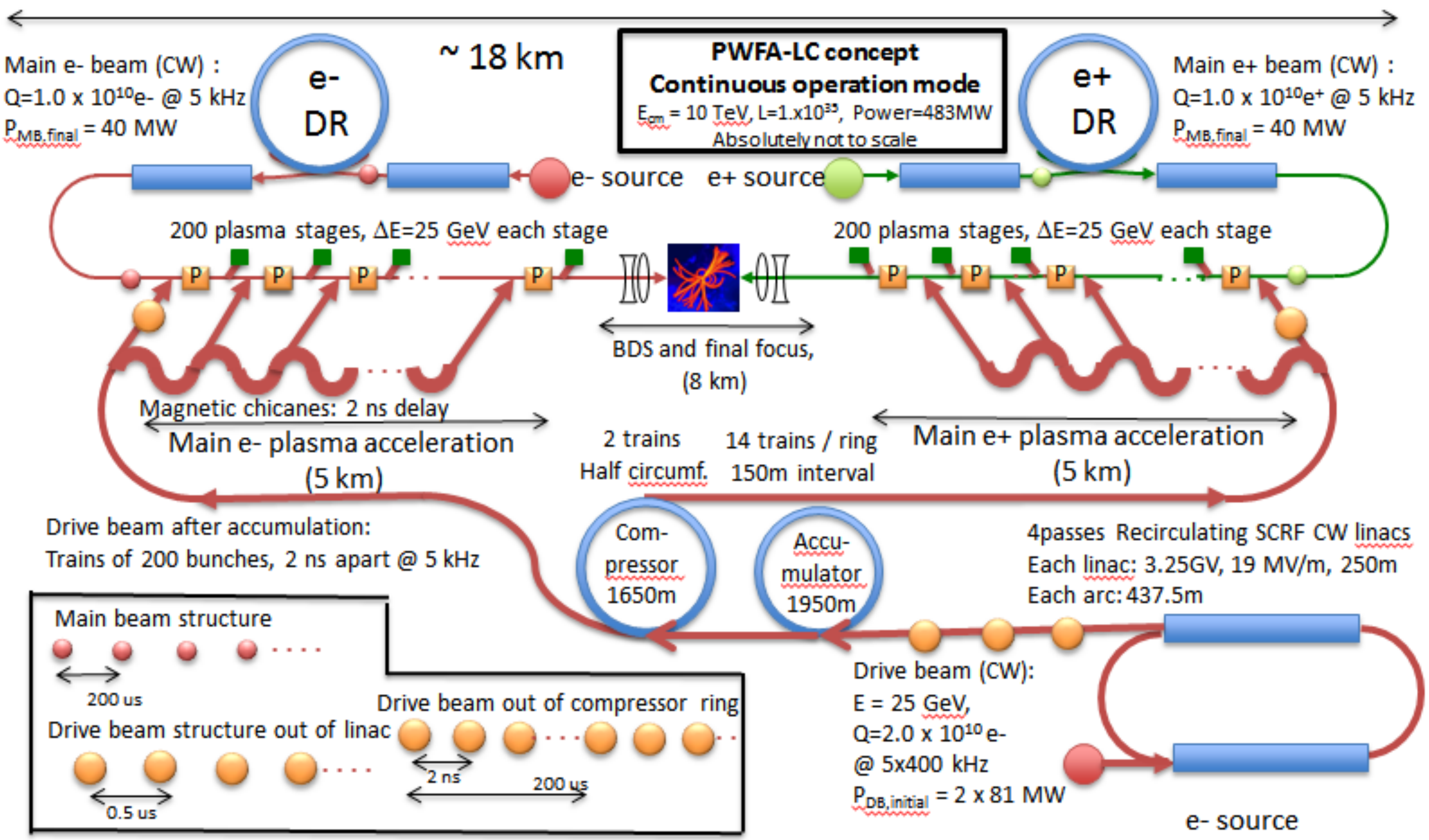
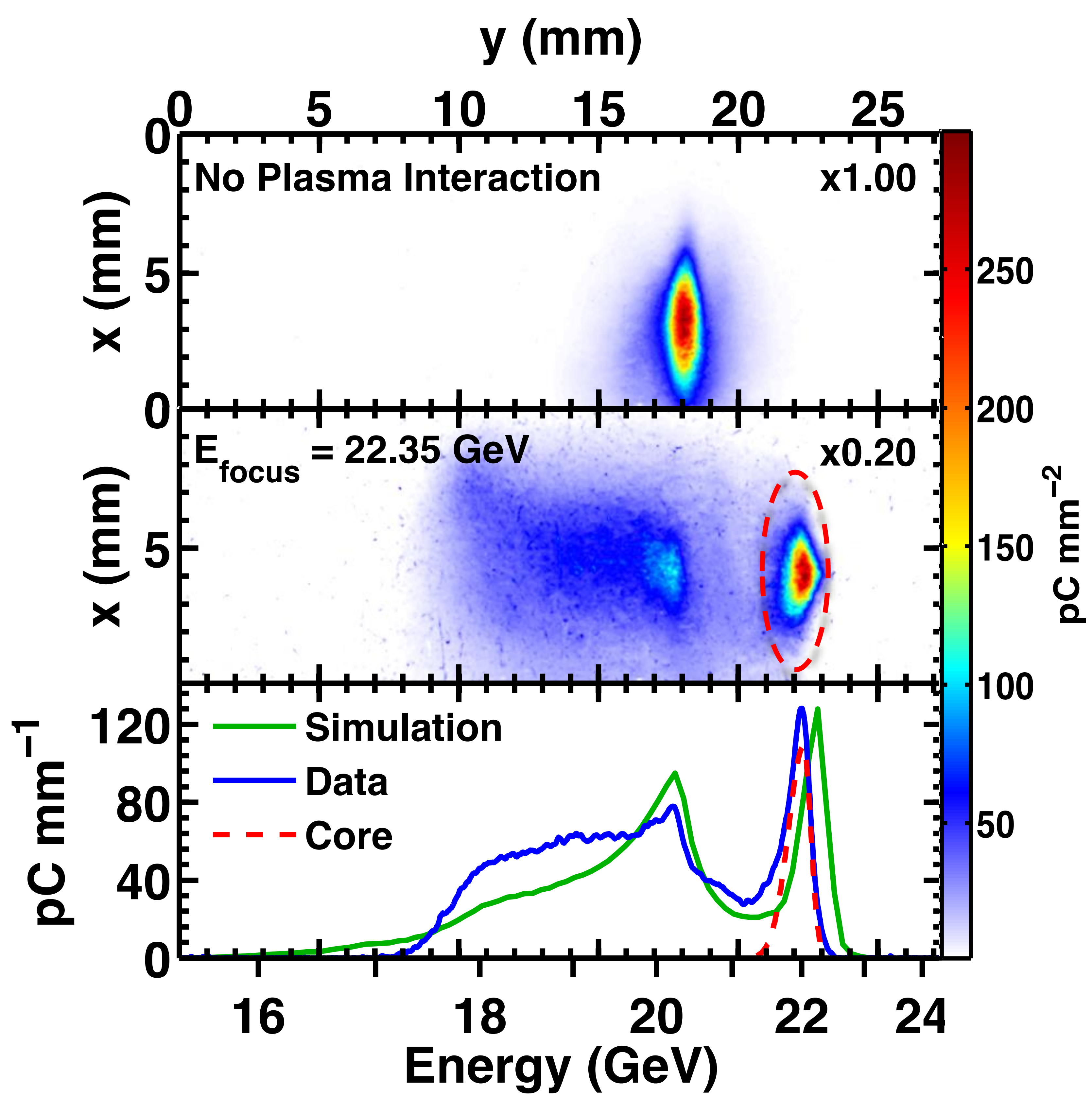


Challenges / required R&D

- **Positron acceleration**
  extensive research program at FACET, SLAC, just started
- **Coupling of two plasma stages**
  beam extraction and injection
  → beam quality preservation
  extensive research program at FLASHForward, DESY, to start in 2016
- **Single acceleration module**
  deliver beam quality
  efficient energy transfer

→ E. Adli *et al.*, SLAC-PUB-15426 (2013)

High efficiency energy transfer of up to 30% measured



by M. Litos, talk at AAC 2014

Acceleration results from FACET, SLAC

Witness bunch

- 70 pC
- accelerated by 1.7 GeV with gradient of 5 GV/m in plasma
- energy transfer from wake to beam of up to 30%

State-of-the-art

- Energy up to ~85 GeV
  → I.Blumenfeld *et al.*, Nature 445, 741 (2007)
- Transverse normalized emittance not well characterized
- Energy spread ~1% level
- Charge ~100 pC

} optimizable by witness beam shaping

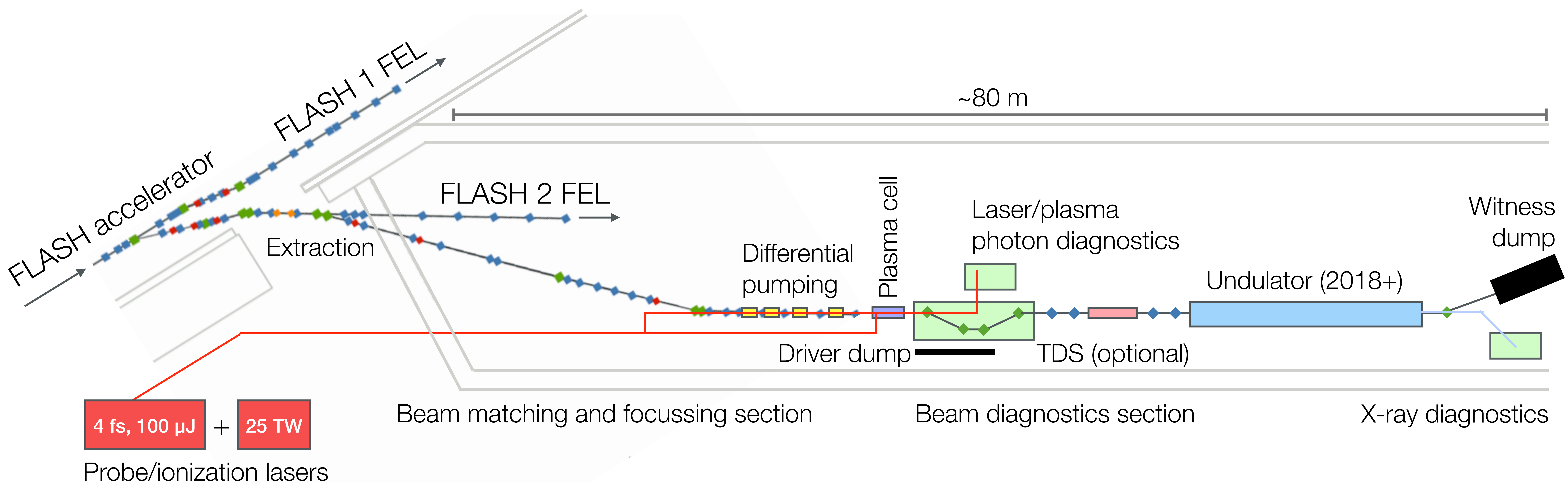
FLASHForward▸▸

Future-oriented wakefield-accelerator research and development at FLASH

Technical design in progress
Operation to start in ~2016, run for 4 years+

Research goals

- controlled in-coupling and release for future staged plasma acceleration schemes
- generation of multi-GeV, < 100 nm transverse normalized emittance, ~1 fs duration, and > 1 kA current electron bunches over acceleration distances of ~10 cm
- to drive a free-electron laser for proof of beam quality



Summary and conclusion

- Plasma-based acceleration has made enormous progress during the last decade
- Two basic collider concepts, one beam-driven, one laser-driven, have been put forward
- Concepts are intriguing, considerable challenges have to be overcome to make them work
- Required basic R&D includes
  - Beam-quality improvement, reduction in energy spread
  - Staging and beam-quality preservation, maintain high average gradient
  - Positron capturing and acceleration
  - Increase of coupling efficiency of driver-to-beam
  - *LWFA:* efficient, high-average, high-peak power laser technology
- Photon science applications will be pursued first as litmus test for plasma-accelerator technology