Deutsches Elektronen-Synchrotron DESY (May 23rd, 2012)

The Wave of the Future

Prospects for plasma-wave acceleration in particle physics.

Jens Osterhoff, *Universität Hamburg*

Outline

> Basics of plasma-based particle acceleration
> A (very) short history of laser-plasma acceleration
> Current research I: pathways to beam stability and control
> Current research II: single-stage limitations
> Envisioning a laser-plasma-based particle-beam collider
> Particle-beam-driven plasma acceleration
> Summary and conclusion

Basics of plasma-based particle acceleration

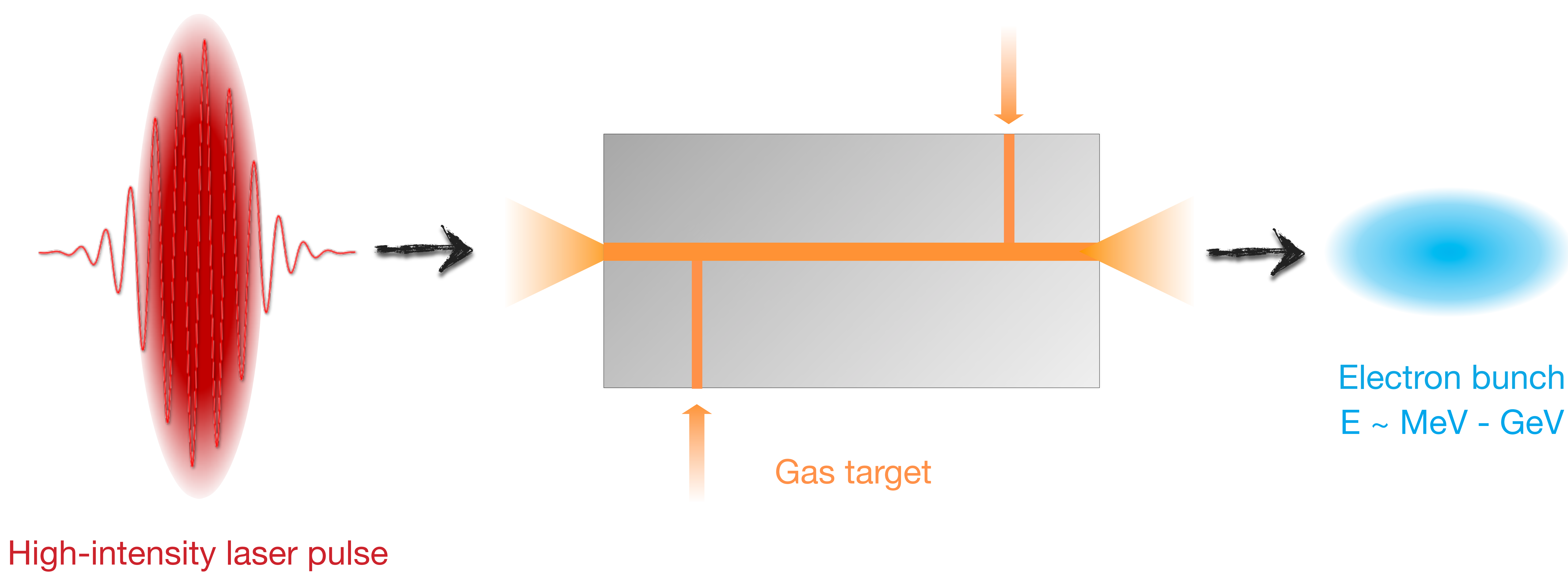
Wake excitation

Basics of plasma-based particle acceleration

Wake excitation

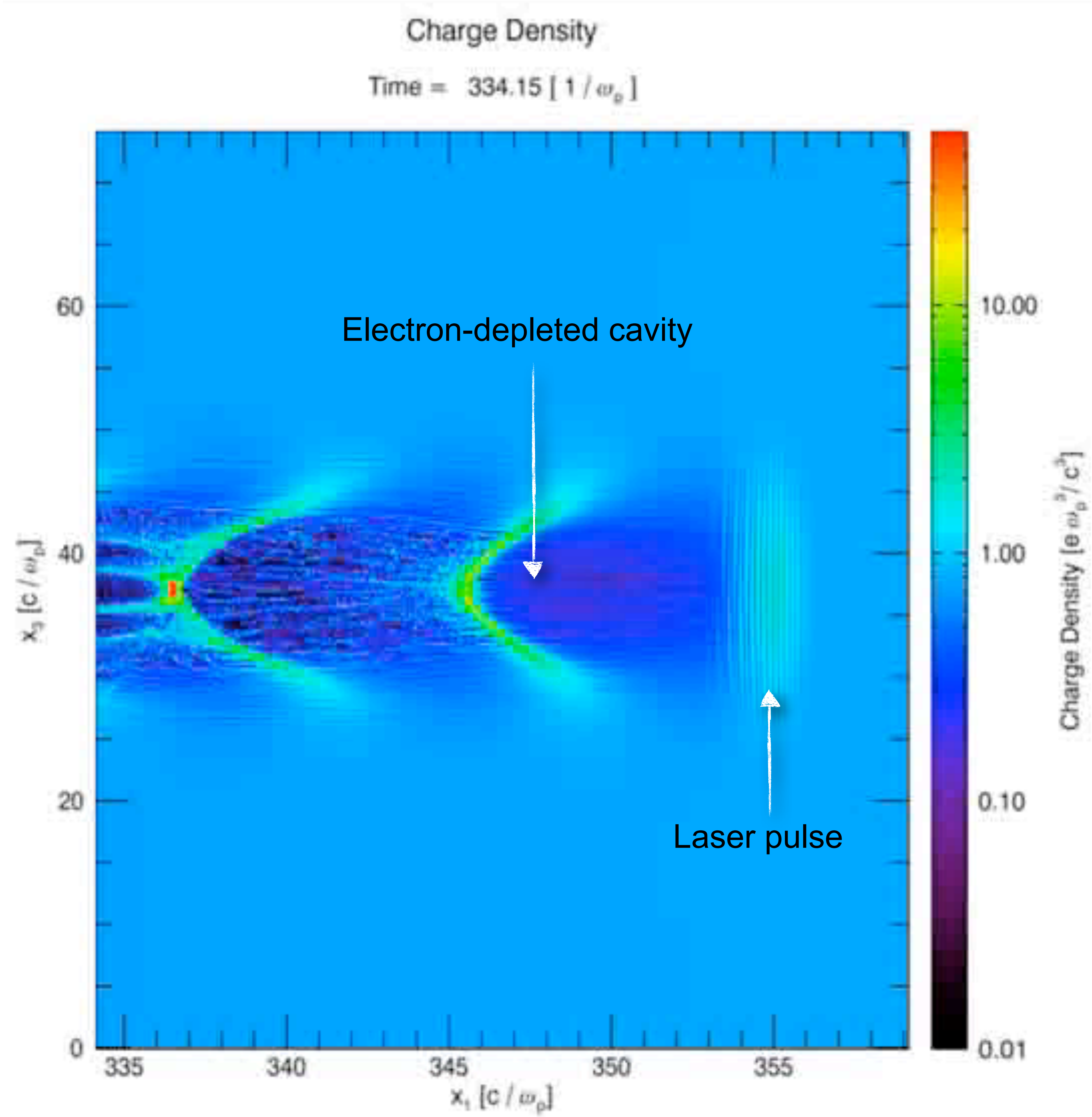
Electron injection

The most simple (and common) experimental setup



Laser excitation of strong plasma waves

- Intense laser-pulse from left to right
- Pushes away electrons by its ponderomotive force (ions are too heavy, hardly move)
- Creates electron-depleted cavity and sets up charge separation
- Strong electrostatic fields pull back electrons on axis
- Electrons oscillate and create co-propagating wakefield



Numerical solution for the scalar wake potential for a Gaussian laser-pulse envelope

1d in space
3d in momentum

$$\frac{\partial^2 \phi_0}{\partial \xi^2} = \frac{\omega_{\mathrm{p}}^2}{2c^2}\left[\frac{1+a_0^2}{(1+\phi_0)^2} - 1\right]$$

Temporal laser-pulse shape in intensity

$$a^2(\xi) = {a_0}^2 \, \exp\left[-\left(\frac{\xi-\xi_0}{L}\right)^2 4\log(2)\right]$$

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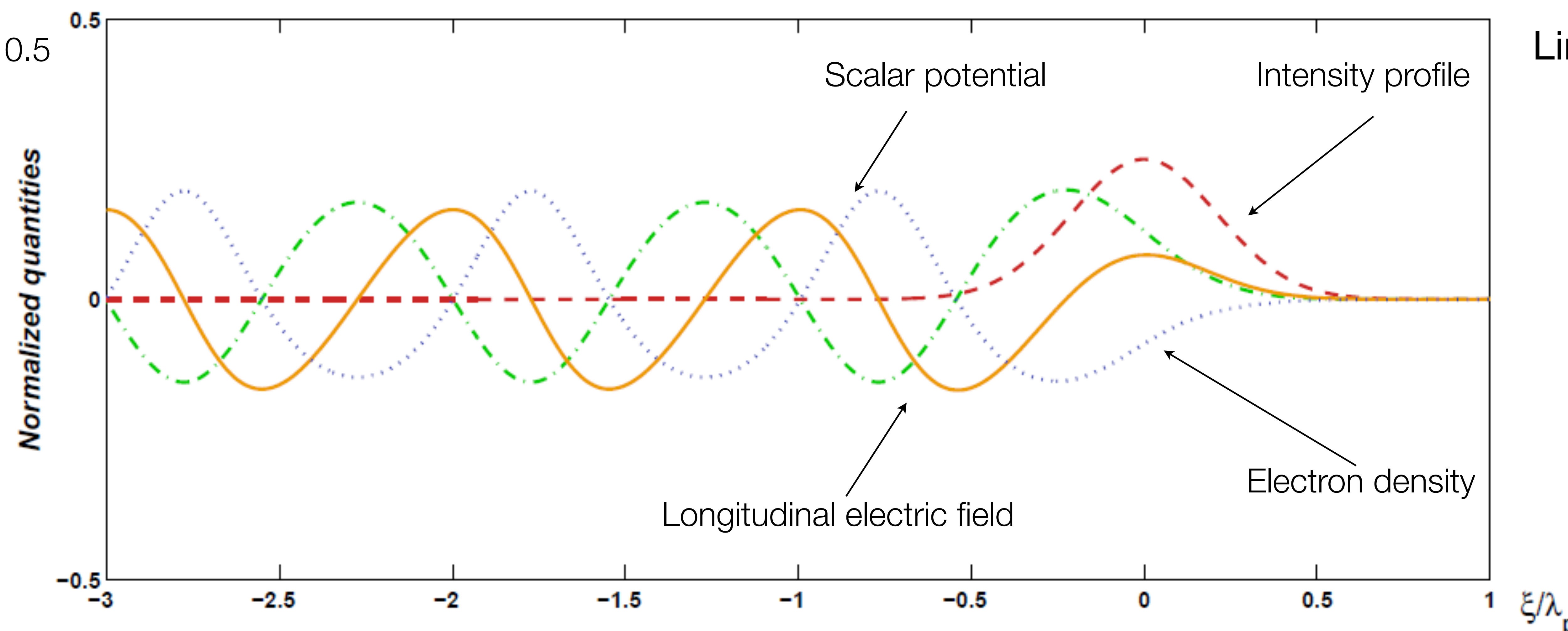
$a_0 = 0.5$



Linear regime

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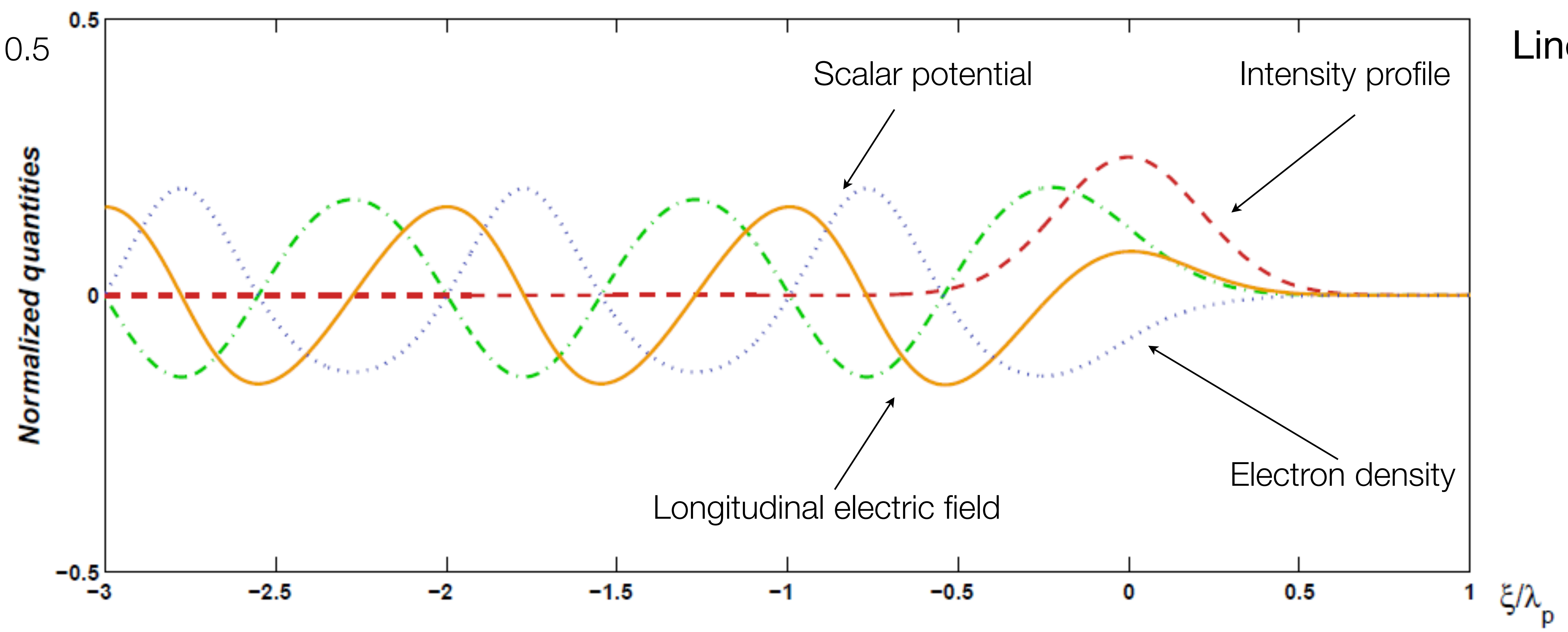
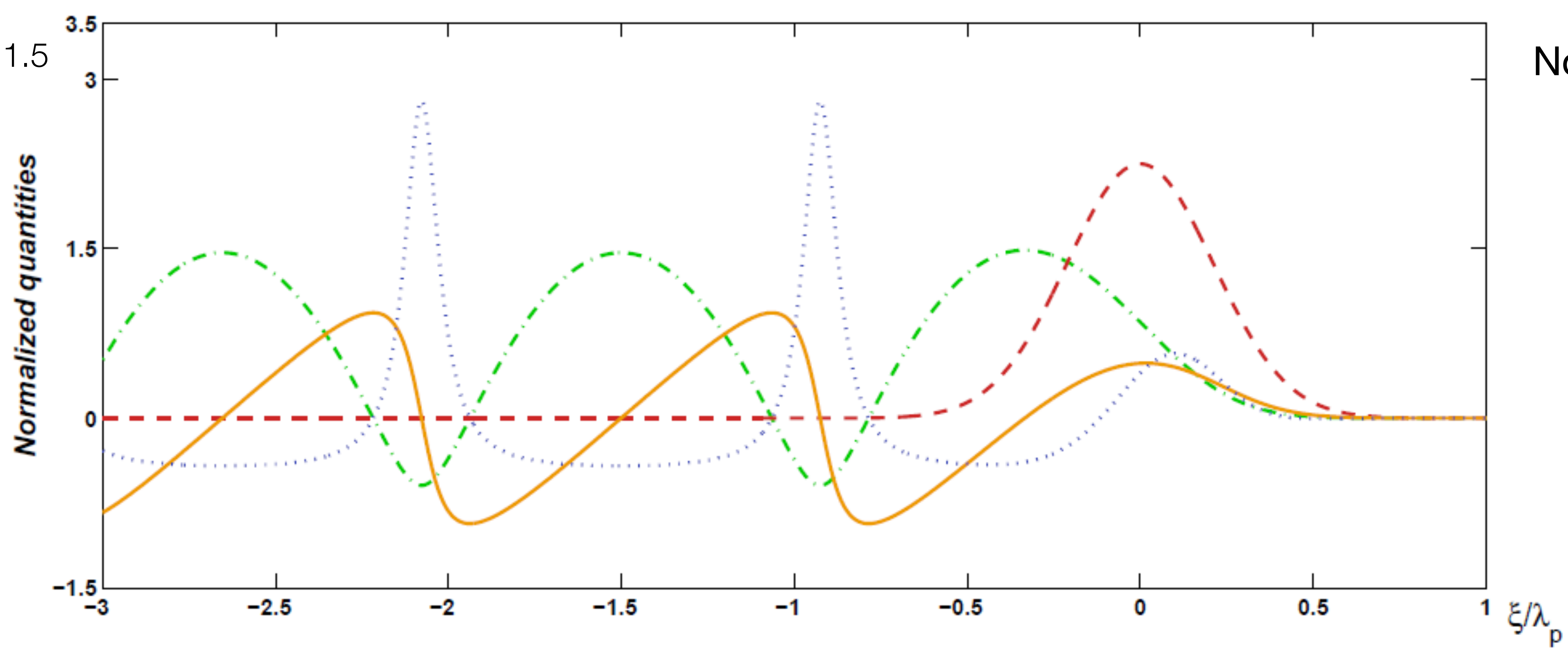


Linear regime

$a_0 = 1.5$



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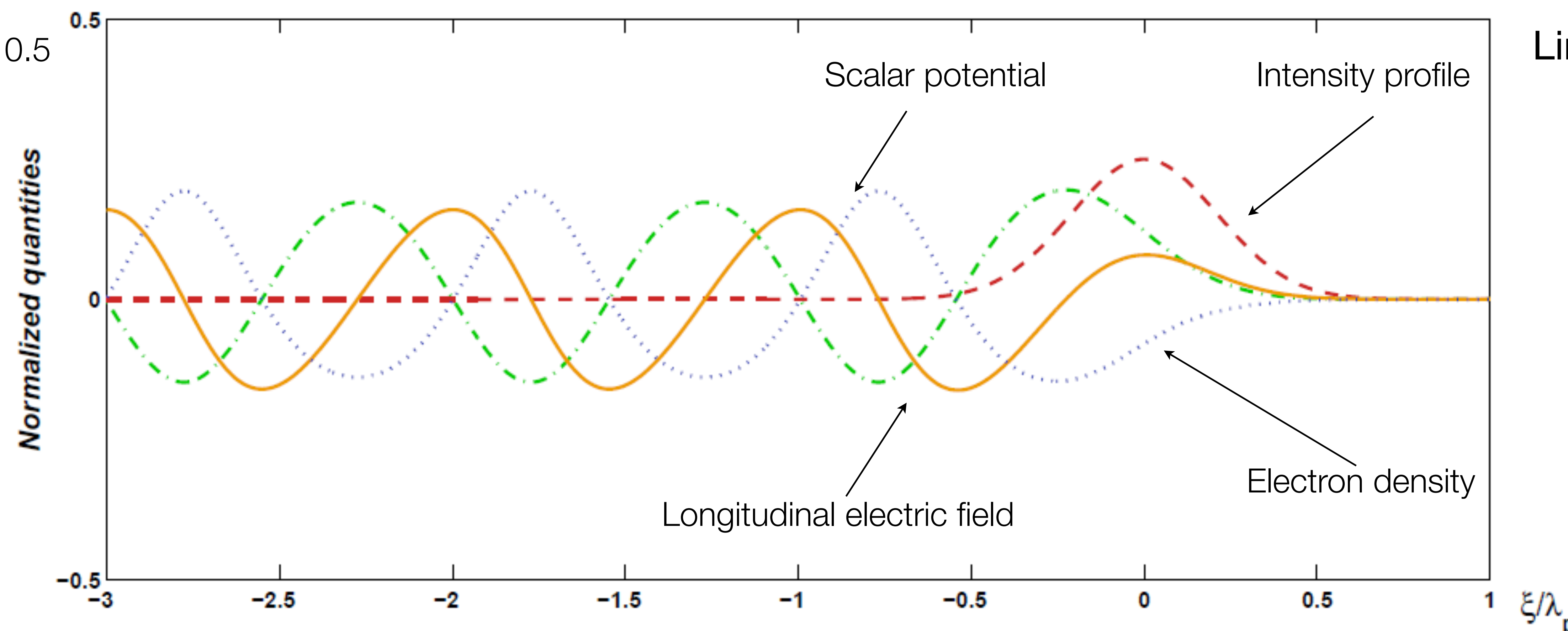

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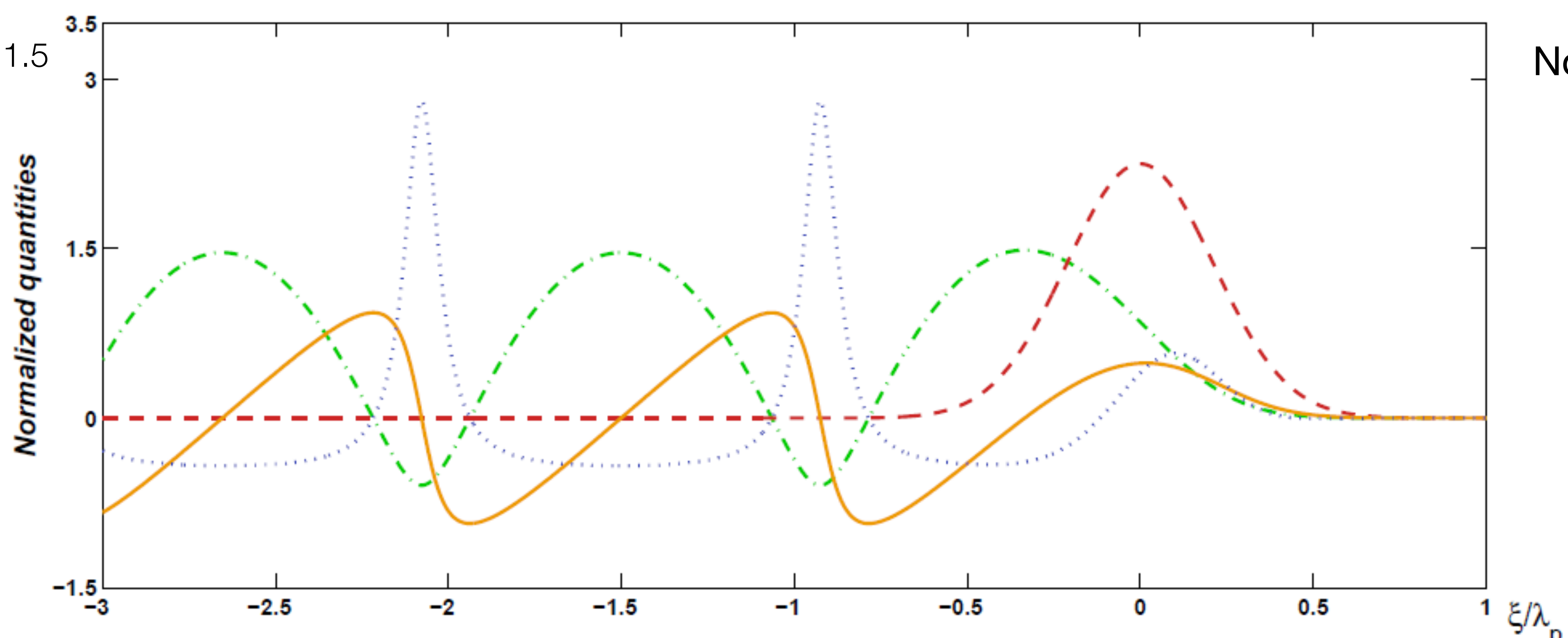


Nonlinear regime

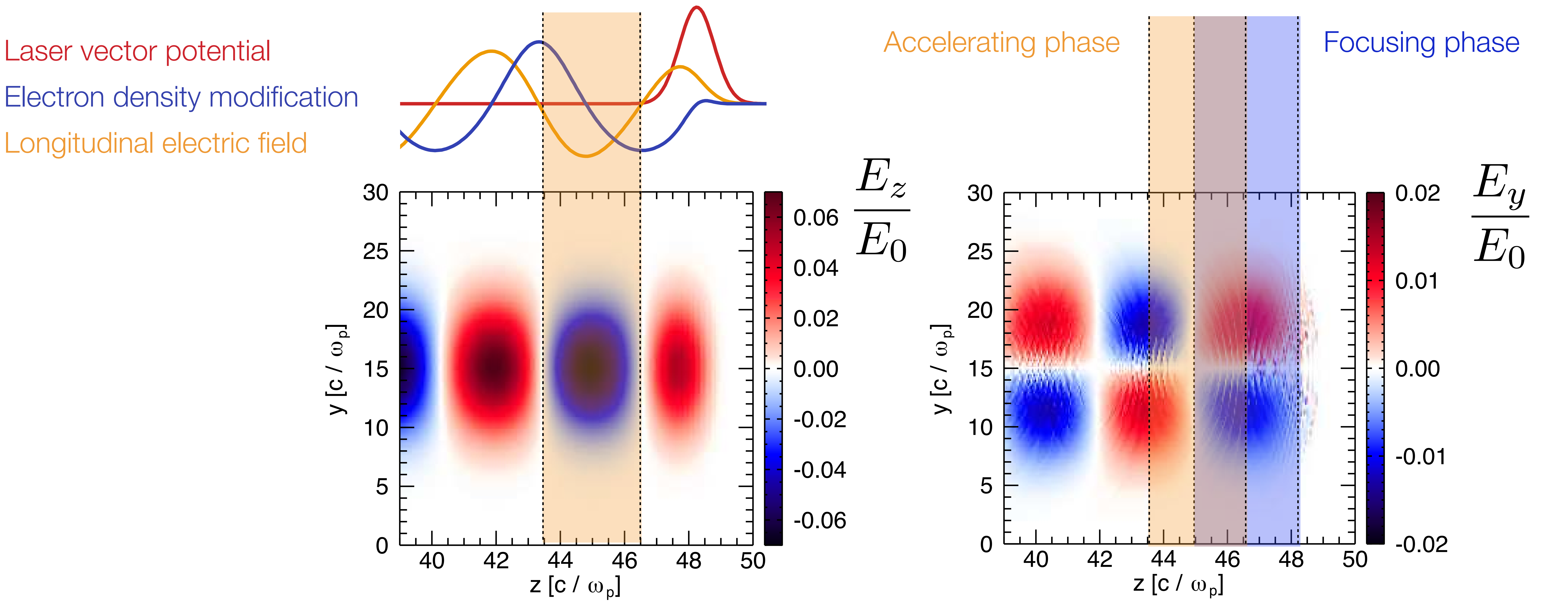
Accelerating field strength

$$E \sim \left(\frac{mc\omega_p}{e}\right)\frac{a^2}{\left(1+a^2/2\right)} \approx (96\mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}\,\frac{a^2}{\left(1+a^2/2\right)}$$

e.g. $E \approx 100$ GV/m (for $n \approx 10^{18}$ cm^{-3}, $a \approx 1$)

Transverse wakefield properties

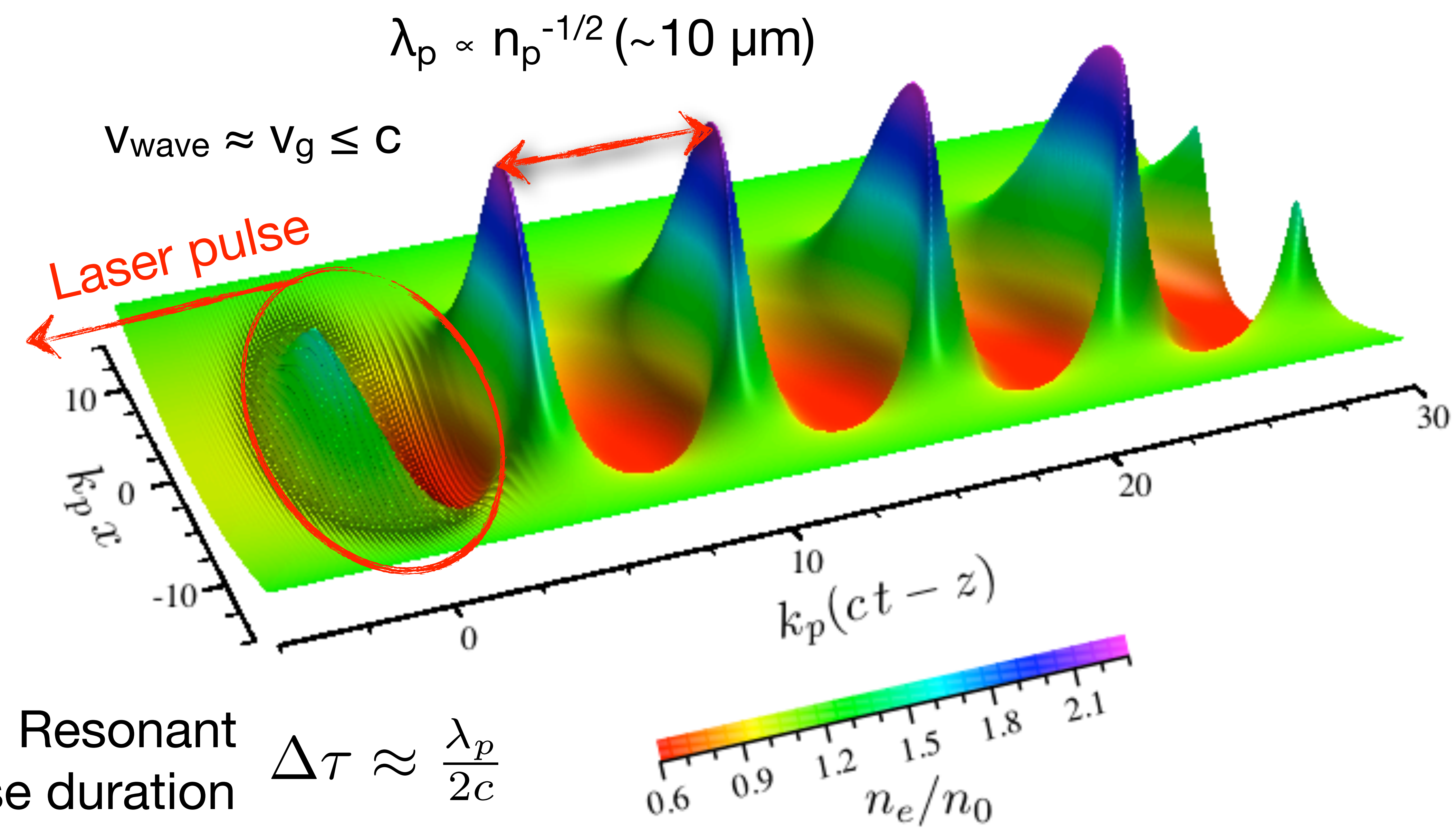
3d in space
3d in momentum



Longitudinal fields
of a quasi-linear plasma wave

Transverse fields
of a quasi-linear plasma wave

Plasma-based accelerators generate intrinsically short beams



Resonant pulse duration $\Delta\tau \approx \frac{\lambda_p}{2c}$

$$\Delta\tau_e \ll \frac{\lambda_p}{c}$$

e.g. $\Delta\tau_e \ll 50$ fs
(for n ≈ 5×10^{18} cm^{-3}, a ≈ 1)

↓

High peak currents:
I ≳ 10 kA (for Q ≈ 100 pC)

↓

Ideal for driving high-brightness photon sources

Advantages of plasma acceleration over conventional technology

- High gradients for acceleration > 10 GV/m vs. < 100 MV/m for RF-technology
- Intrinsically short pulse duration of ~10 fs
- Synchronization to other laser-driven particle/photon sources down to sub-fs time scales (for laser-driven accelerators)

A short history of laser-plasma acceleration: the start

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

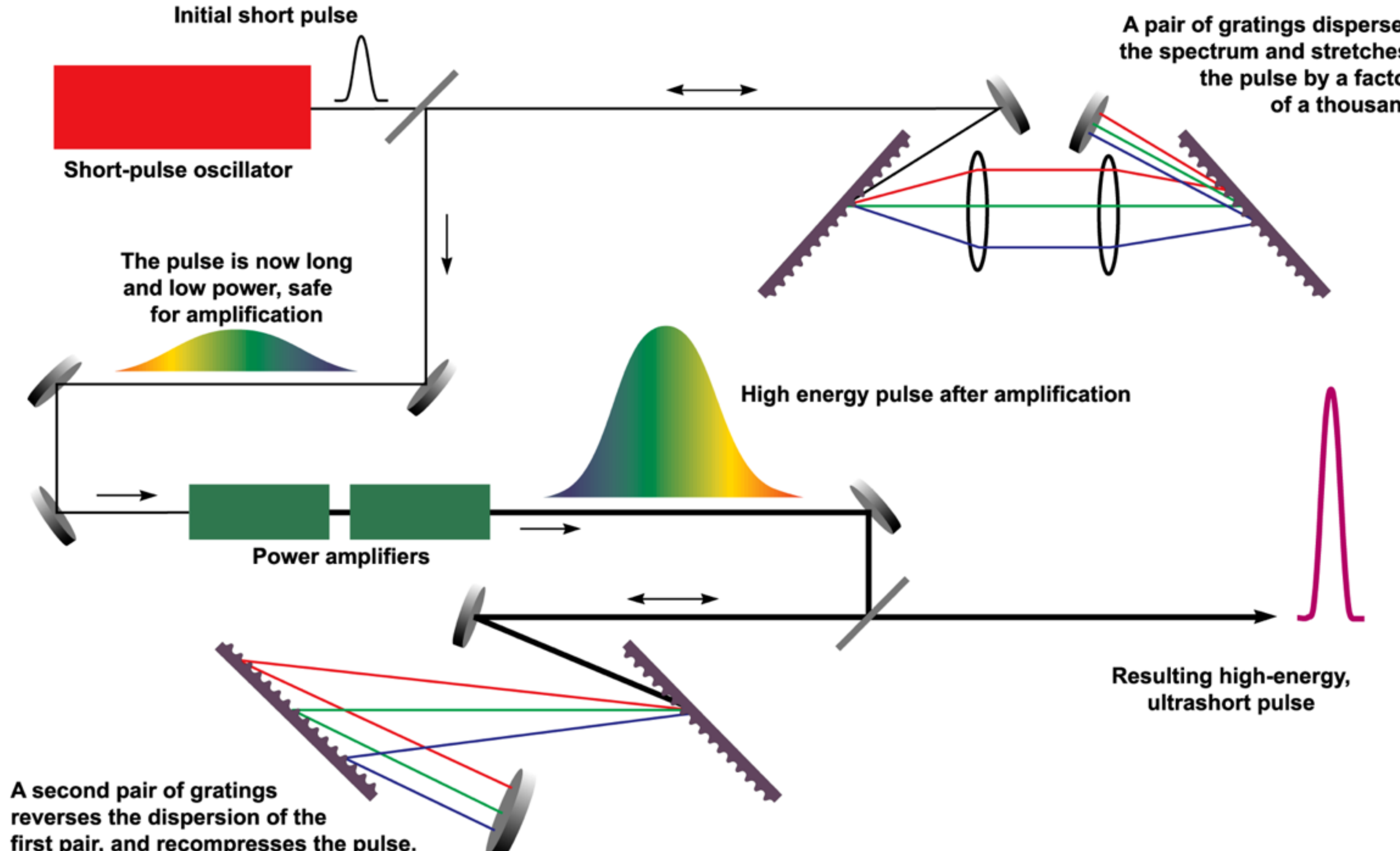
An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.

- Great idea of a theorist!
- But common theorist problem: in reality these lasers could not be build at the time…

…they self-destroyed!

The invention of chirped-pulse amplification

→ Strickland and Mourou, *Opt. Comm.* **55**, 447 (1985)



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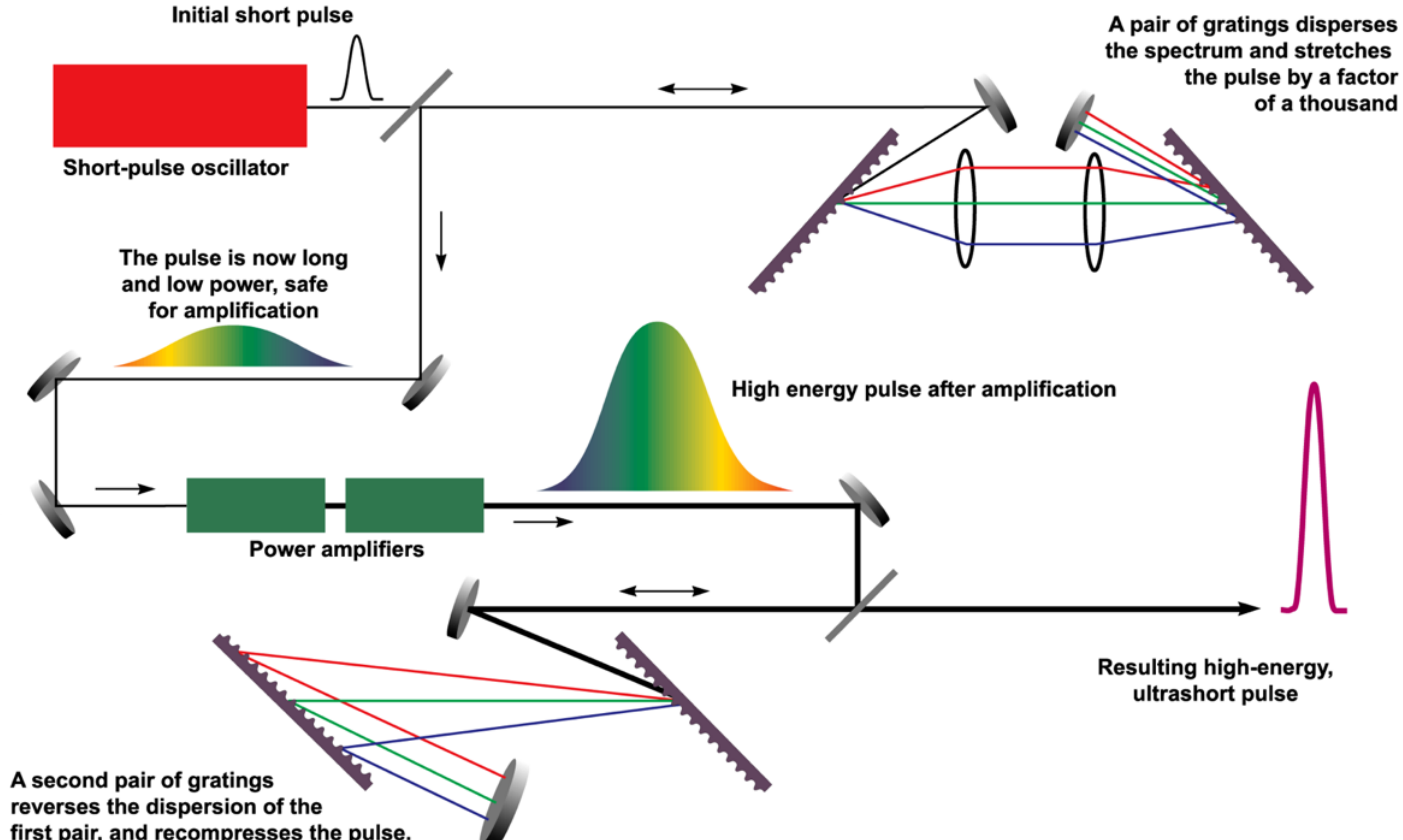
- CPA solved laser self-destruction problem
- Laser intensities nowadays into the few 10^{22} W/cm^2
- Technology and physics understanding took another 10 years to mature before wavebreaking was observed

→ Modena et al., *Nature* **377**, 606 (1995)



Electron self-injection by breaking of the plasma wave

- Laser pulse may undergo self-focussing and self-compression
- Wave can continuously break in an uncontrolled fashion
- Small fluctuations in laser and plasma conditions may lead to vastly different results

Electron depleted cavity

Trapped electrons

Laser pulse

Initial laser pulse
$a = 2$
$\lambda_c = 800$ nm
$\Delta\tau = 25$ fs FWHM
$w_0 = 23$ μm FWHM

Plasma density
$n_p \leq 5\times10^{18}$ cm^{-3}

osiris v2.0

3D particle-in-cell (PIC) simulation

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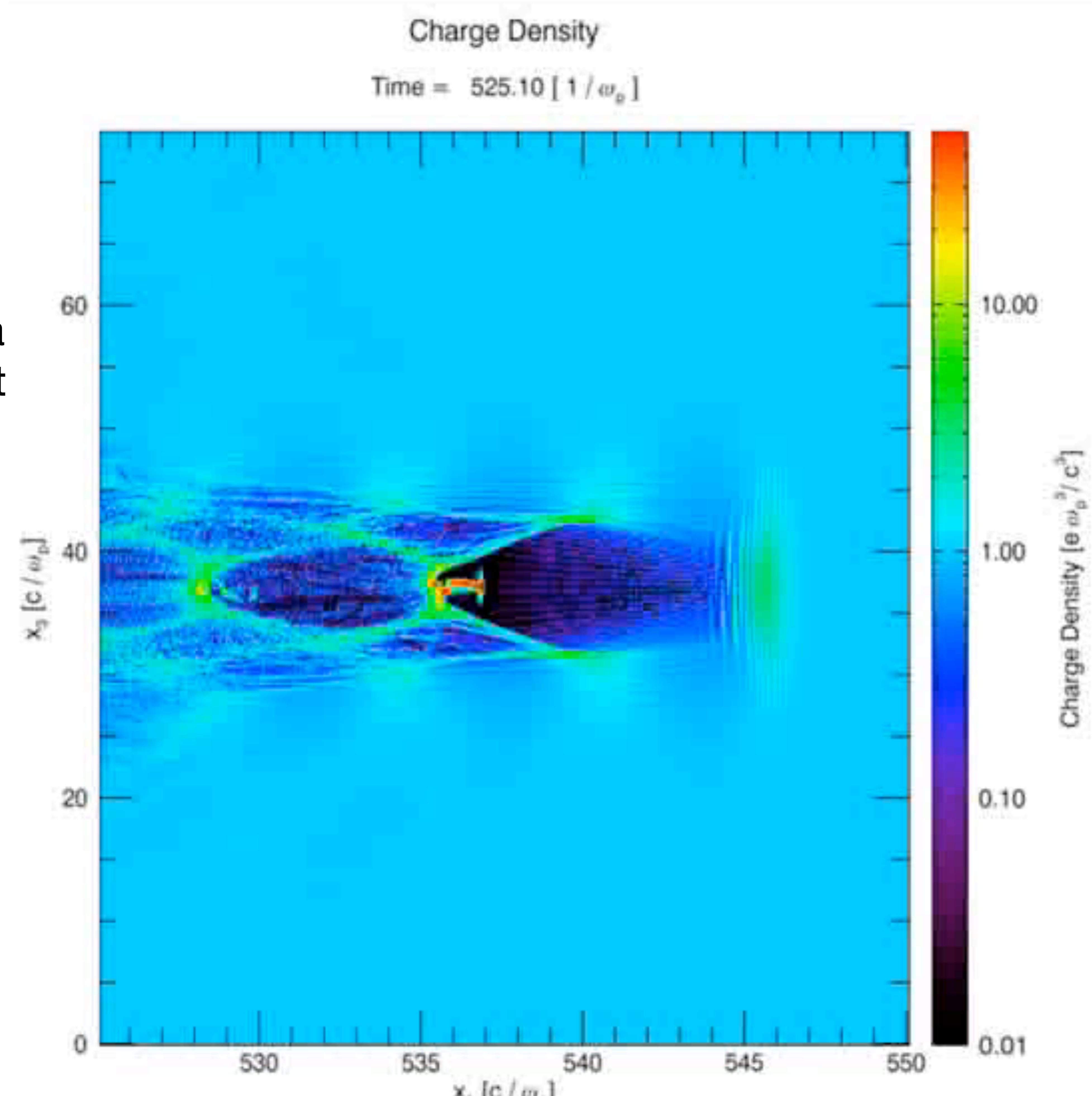

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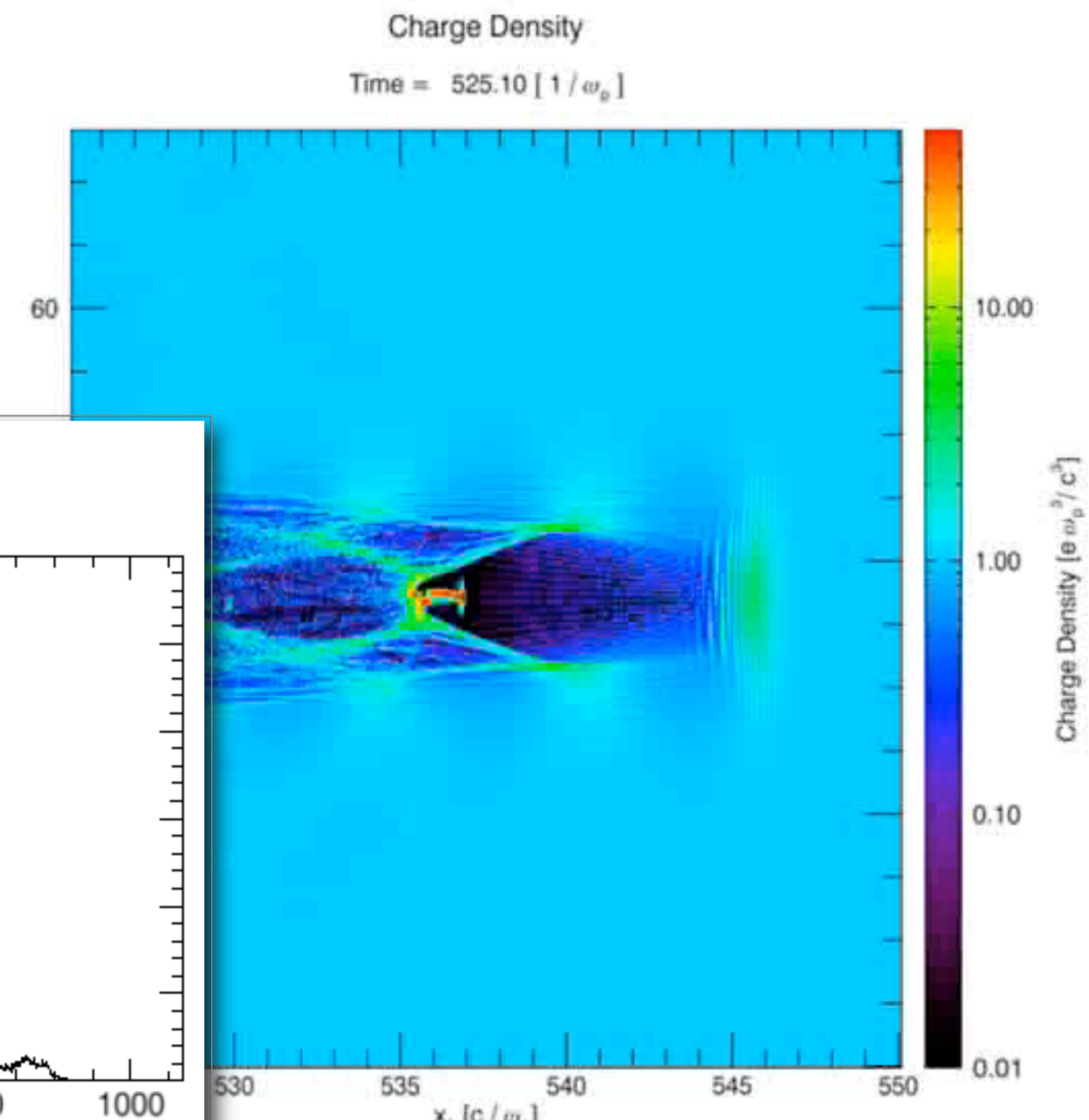

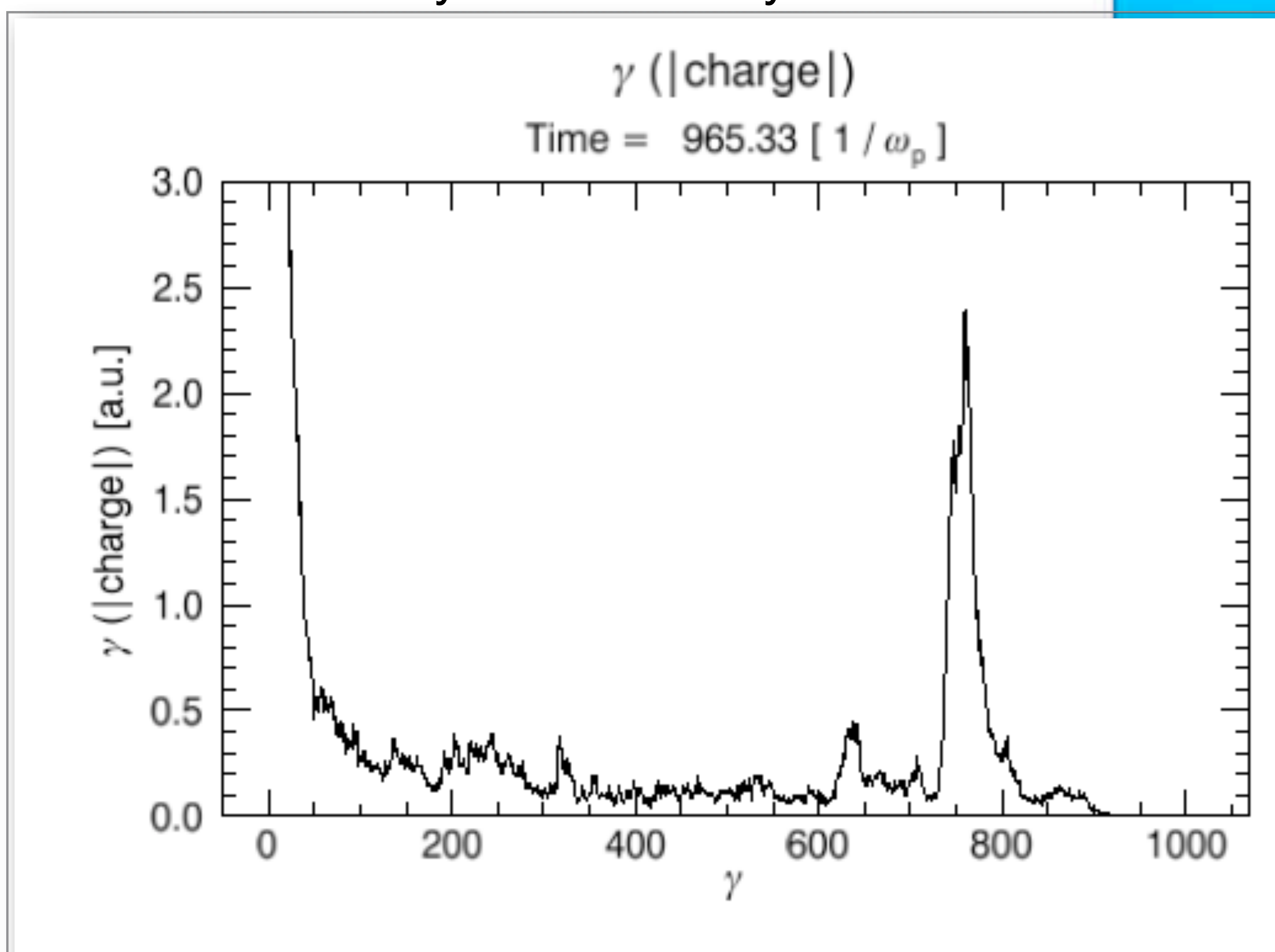

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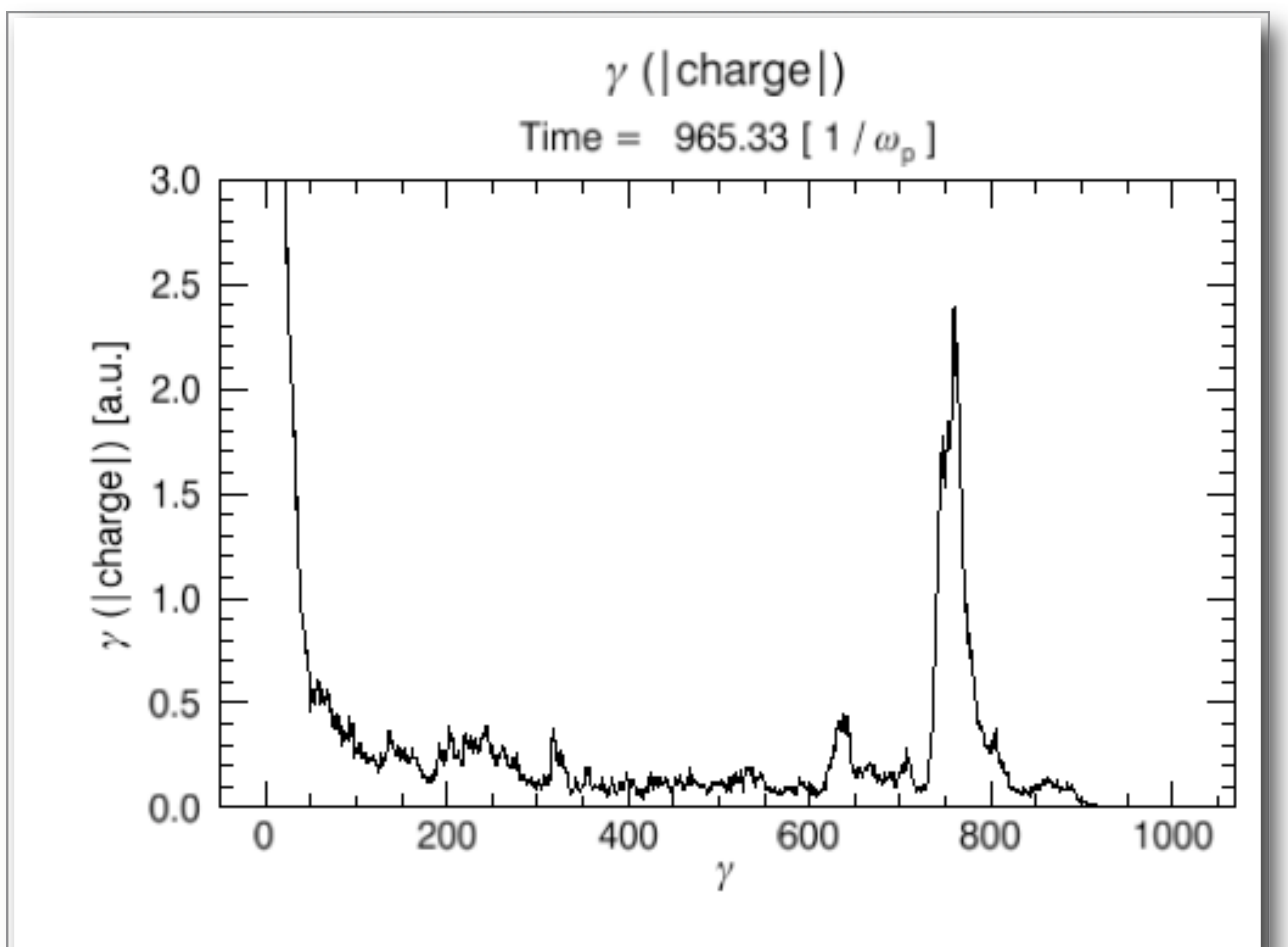
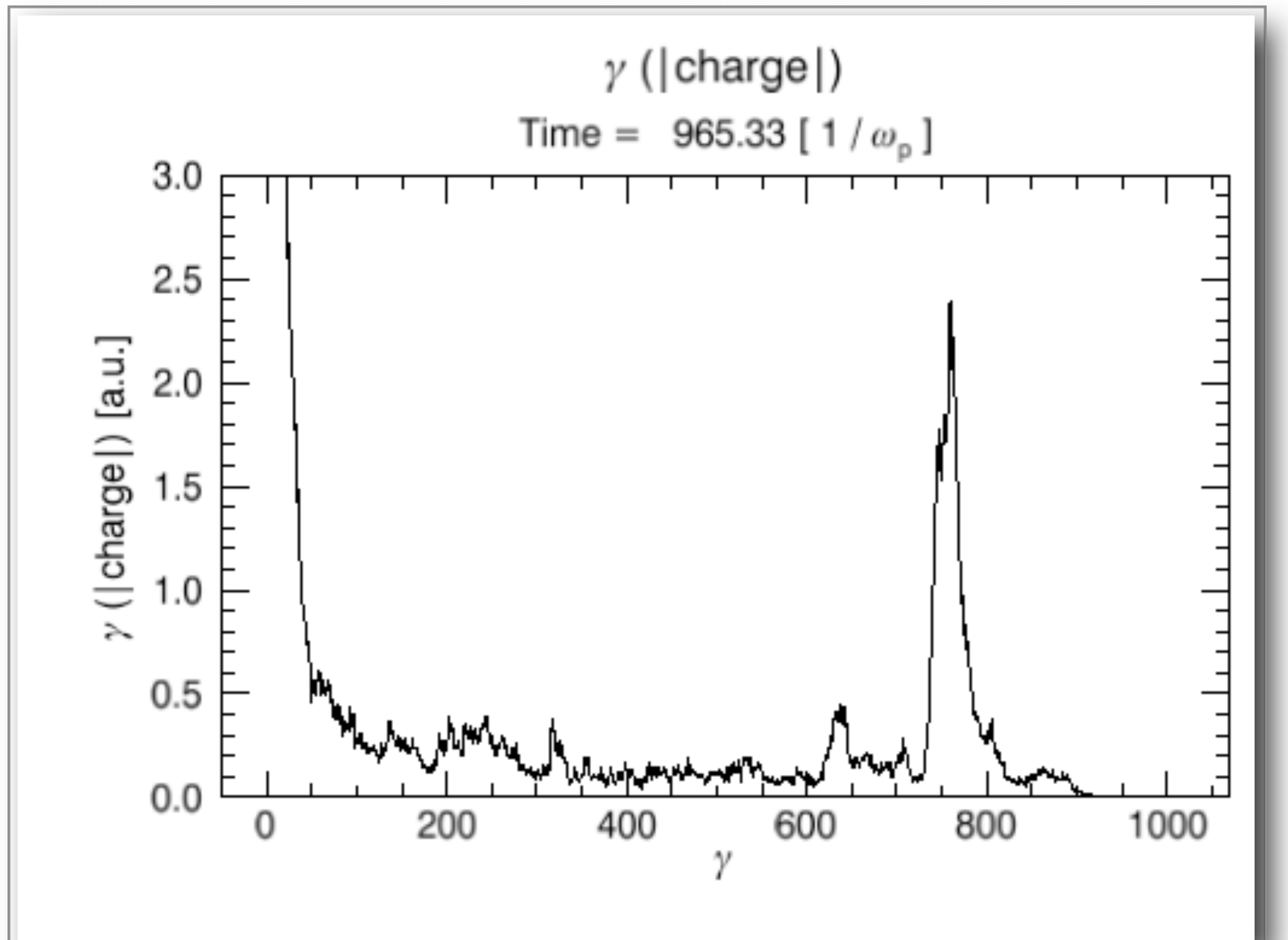
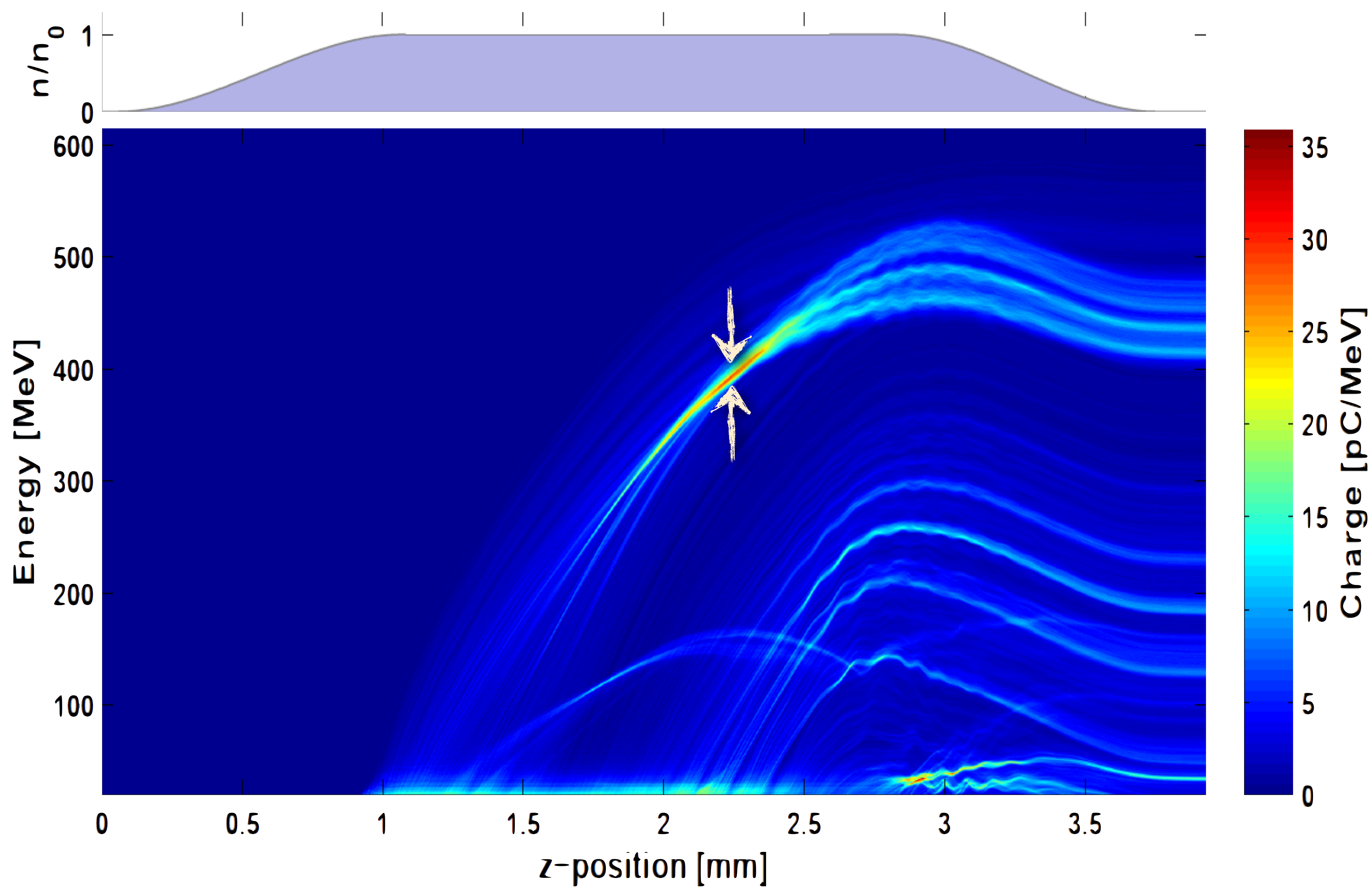


Self-injection may lead to quasi-monoenergetic features

→ Pukhov and Meyer-ter-Vehn, *Appl. Phys. B* **74**, 355 (2002)

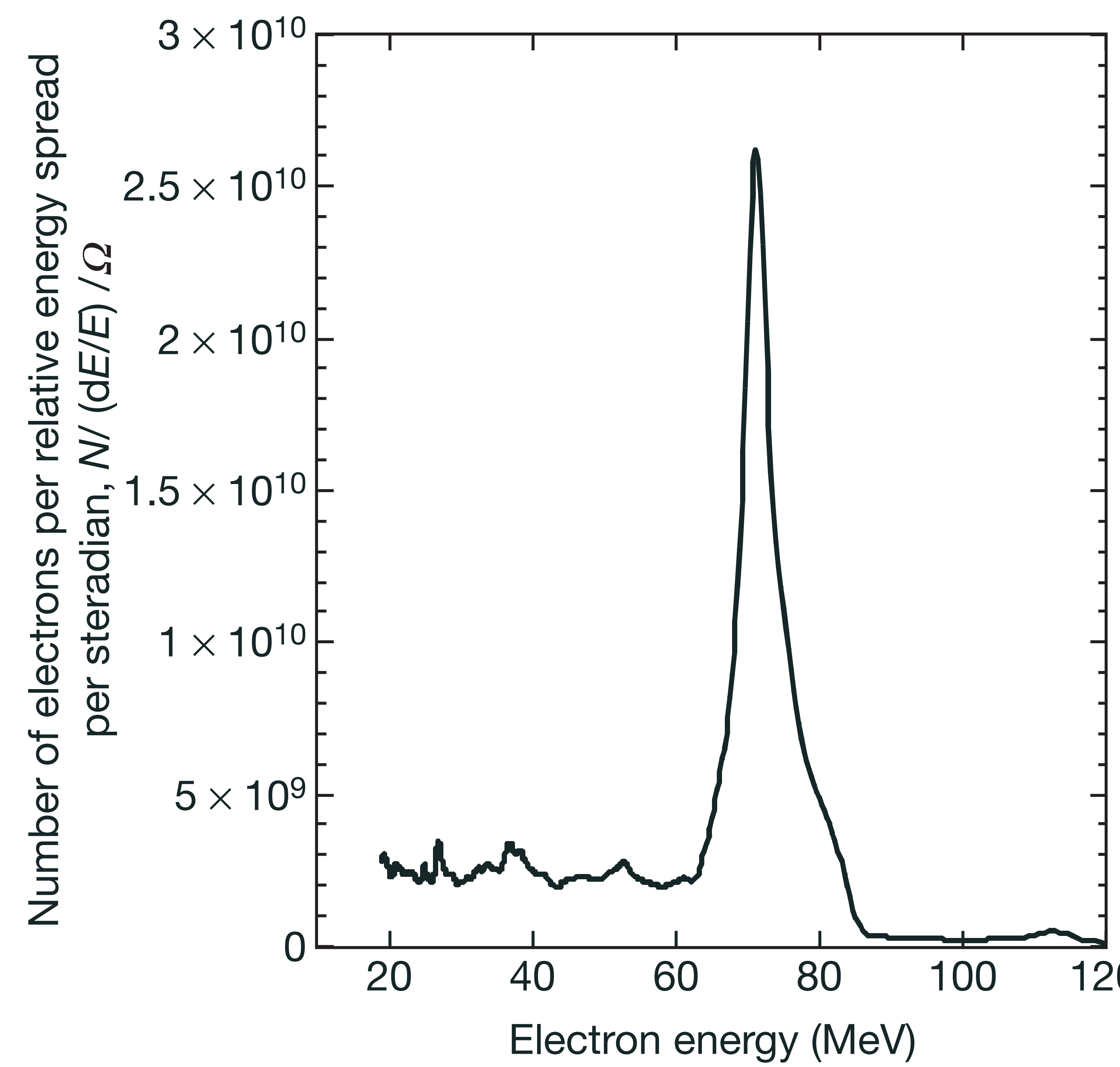




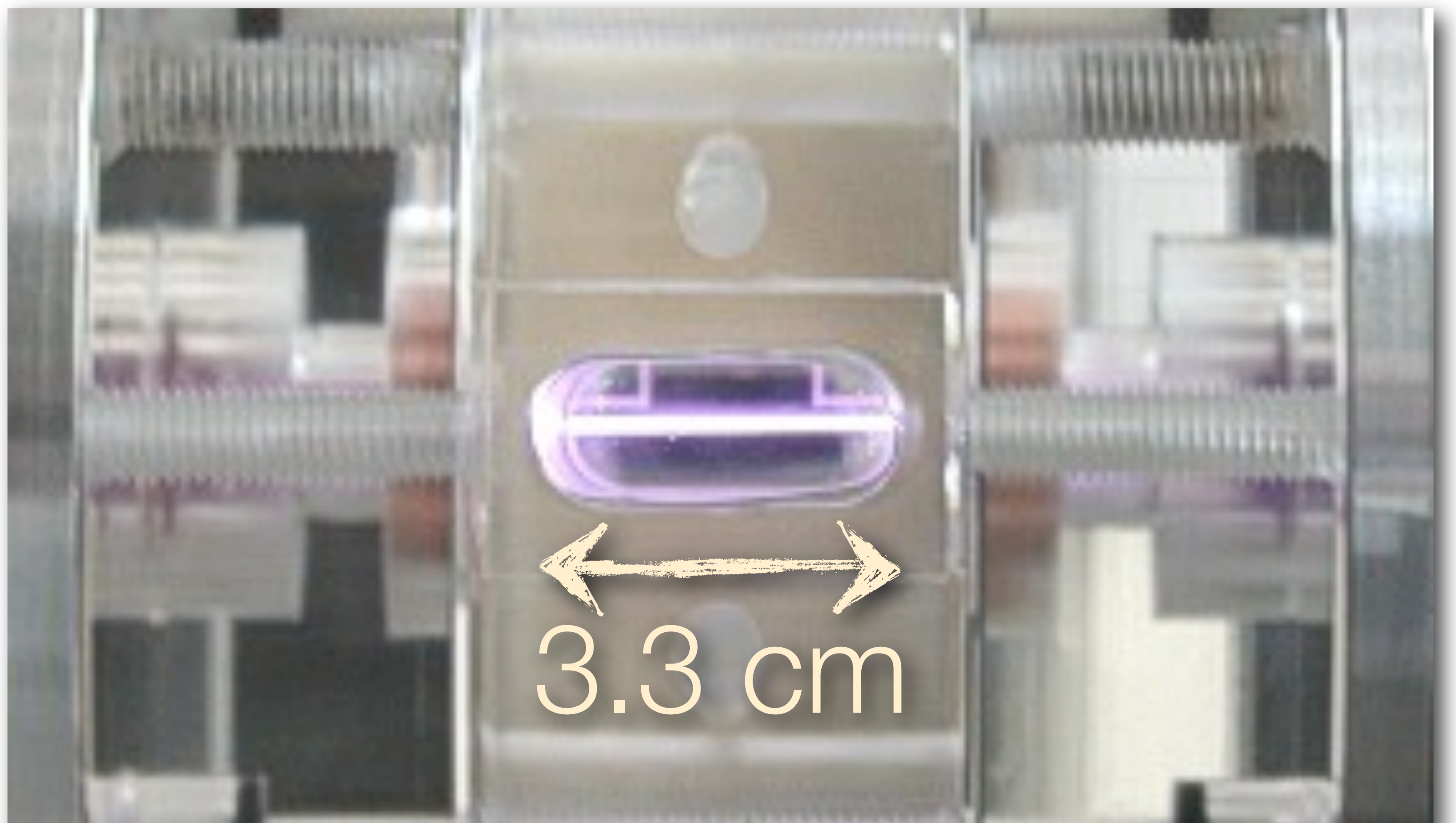
- Quasi mono-energetic spectral features may develop by *dephasing* and *dynamic changes* in the accelerating field profile
- However, broadband spectral tail and shot-to-shot fluctuations hard to avoid

A short history of laser-plasma acceleration: dream beams

Mangles et al., *Nature* **431**, 535 (2004)
Geddes et al., *Nature* **431**, 538 (2004)
Faure et al., *Nature* **431**, 541 (2004)



A short history of laser-plasma acceleration: GeV beams

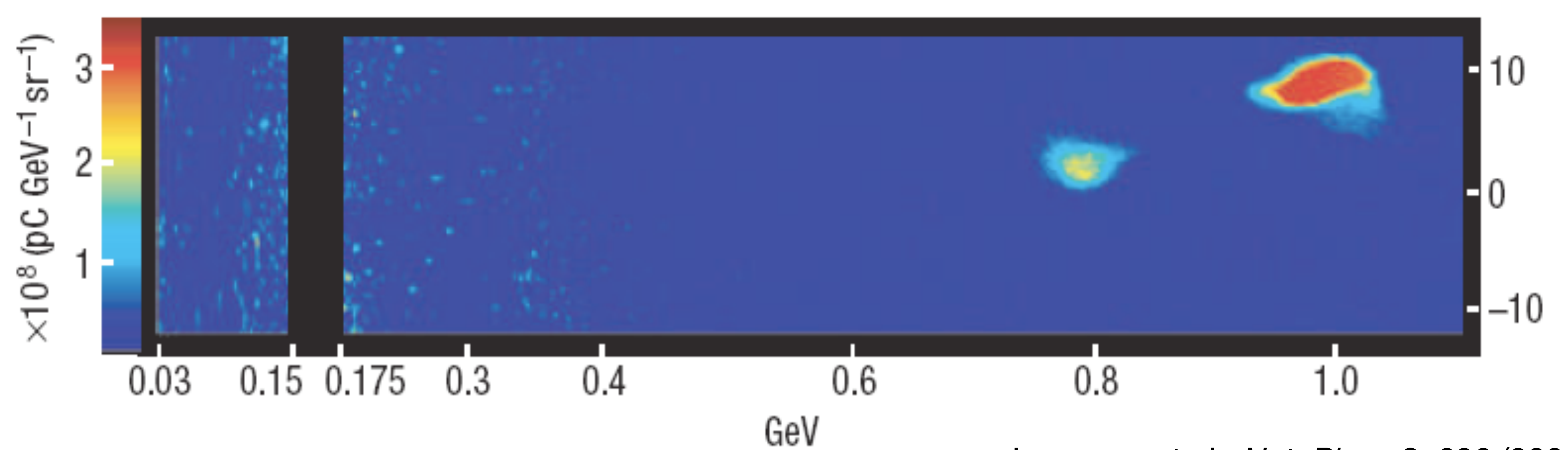


> Plasma channels to increase energy

40 TW laser pulse (3×10^{18} W/cm^2 intensity) into a plasma of density $n_e = 4.3\times10^{18}$ cm^{-3}

→ 30 pC of electrons at ~1 GeV

Average accelerating field strength > 33 GV/m



→ Leemans et al., *Nat. Phys.* **2**, 696 (2006)

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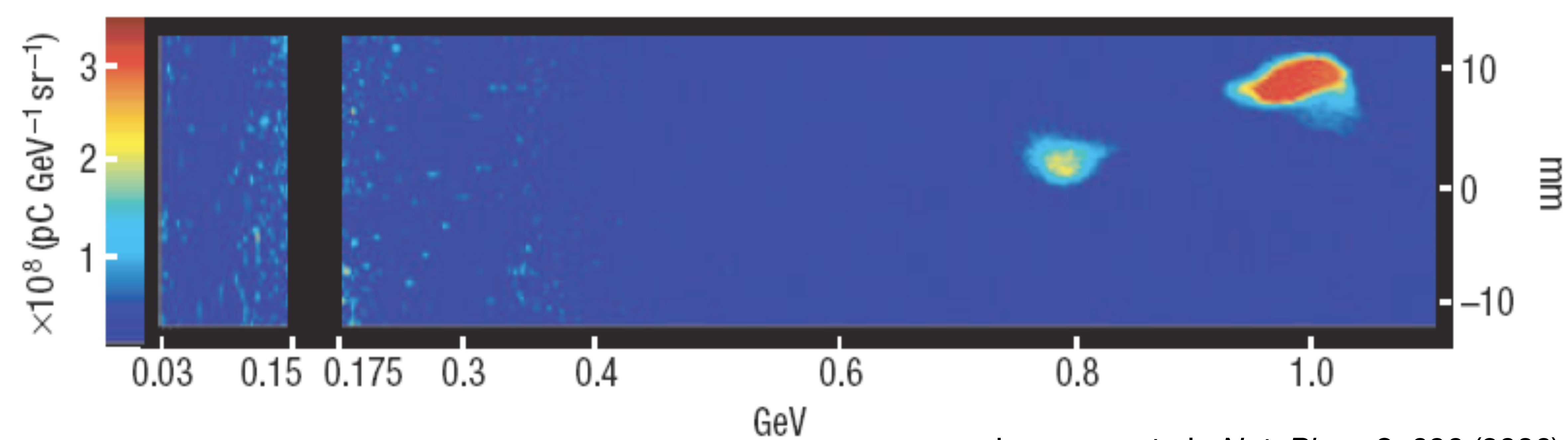

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Strategy towards stable plasma-based electron-beam sources

Electron beam fluctuations originate from

variations in
laser pulse parameters
(spatial and temporal energy profiles, pointing)

amplified through
nonlinear processes

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(mainly three-dimensional density profile)

(laser self-modulation effects, wavebreaking)

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Influence of intensity-pulse-front tilt:
Popp *et al.*, Phys. Rev. Lett. 105, 215001 (2010)

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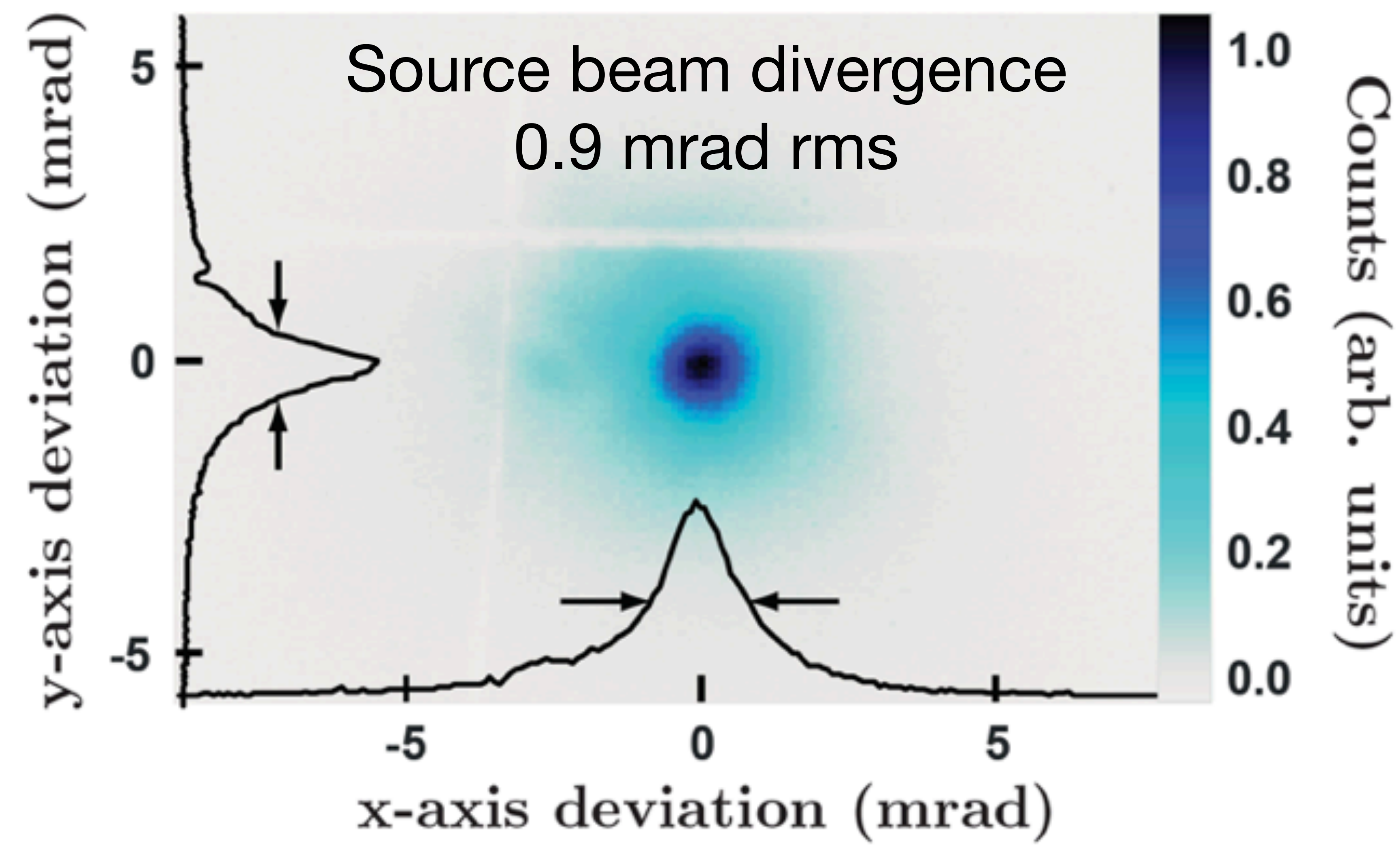
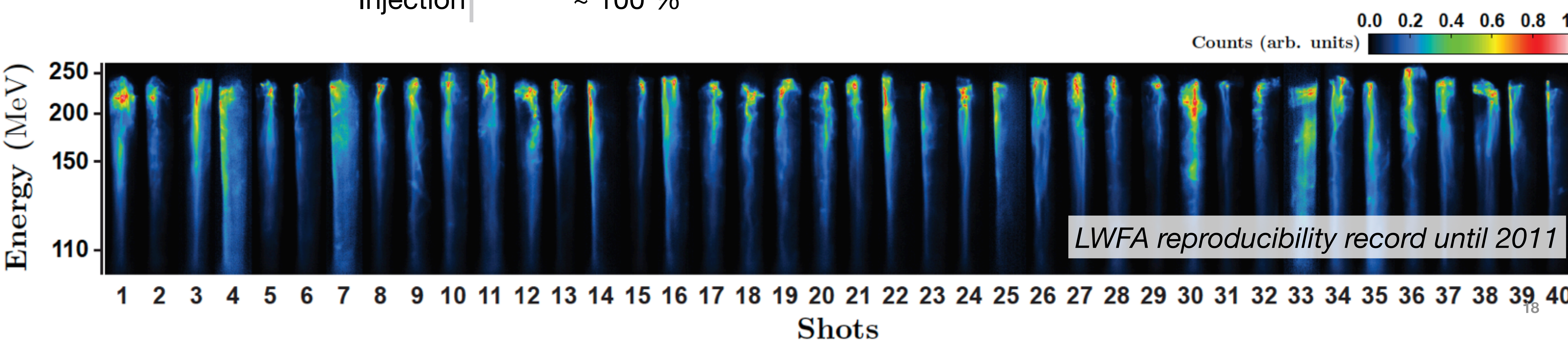
Osterhoff *et al.,* Phys. Rev. Lett. 101, 085002 (2008)

A steady-state-flow gas cell stabilizes plasma conditions

Acceleration results	Gas cell
Peak energies	220 MeV
Energy fluctuations	± 2.5 %
Energy spread	> 2 % RMS
Peak charge	~ 10 pC
Charge fluctuations	±16 %
Divergence	0.9 mrad RMS
Pointing stability	1.4 mrad RMS
Injection	~ 100 %

J. Osterhoff *et al.*,
Phys. Rev. Lett. 101, 085002 (2008)





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a) mildly nonlinear wake → no dark current

b) control of phase space population by controlled injection:

- density downramp injection
  Bulanov et al., Phys. Rev. E 58, R5257 (1998); Geddes et al., Phys. Rev. Lett. 100, 215004 (2008)
- well-localized ionization injection
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  Esarey et al., Phys. Rev. Lett. 79, 2682 (1997); Faure et al., Nature 444, 737 (2006)
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  Dewa et al., Nucl. Instrum. & Methods Phys. Res. A 410, 357 (1998); Dorchies et al., Phys. Plasmas 6 2903 (1999)

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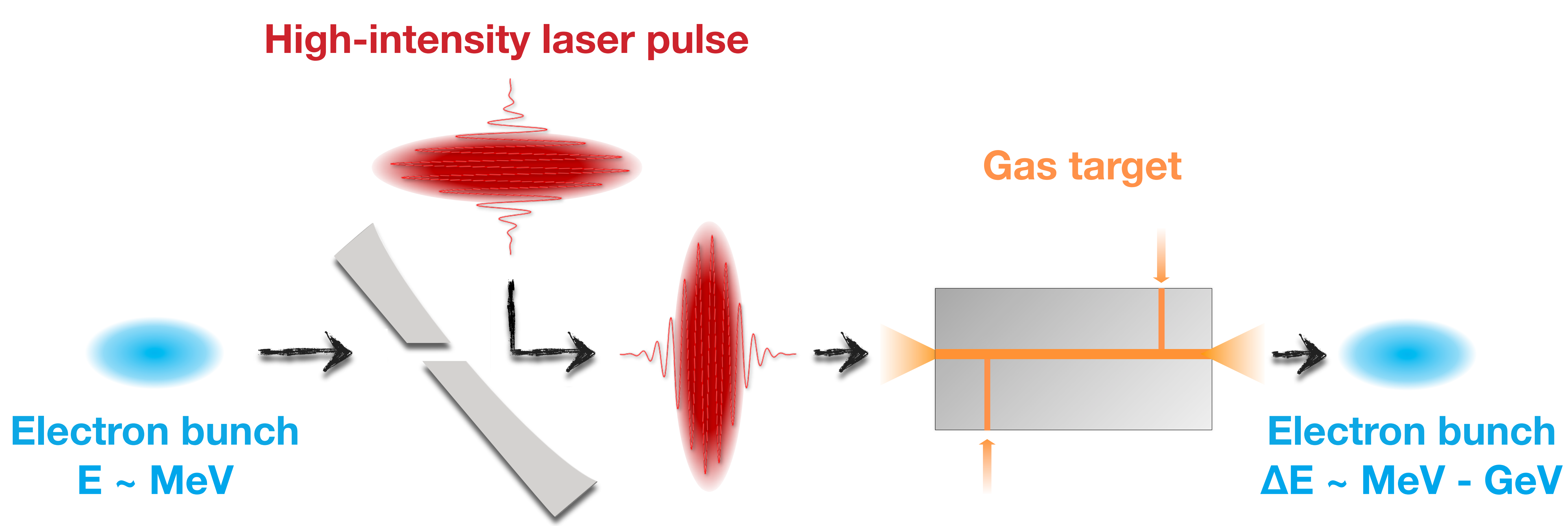
External beam injection offers maximal control over phase-space population

Post-acceleration of tailored beams from conventional sources in a plasma allows to

- start from a well-characterized, 6d-tunable (space and momentum), stable electron beam
  → shaped and chirped beams to control beam-loading effects and final energy spread
- fine-tune the plasma-wave phase-space population
  → gives control over charge, emittance, energy spread
- operate the wake in a mildly nonlinear regime ($a_0 \approx 1$) and prevent dark-current generation
- potentially useful to inject and accelerate other types of charged particles (positrons, muons, protons)



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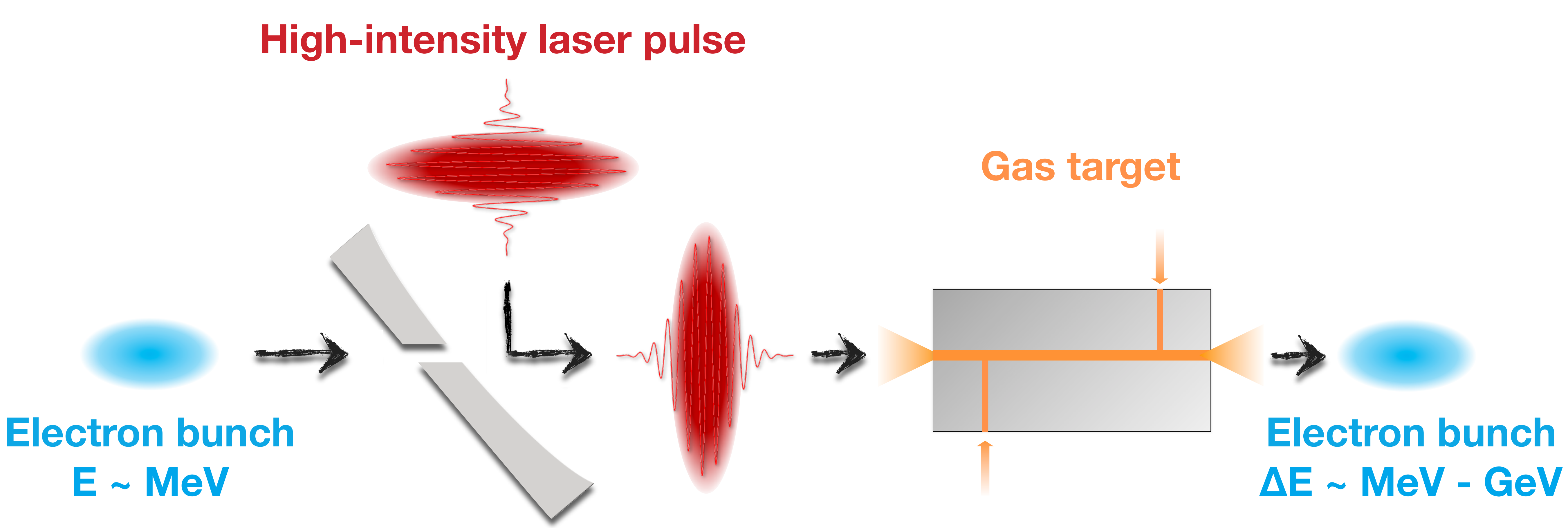
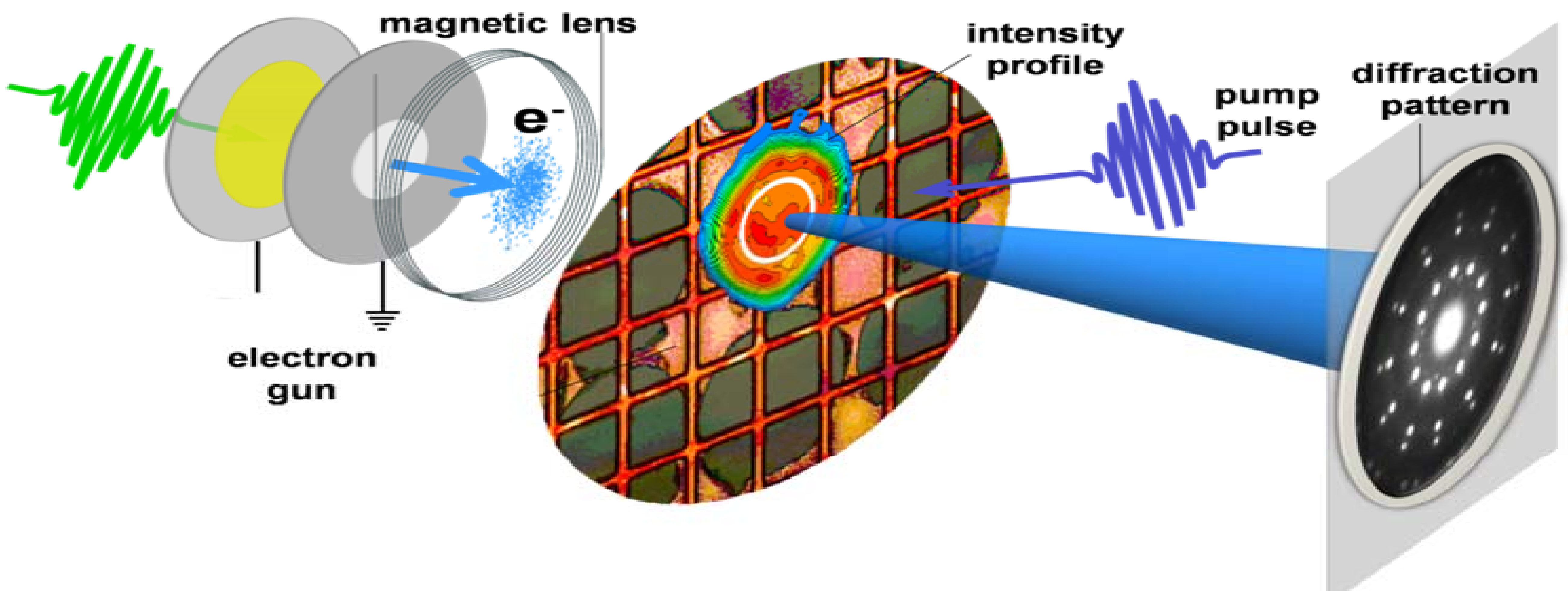


Requirements:

- Spatial and temporal matching
  → electron bunch length must be a fraction of λ_p
  → transverse size must be smaller than transverse wake
- Spatial and temporal overlap jitter must be small

First external injection experiments planned at REGAE

Relativistic ***E***lectron ***G***un for ***A***tomic ***E***xploration



RF-accelerator with

$E = 5$ MeV
$\Delta E = 33$ keV
$\tau = 14$ fs RMS
$\varepsilon_n = 0.3$ mm mrad
$\sigma_{trans} = 8.5$ µm RMS
$Q = 1$ pC

synch'ed to a Ti:Sa laser
(~10 fs rms accuracy)

Courtesy of G. Sciaini, K. Flöttmann, and D. Miller

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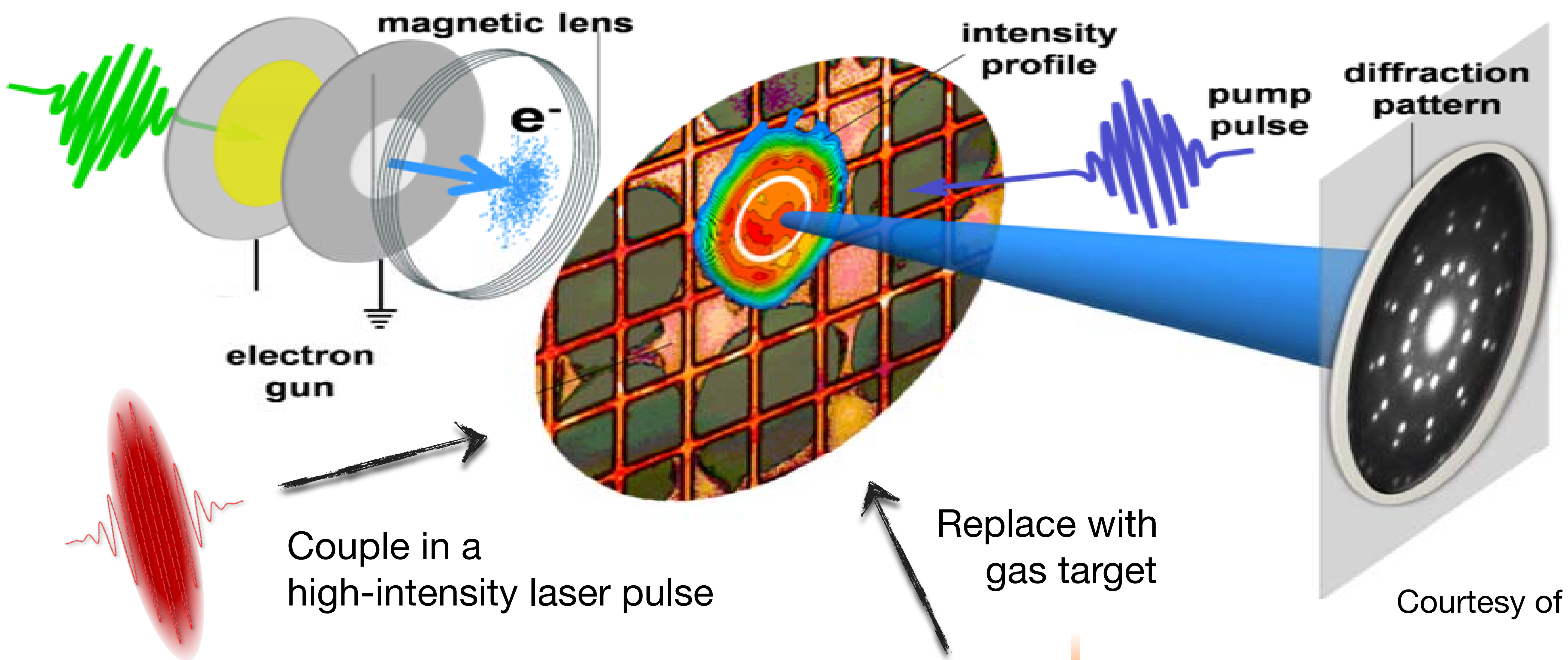

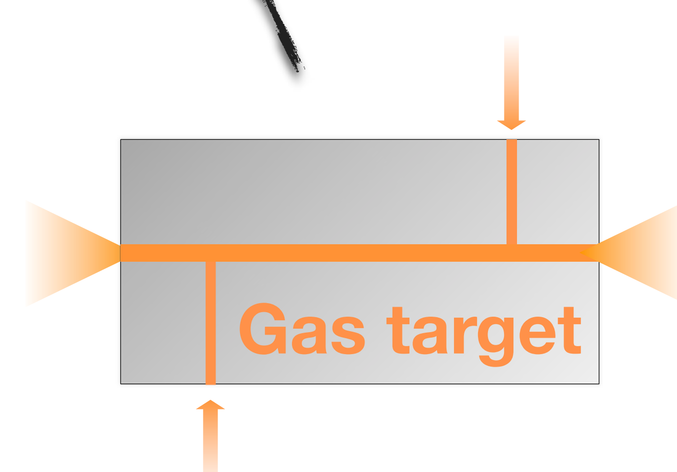

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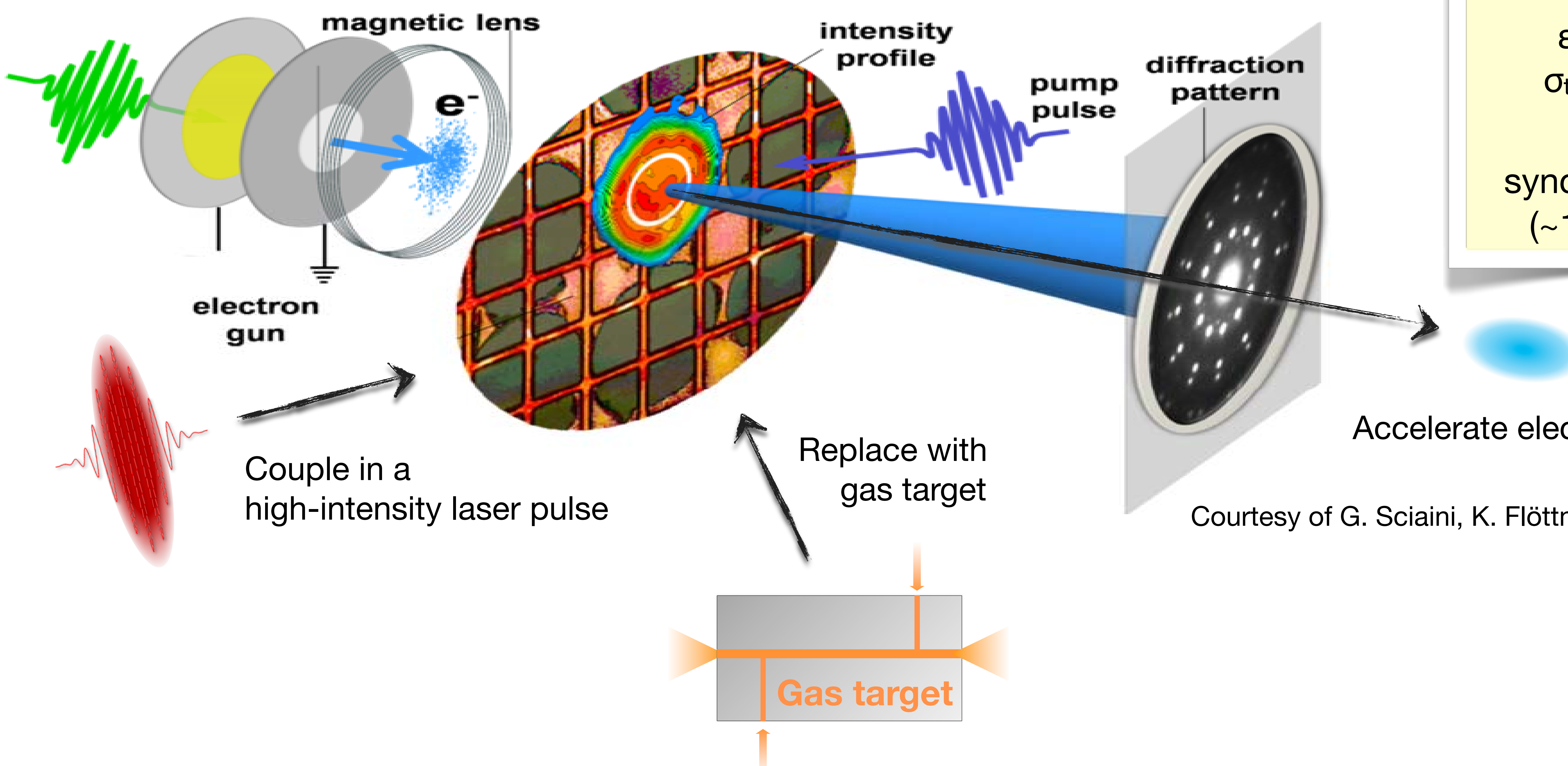

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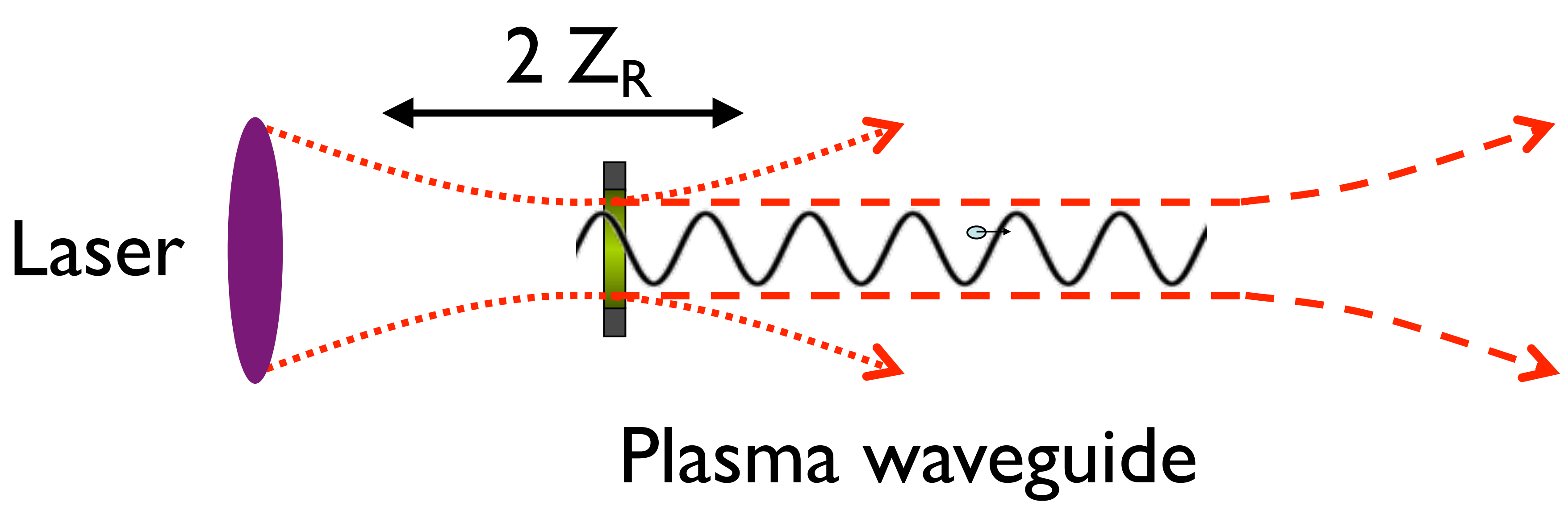
Energy gain scalings and single-stage limitations

1. Laser diffraction: mitigated by transverse plasma density tailoring (plasma channel)



Energy gain scalings and single-stage limitations

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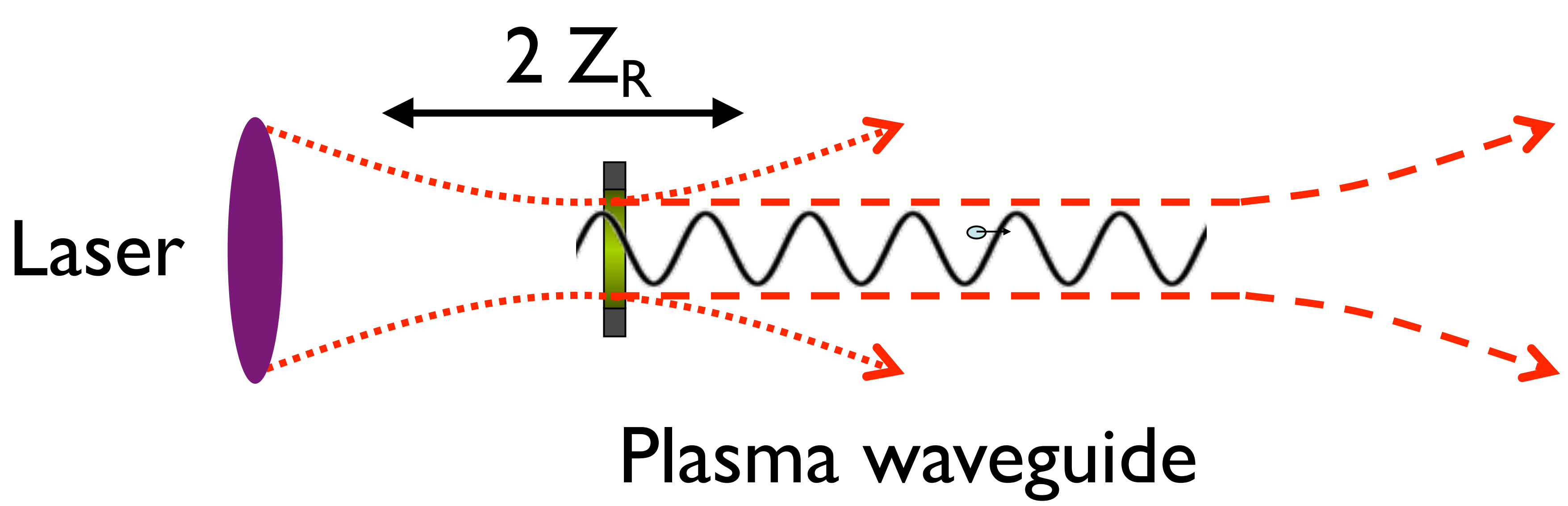
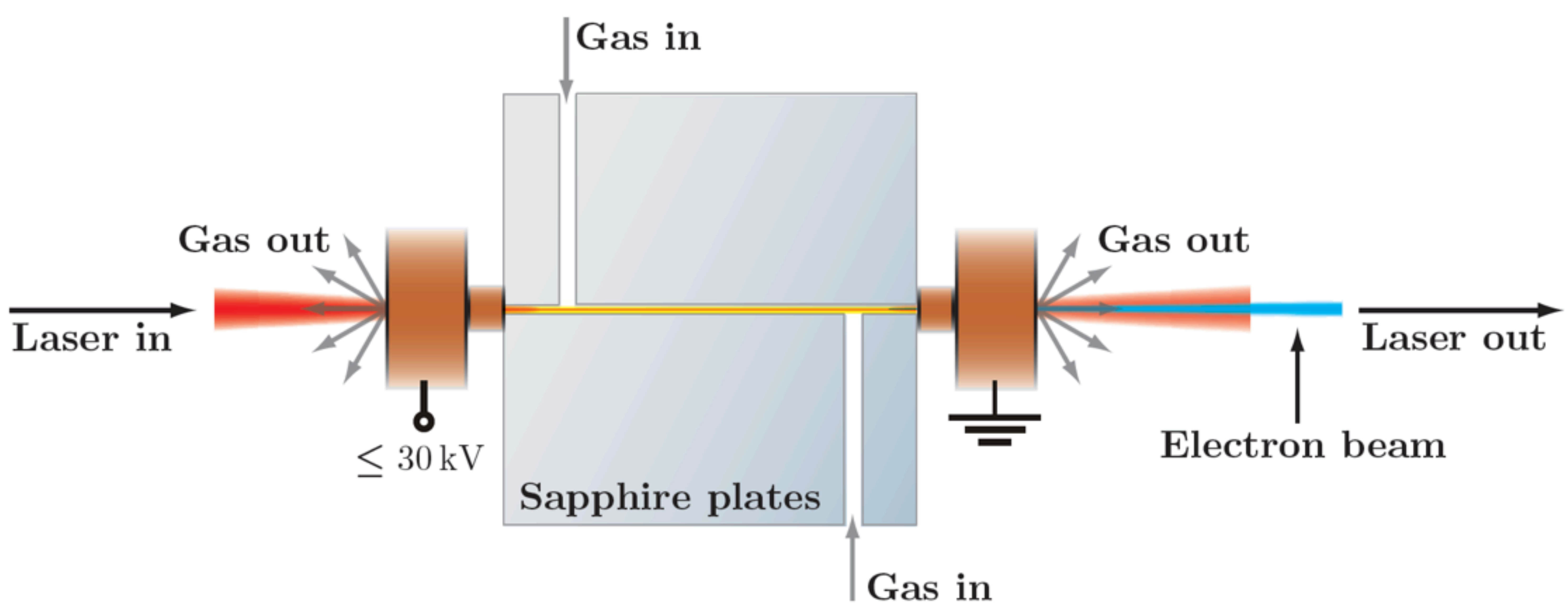


Capillary discharge plasma waveguides

- Plasma fully ionized for t > 50 ns
- After t ~ 80 ns plasma is in quasi-equilibrium: Ohmic heating is balanced by conduction of heat to wall
- Ablation rate small: cap. lasts for >10^6 shots
- $n_p \approx 10^{17}$ - 10^{19} cm^{-3}



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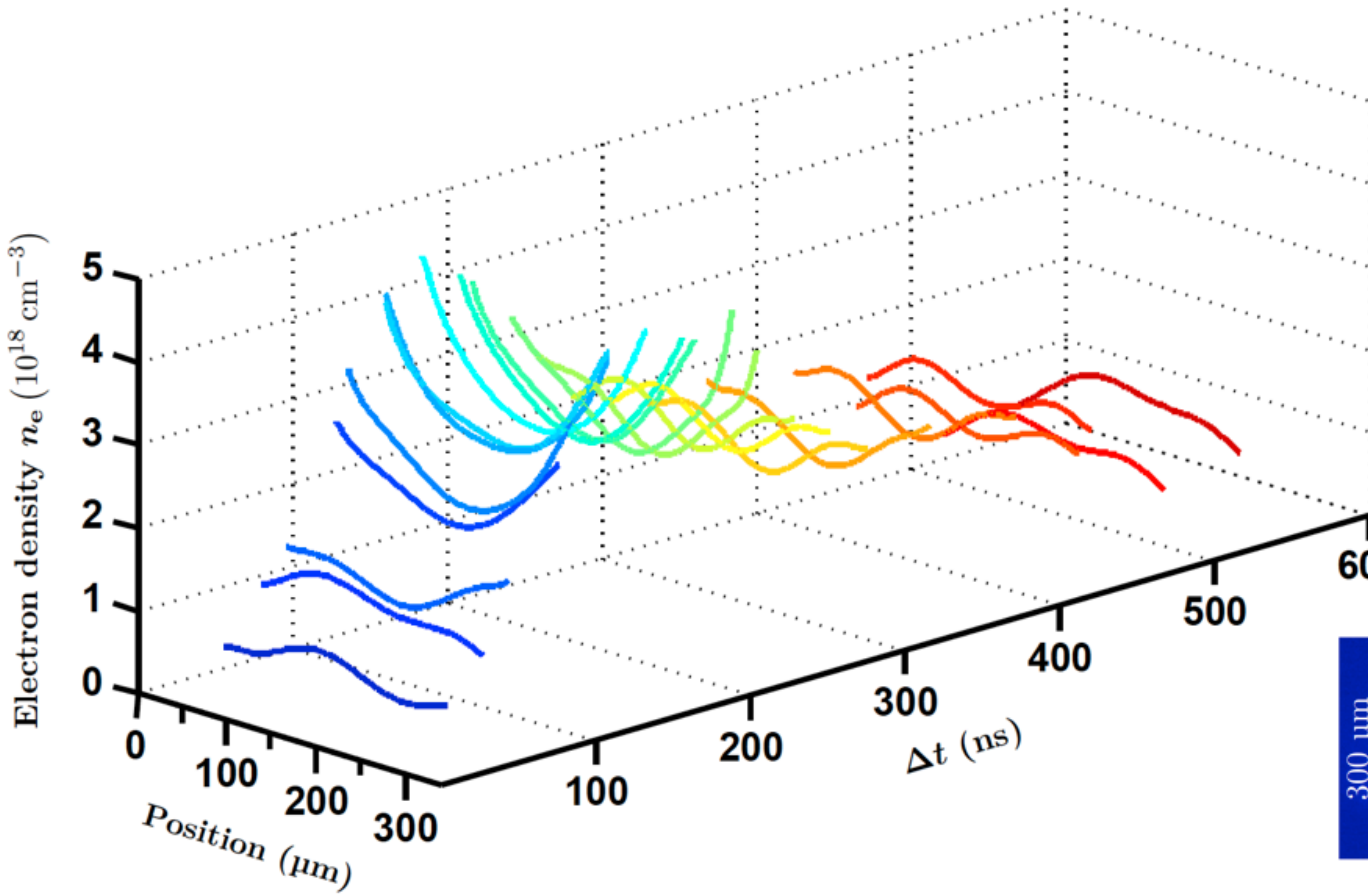

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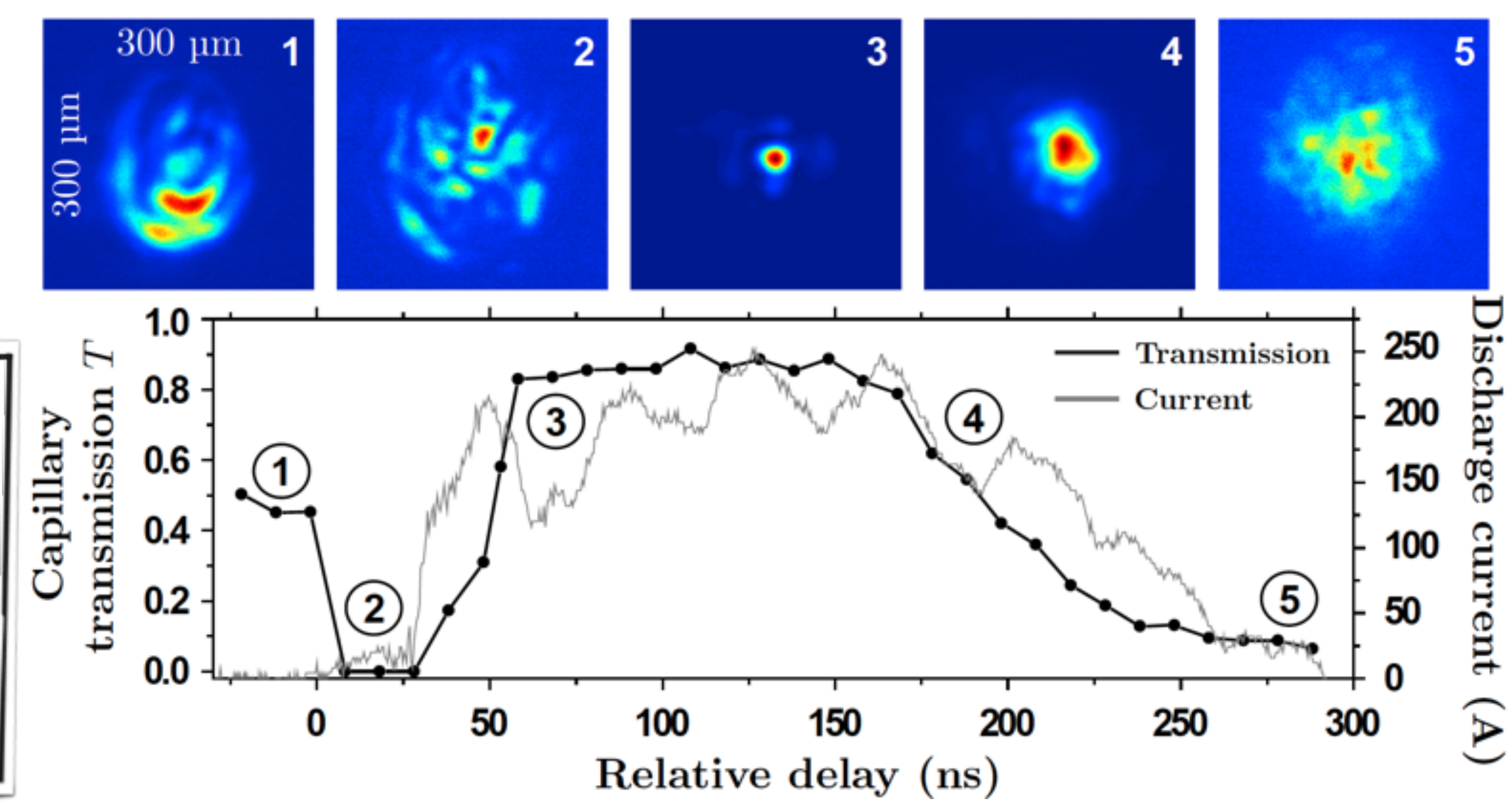
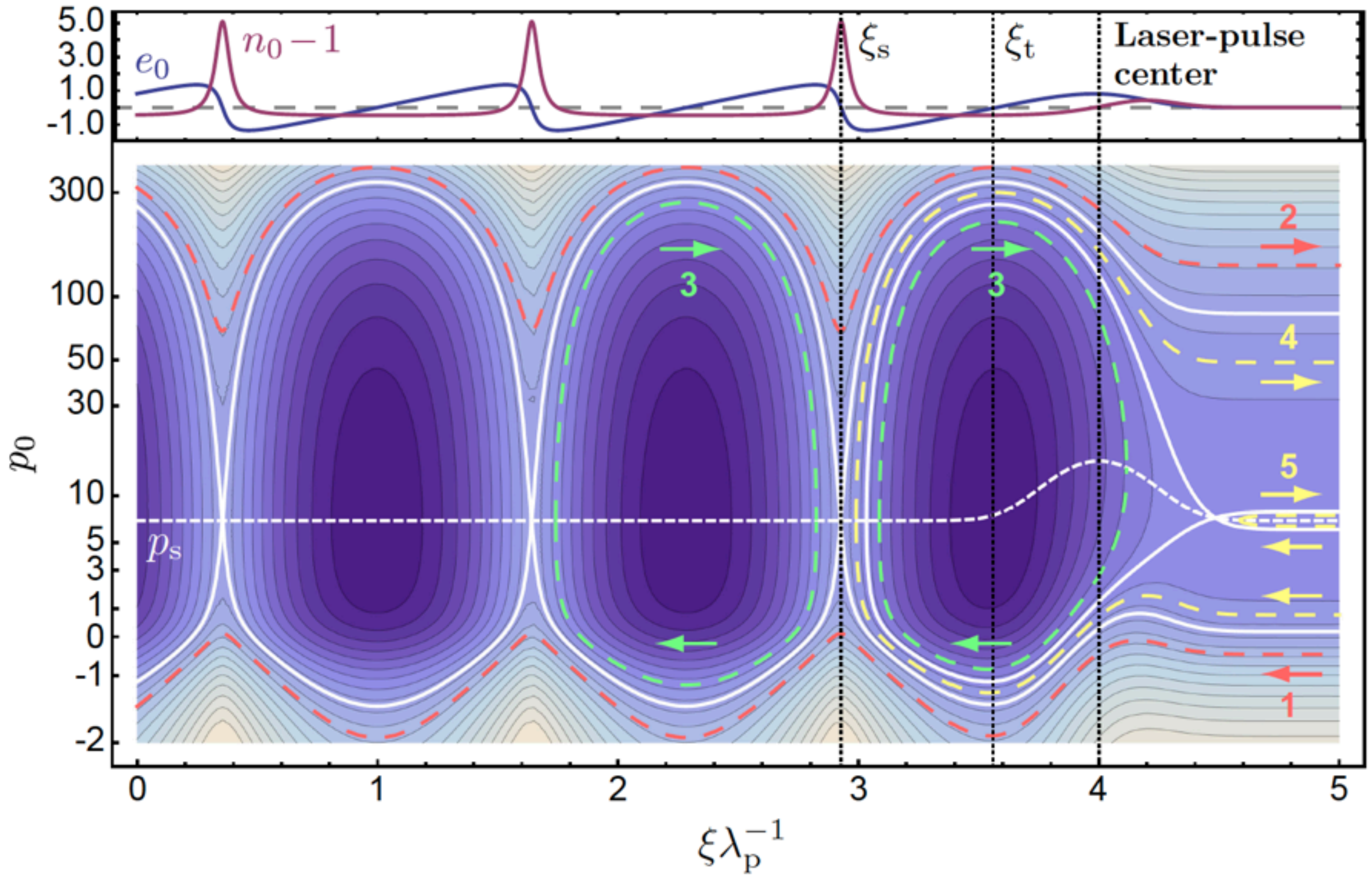


In this example:
Z_R = 2 mm, guiding over 16 mm, guiding efficiency > 90 %

Karsch, Osterhoff *et al.*, New J. Phys. 9, 415 (2007)

Energy gain scalings and single-stage limitations

2. Electron-laser dephasing: mitigated by longitudinal plasma density tailoring (plasma taper)



Constant density plasma

Laser pulse, plasma wave travel with $v_{wave} = v_g < c$

Electrons travel with $v_e \approx c > v_{wave}$

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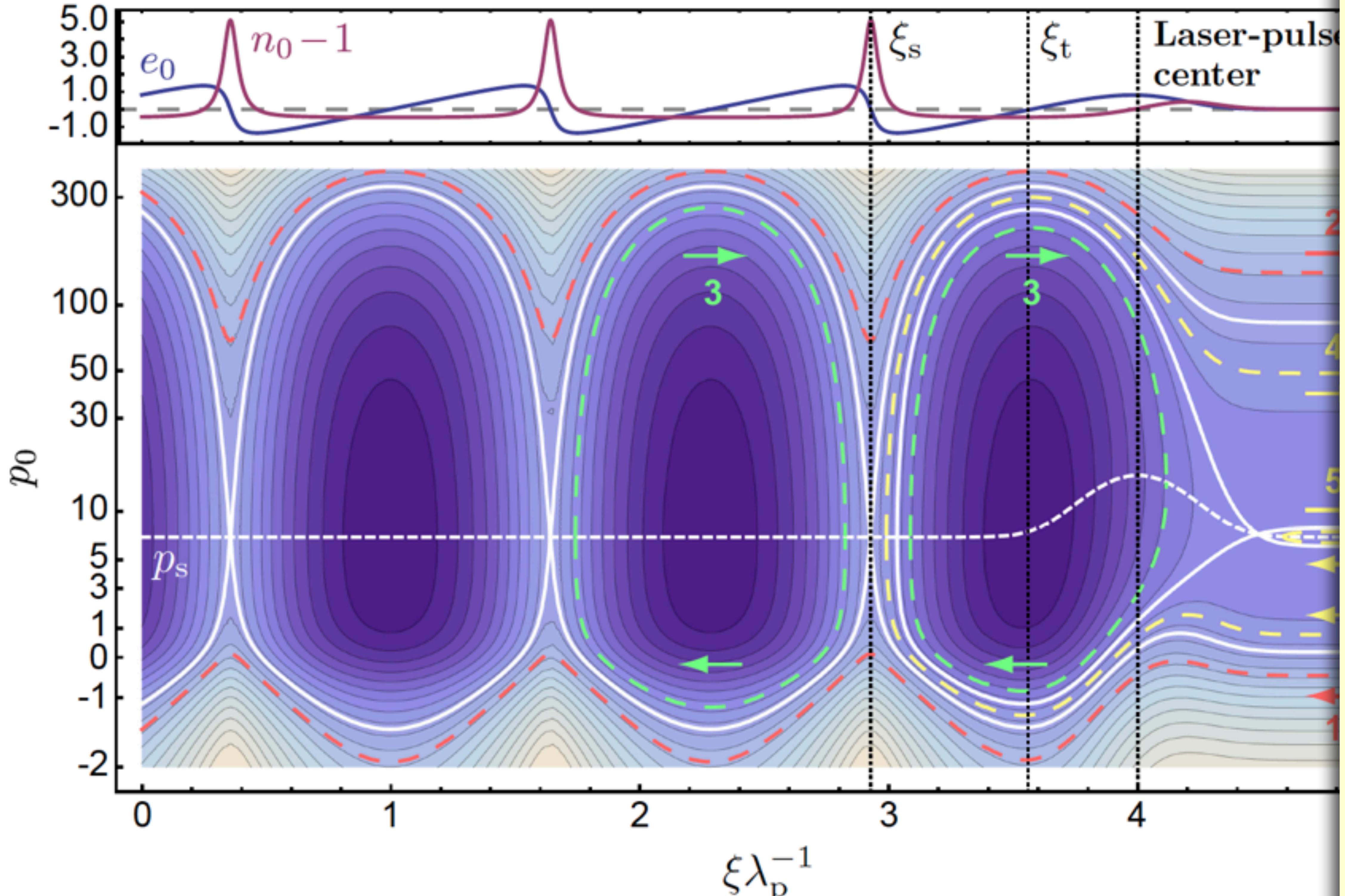

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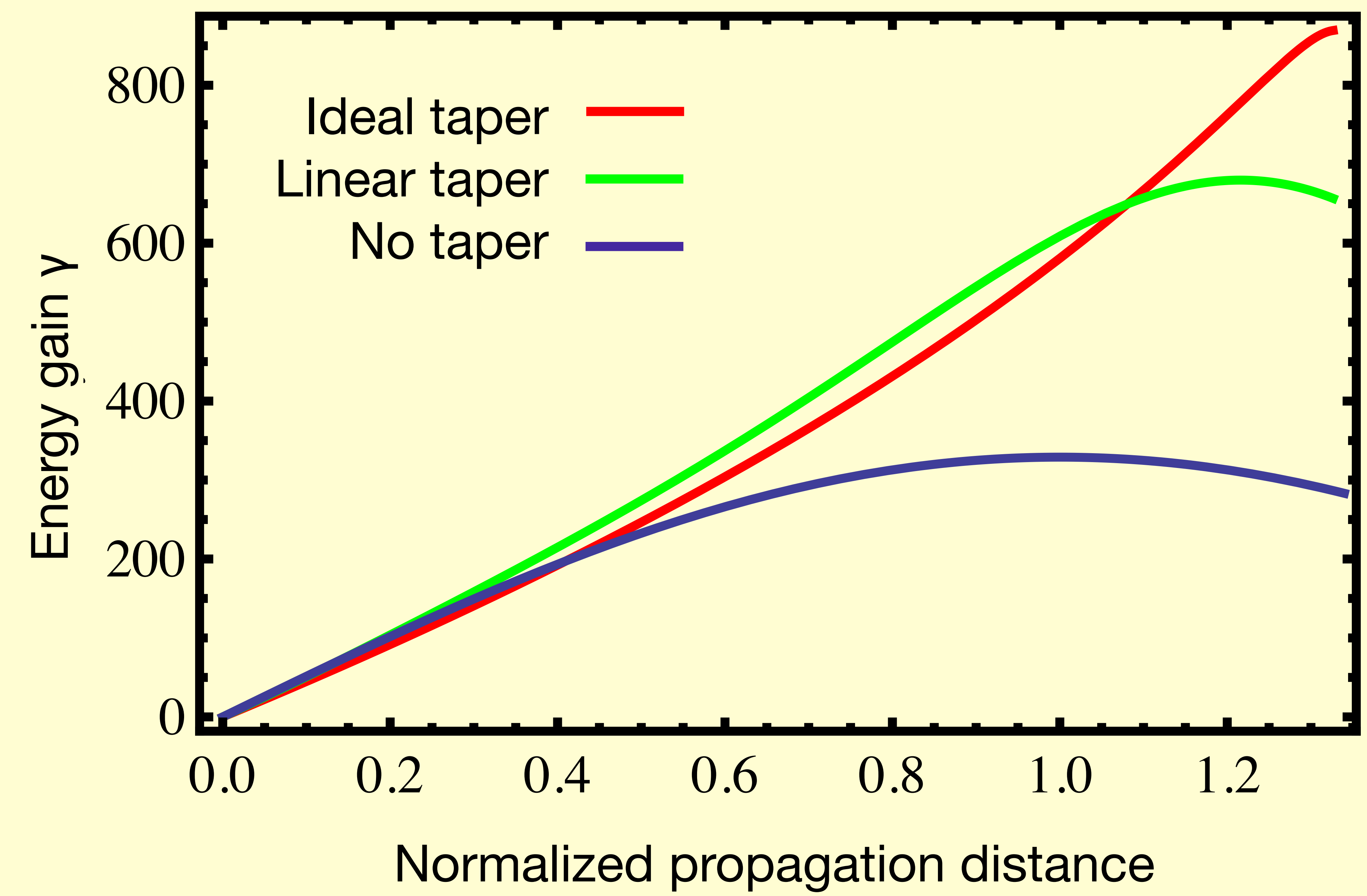


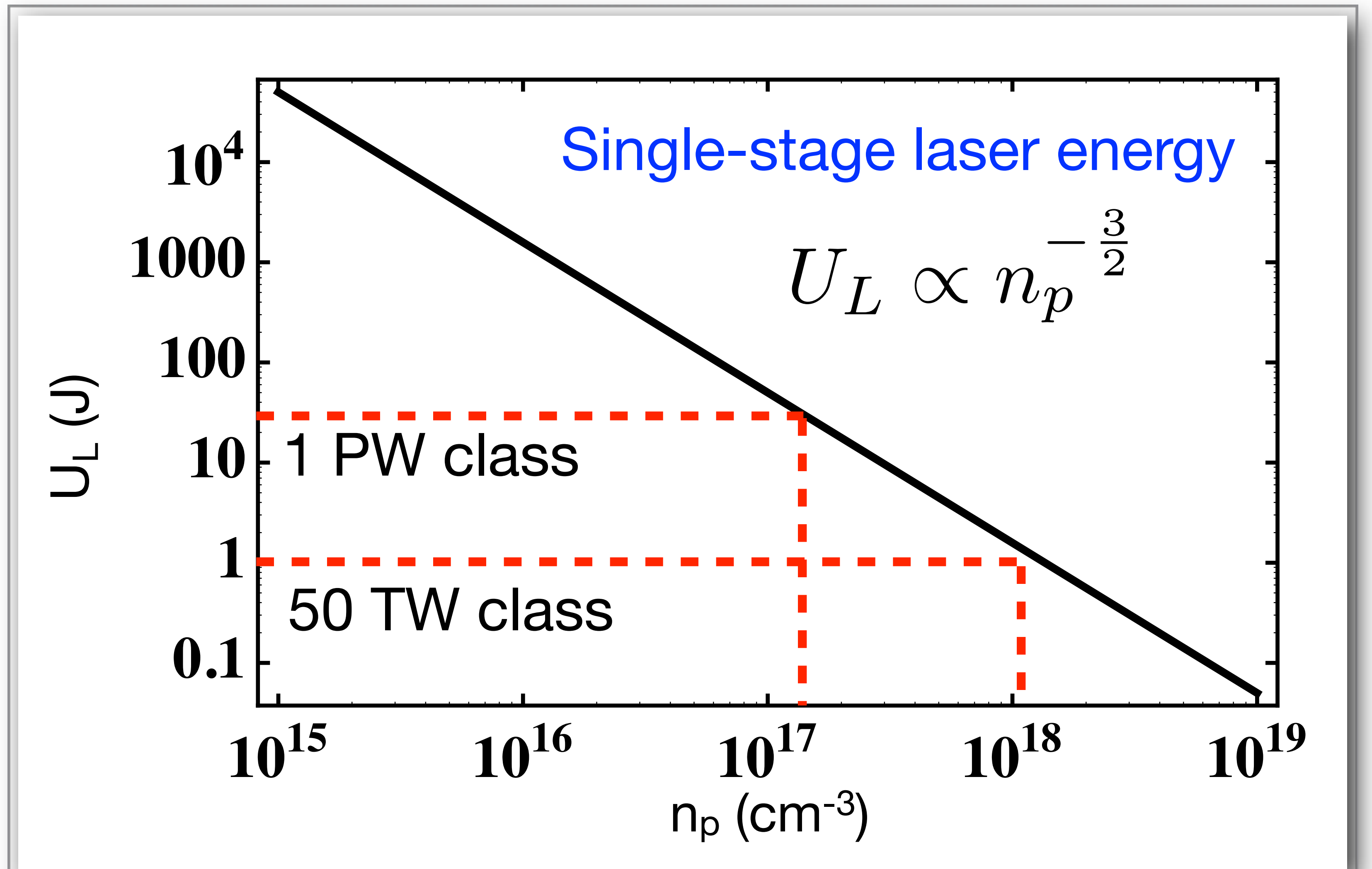
Rising density plasma

Plasma wave phase velocity v_{wave} may be set to v_e
⇒ electrons can be phase locked

→ Rittershofer et al., *Phys. Plasmas* **17**, 063104 (2010)

Energy gain scalings and single-stage limitations

3. Laser depletion: energy loss into plasma wave excitation



Coefficients determined from PIC simulations in the quasi-linear regime (a_0 = 1.5)

by courtesy of
C. B. Schroeder *et al.*, AAC Proc. (2010)

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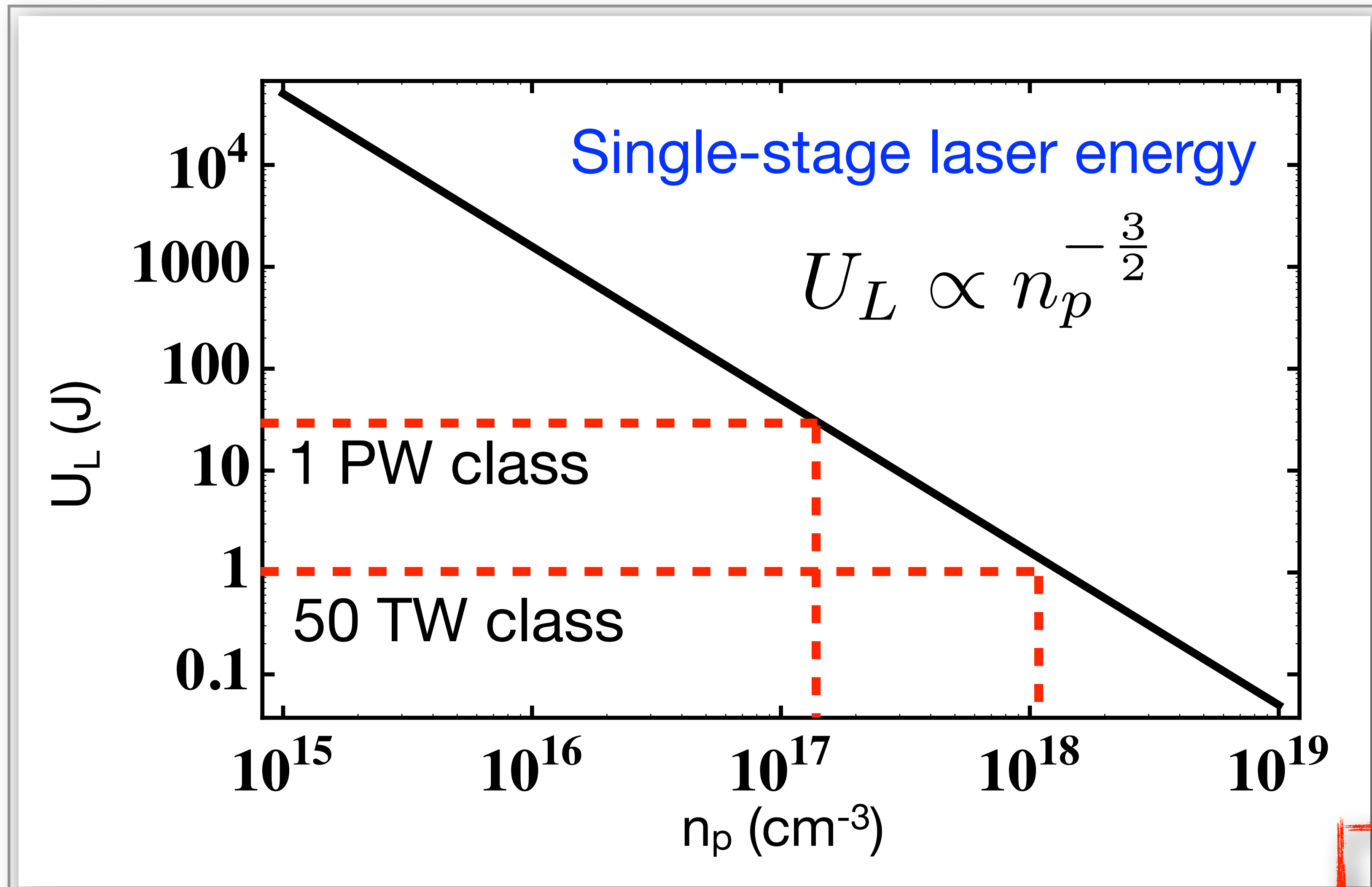

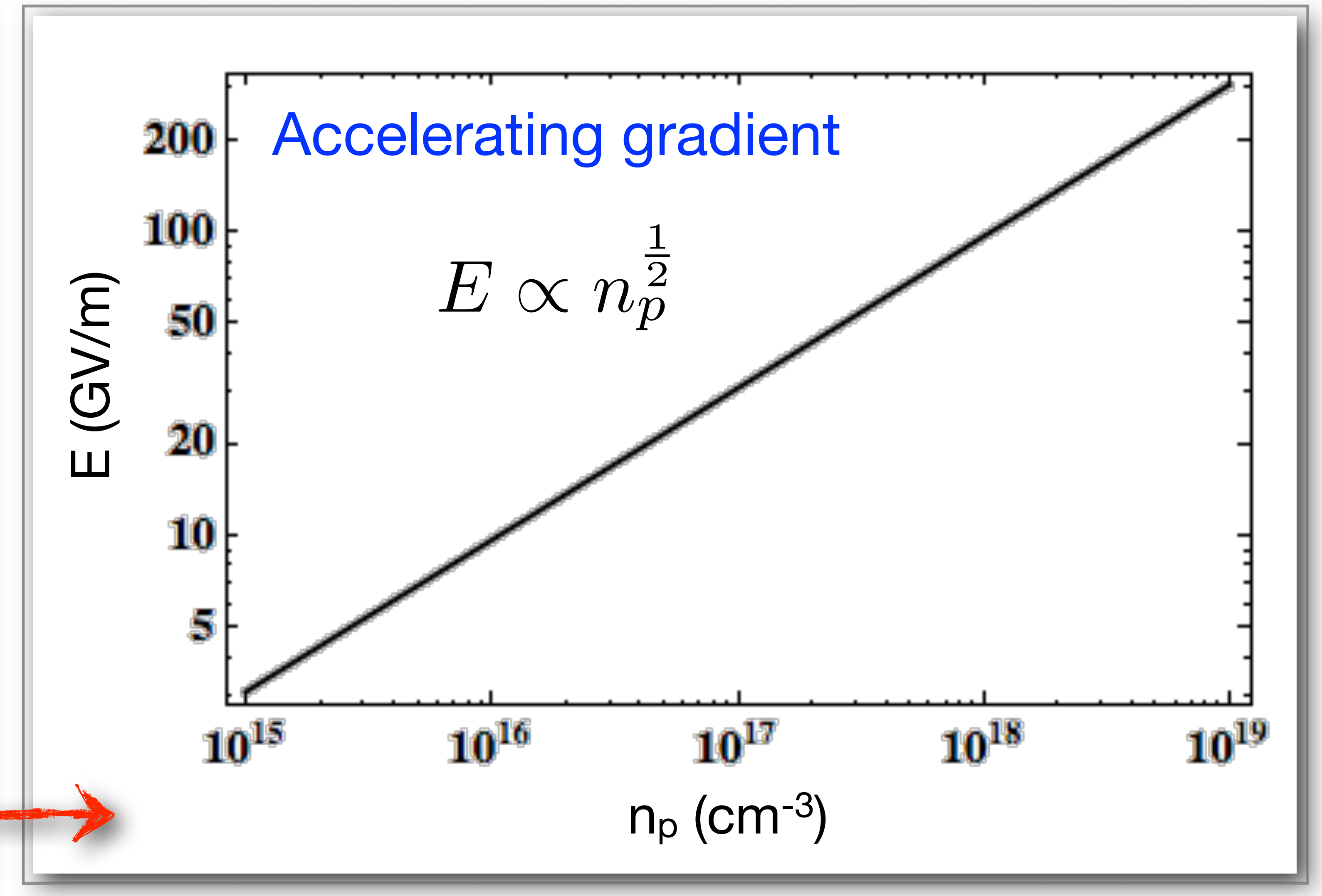

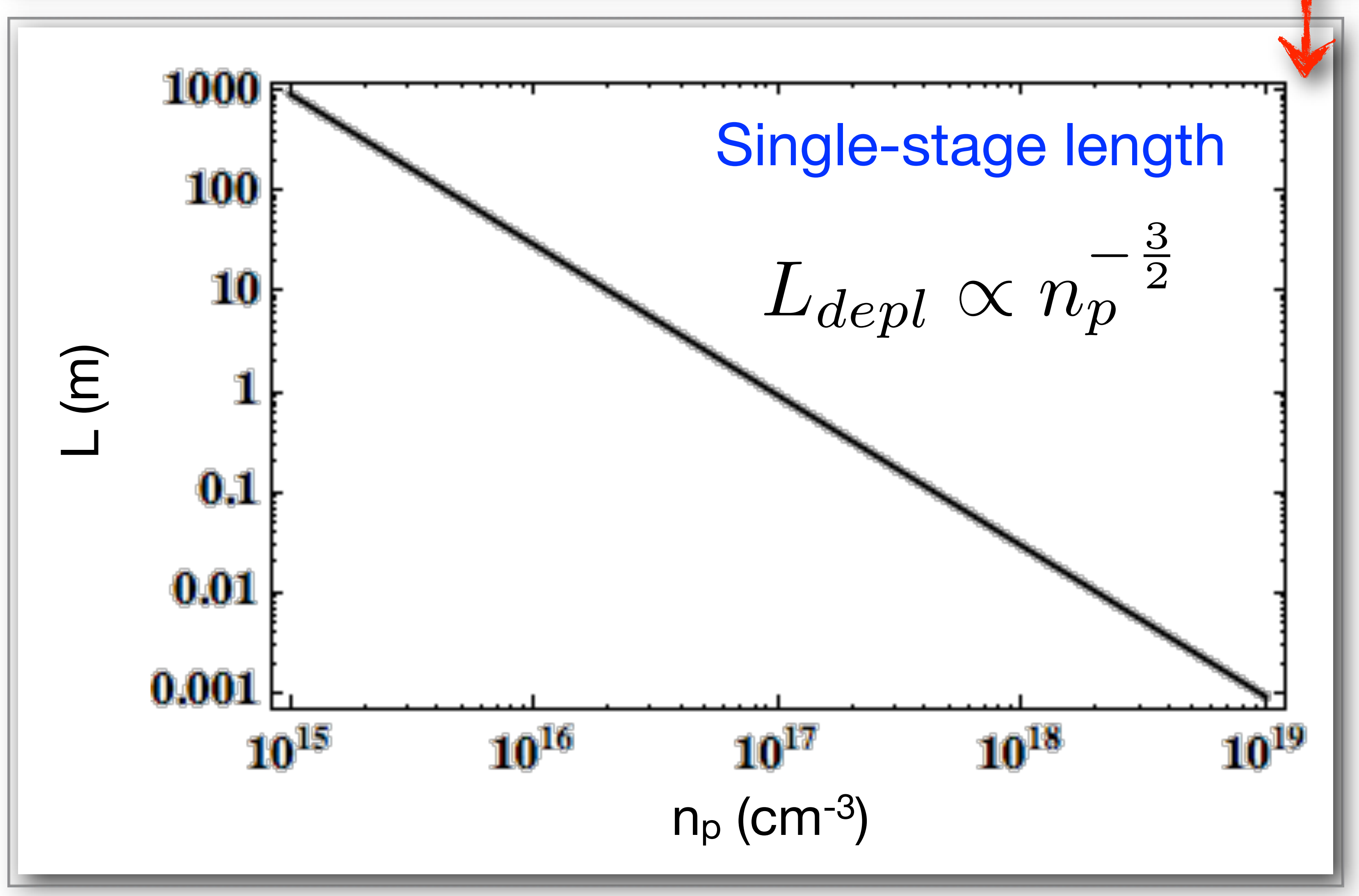

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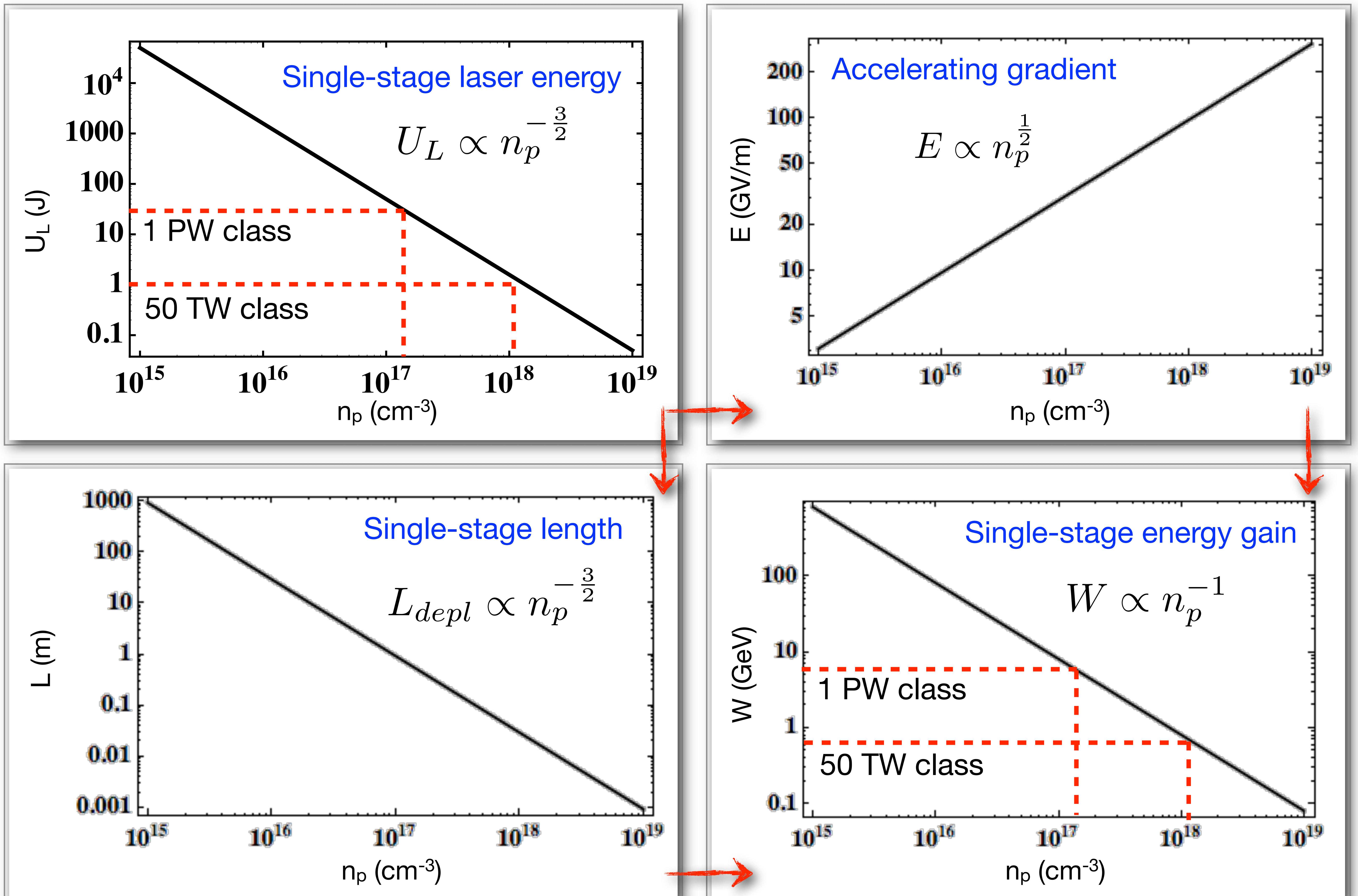

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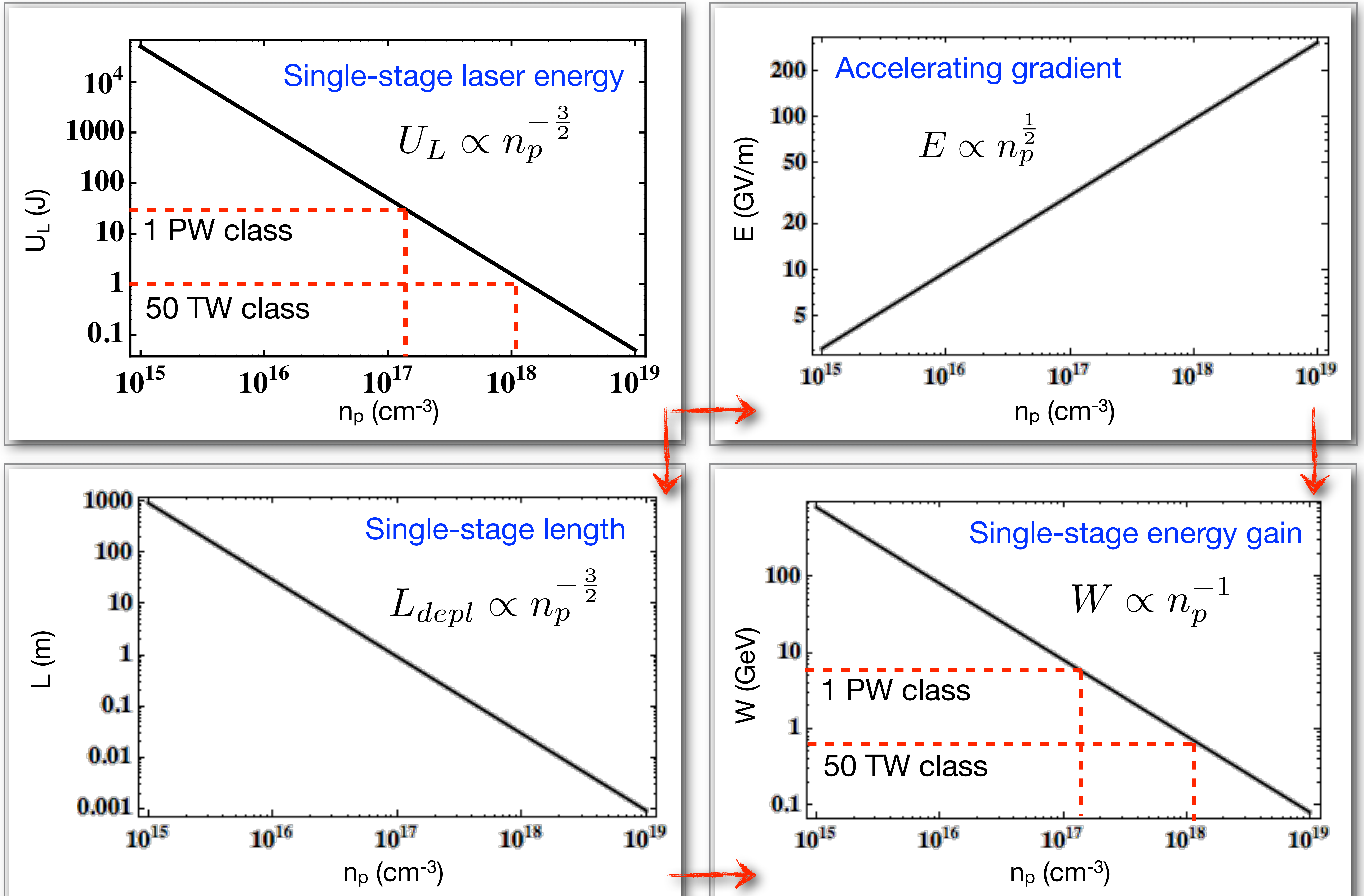

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Staging necessary for higher electron energies

by courtesy of
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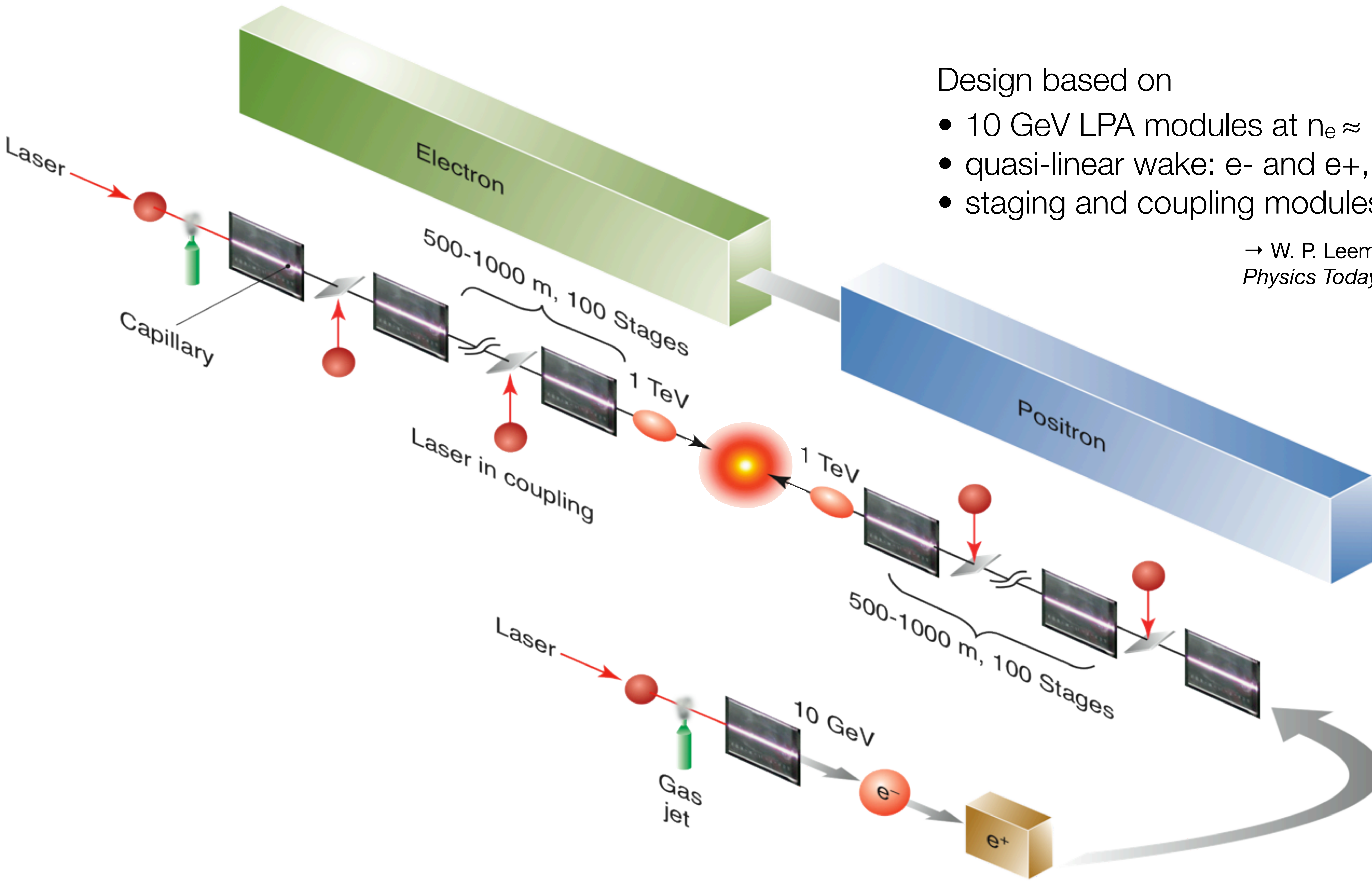
Envisioning a TeV-class LPA-based linear collider



Design based on

- 10 GeV LPA modules at $n_e \approx 10^{17}$ cm^{-3}
- quasi-linear wake: e- and e+, wake control
- staging and coupling modules

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

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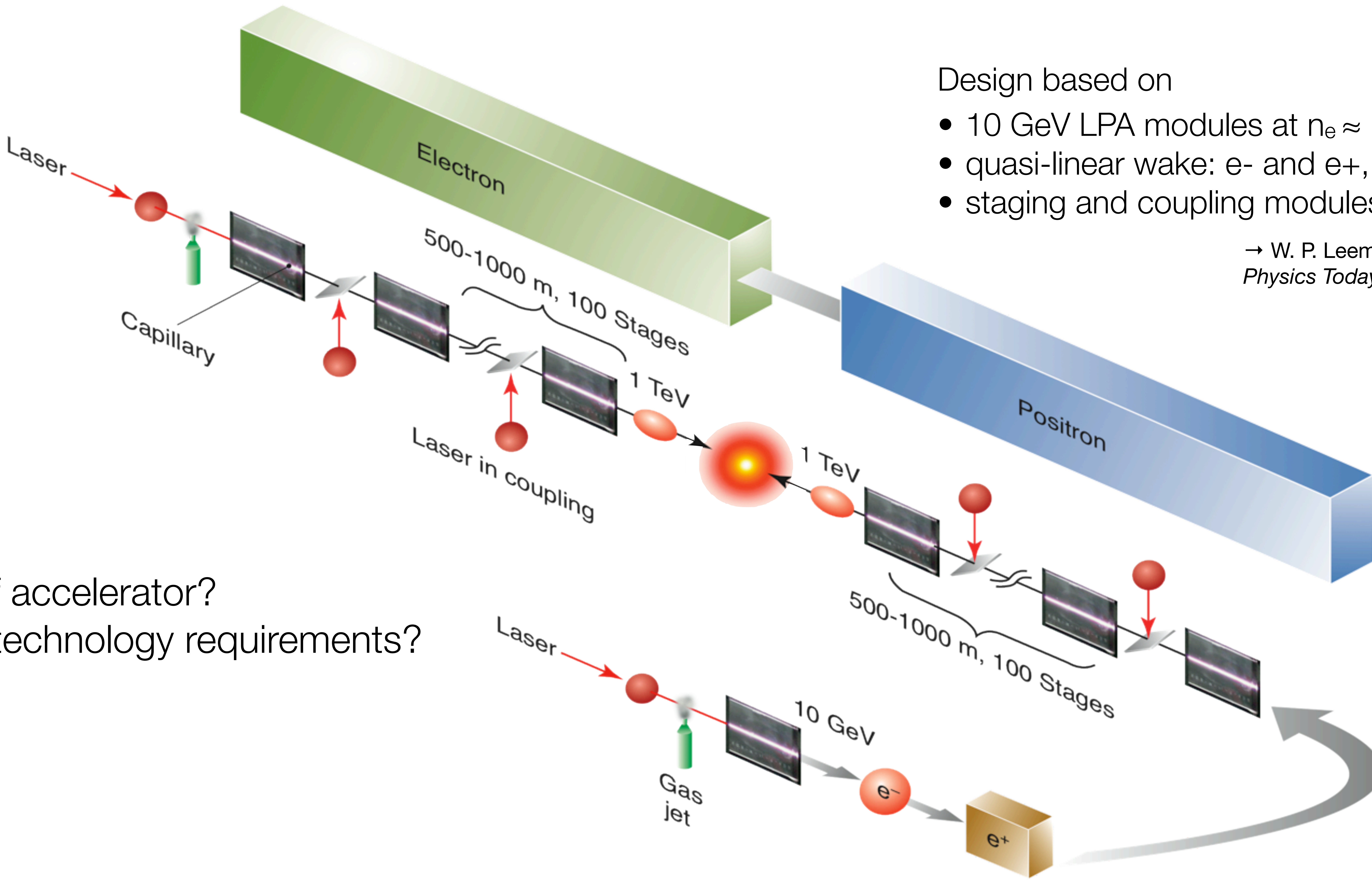

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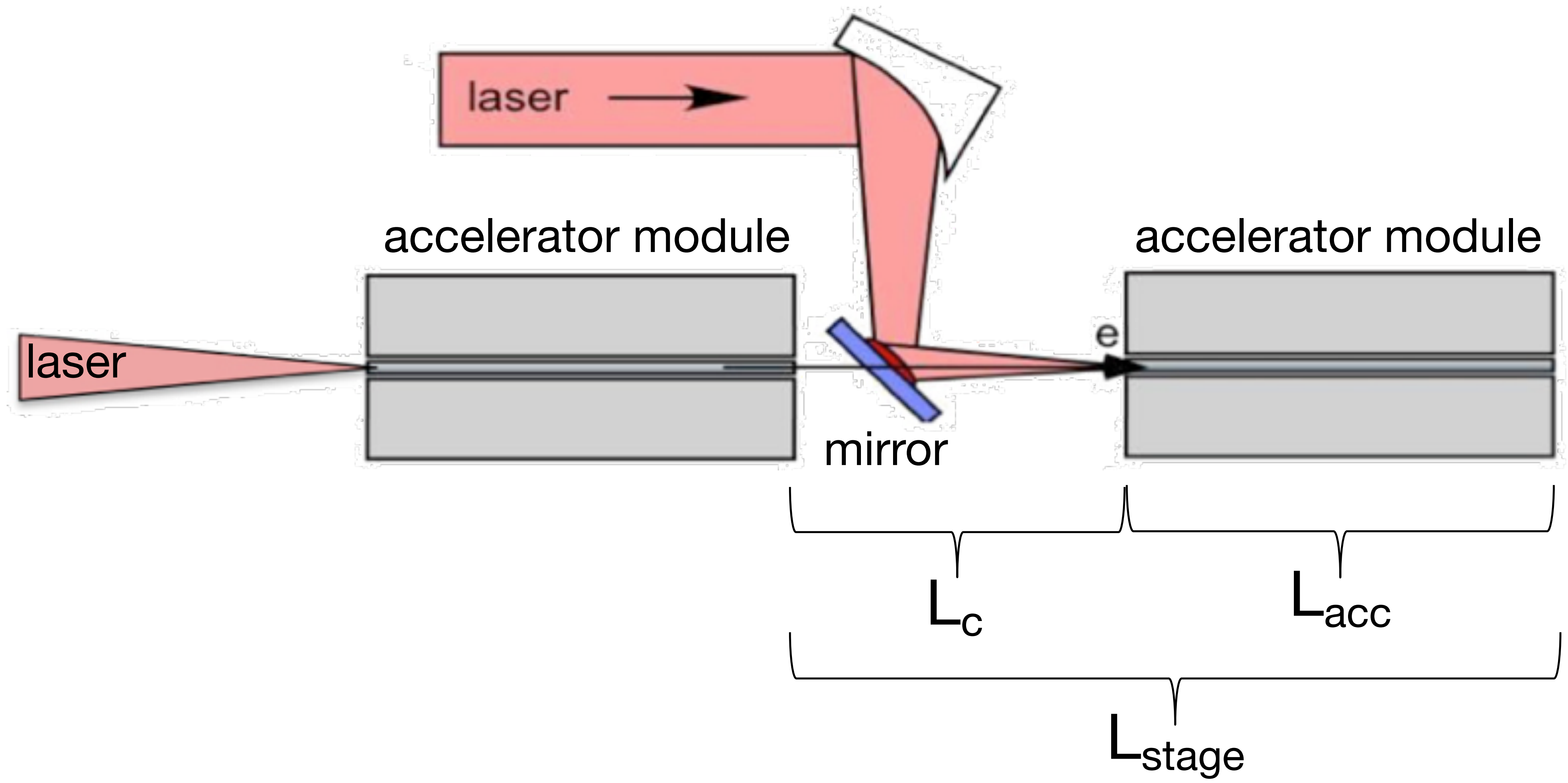
- Size of accelerator?
- Laser technology requirements?

Accelerator length is determined by staging technology



L_{acc} fixed by laser and plasma properties
(0.1 to 1.0 m per stage)

L_c determined by employed laser coupling method
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→ largely dictates multi-stage accelerator length

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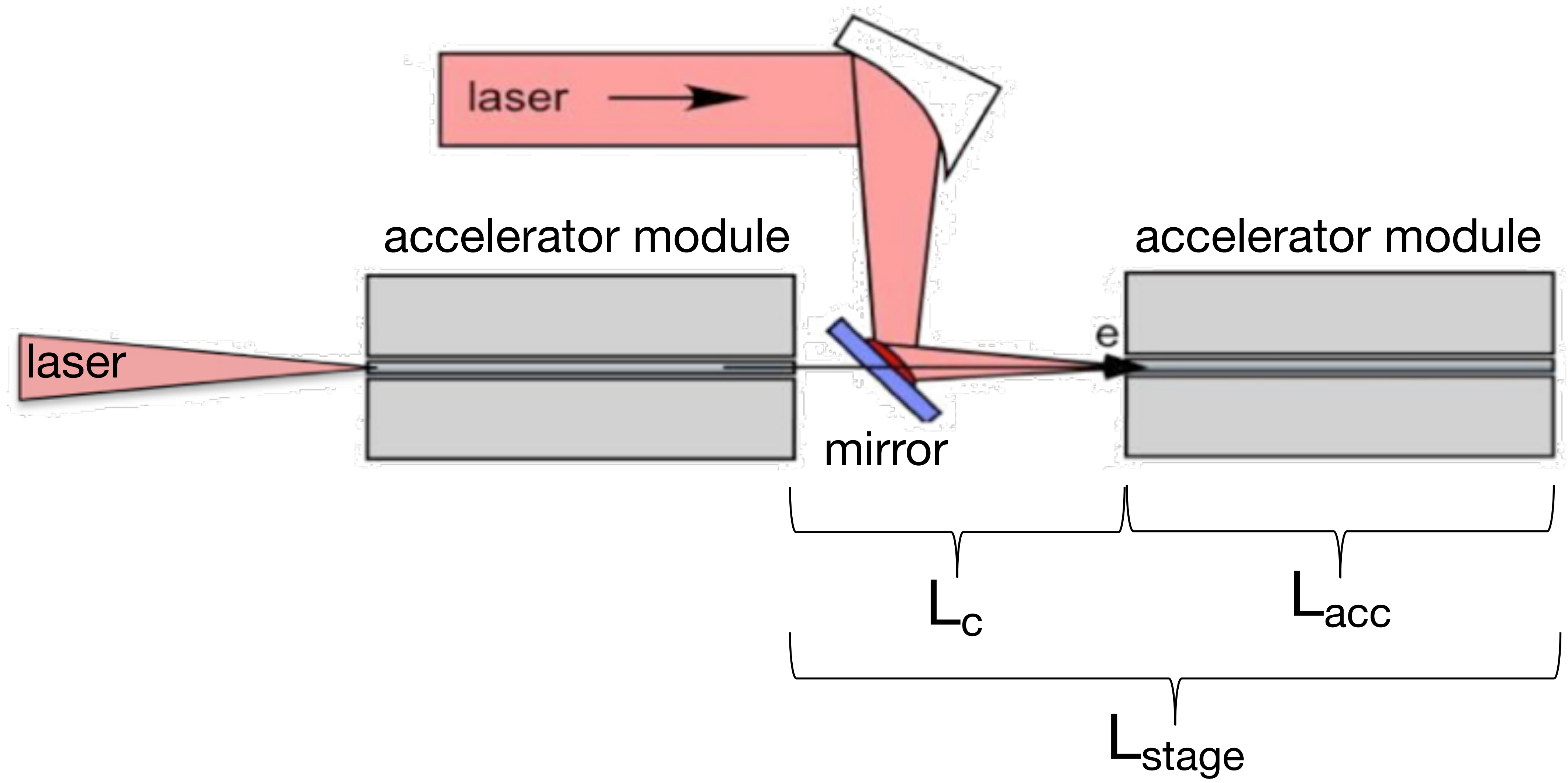

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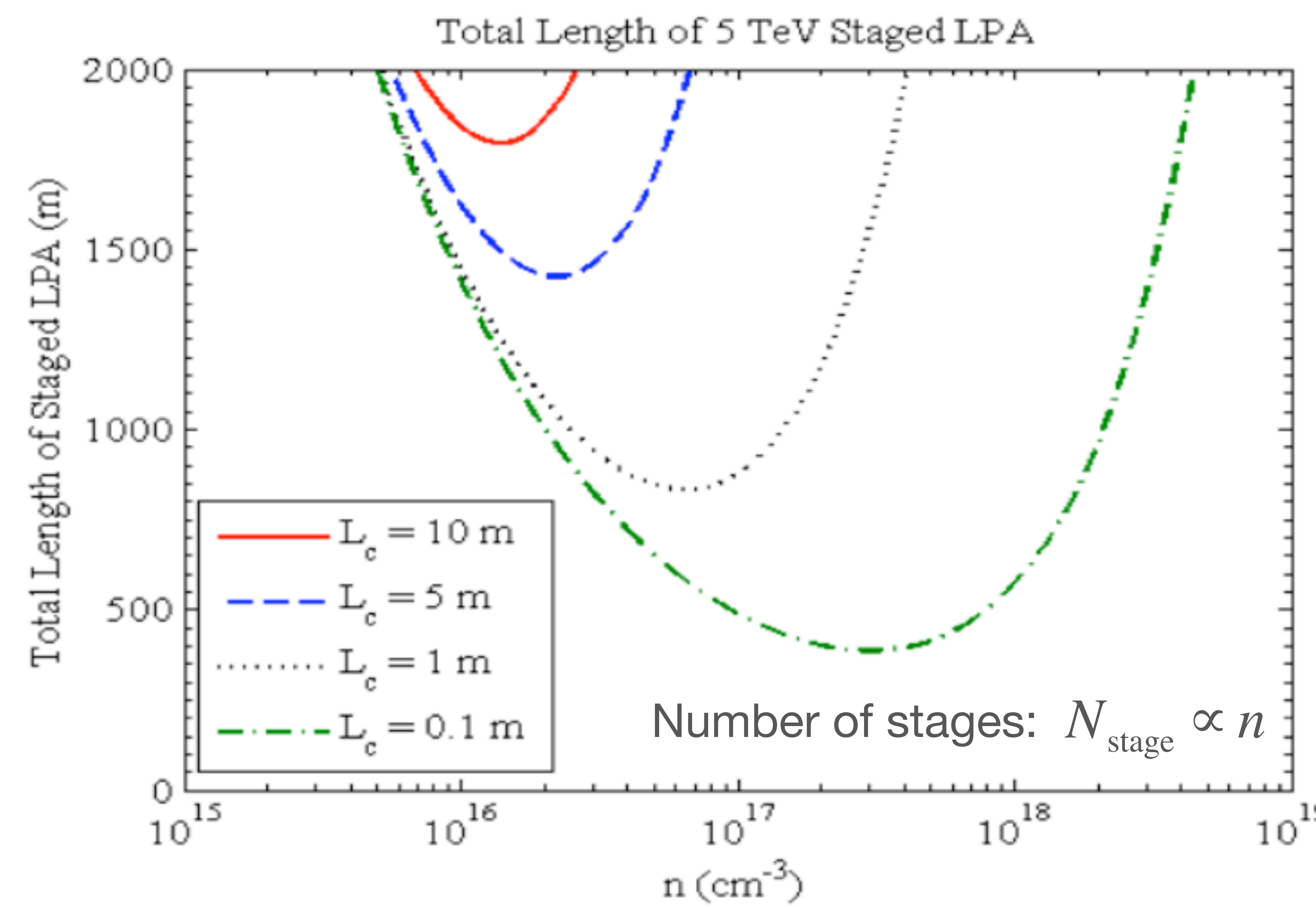
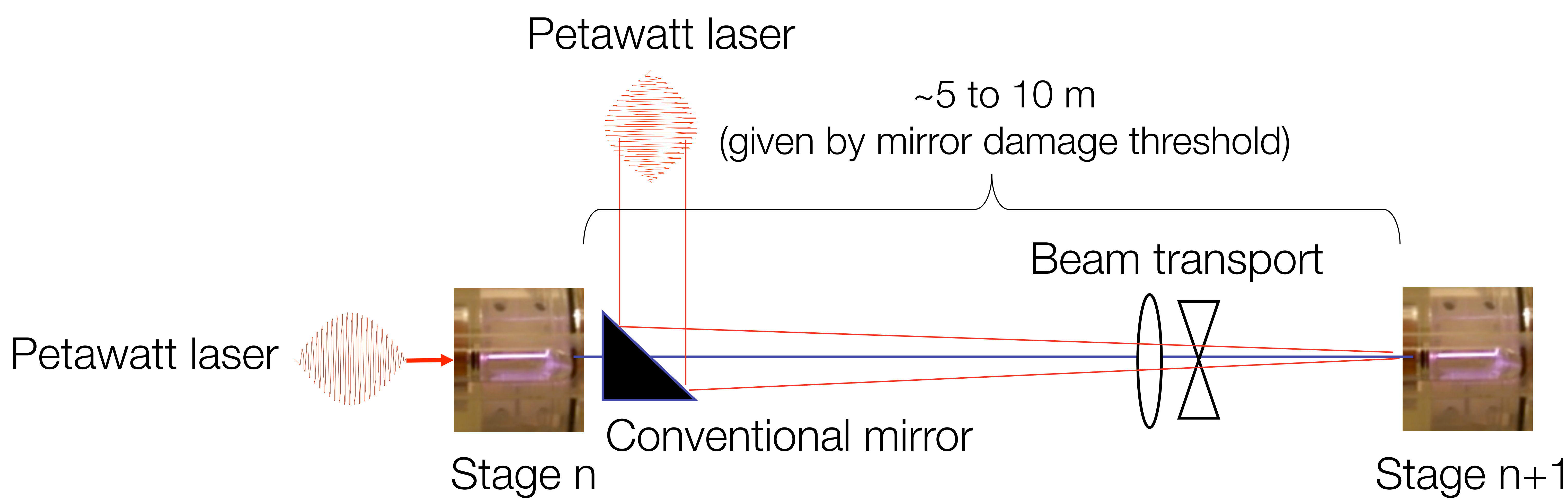


→ Schroeder et al., *AIP Conf. Proc.* **1086**, 208 (2009)

Development of compact staging technology critical to collider application

Plasma mirrors allow for compact staging modules

Conventional optics approach - stage length determined by damage threshold of final laser optic



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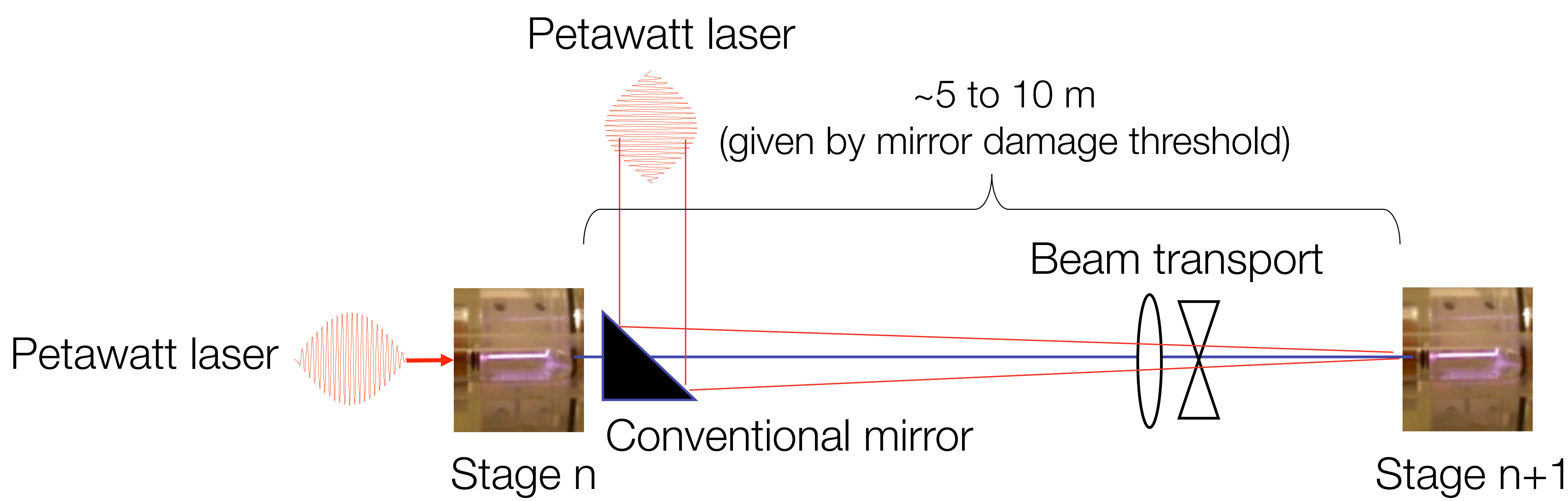

Plasma-optics approach - minimizing stage length relies on destruction of final laser mirror

High laser intensity (10^{16} W/cm^2) generates a smooth, critical density plasma surface
→ minimizes $L_C \approx 0.005$ to 0.100 m

Crucial points:

- Renewable mirror surface required → Optically flat liquid jet or tape drive
- High demands on temporal laser contrast

→ Sokollik et al., *AIP Conf. Proc*. **1299**, 233 (2010)

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

1 TeV LPA collider design

Plasma number density, n_0	10^{17} cm^{-3}
Energy, center of mass, E_{cm}	1 TeV
Beam energy, γmc^2	0.5 TeV
Number per bunch, N	4×10^9
Collision rate, f	15 kHz
Beam Power, $P_b = fN\gamma mc^2$	4.8 MW
Luminosity, $\mathscr{L}$	2×10^{34} s^{-1} cm^{-2}
Bunch length, σ_z	1 μm
Horizontal rms beam size at IP, σ_x	0.1 μm
Vertical rms beam size at IP, σ_y	1 nm
Horizontal normalized emittance, ε_{nx}	1 mm-mrad
Vertical normalized emittance, ε_{ny}	0.01 mm-mrad
Beamstrahlung parameter, Υ	35
Plasma wavelength, λ_p	105 μm
Energy gain per stage, W_{stage}	10 GeV
Single stage laser-plasma interaction length	0.9 m
Drive laser coupling distance between stages	0.5 m
Laser energy per stage	40 J
Laser wavelength	1 μm
Initial normalized laser intensity, a_0	1.5
Average laser power per stage	600 kW
Number of stages	50
Main linac length	70 m
Efficiency (wall-plug to beam)	5%
Total wall-plug power	190 MW

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

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However: such laser are not optimized for efficiency. Fiber technology and diode pumping may increase efficiency by orders of magnitude. Fiber lasers have demonstrated up to 60%.

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⇒ 40 J laser energy per module at 15 kHz repetition rate

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However: new laser technologies (OPA, fibers, thin-disc amps) promise much higher average powers. → *ICAN, CALA projects*

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Warning: energy remaining in damped plasma wave
⇒ 10 J per stage per beam ⇒ ~100 kW/m

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Particle-driven plasma wakefield schemes: electron beams

- Plasma wakefields may be excited by high-current-density particle beams
- Wall-plug efficiency much higher than laser-driven acceleration in plasma
- Technique first proposed in 1956!
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- Most significant result: energy doubling of 42 GeV SLAC linac beam
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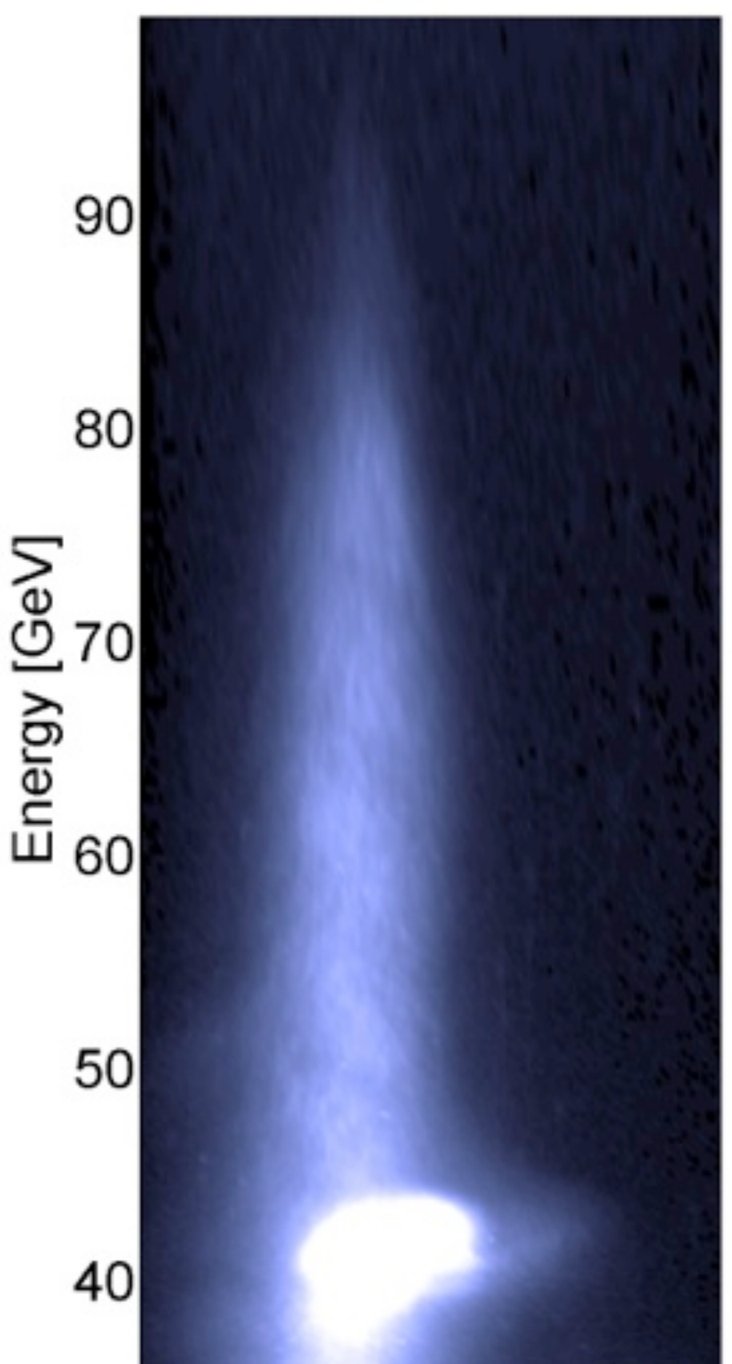

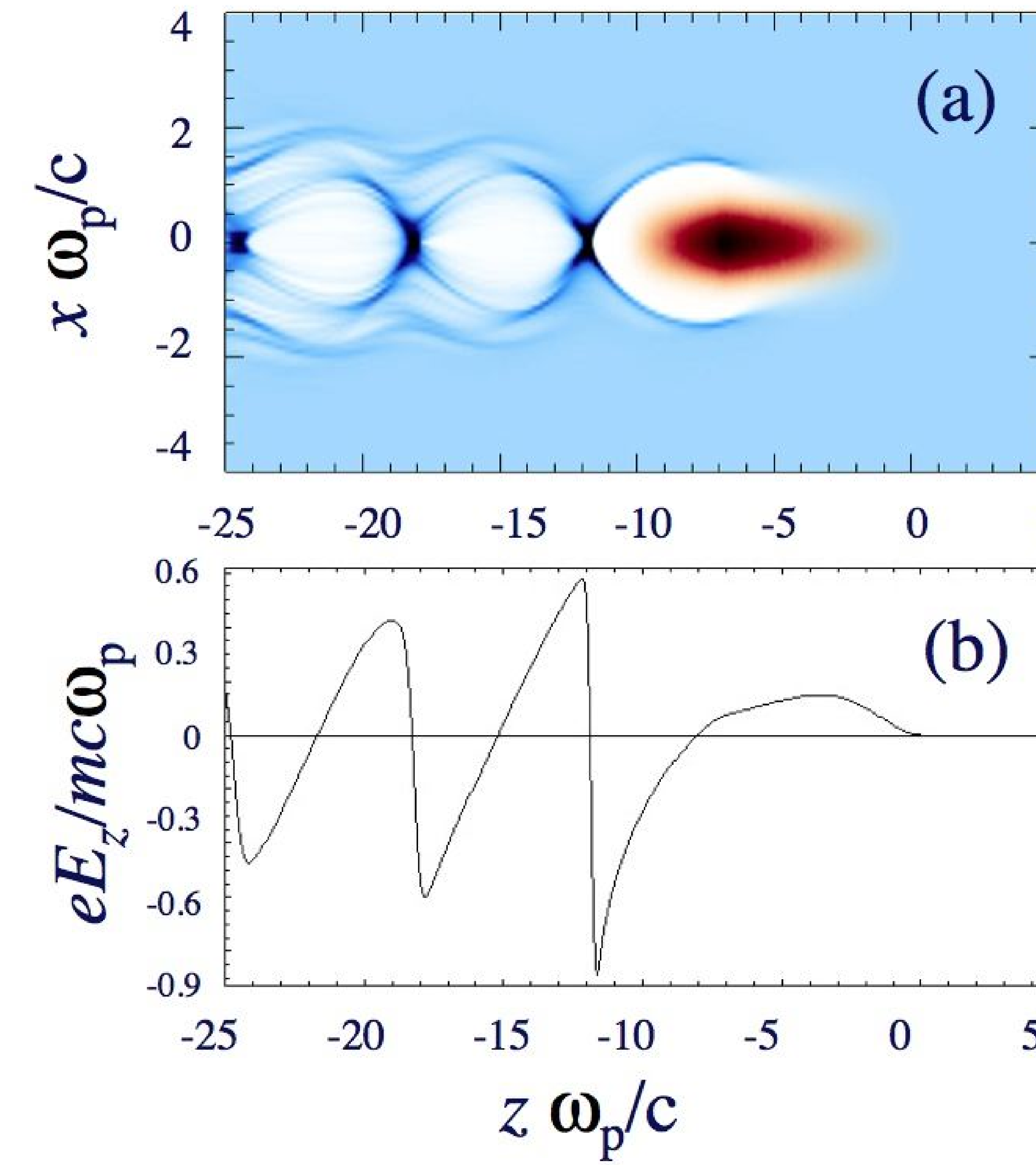

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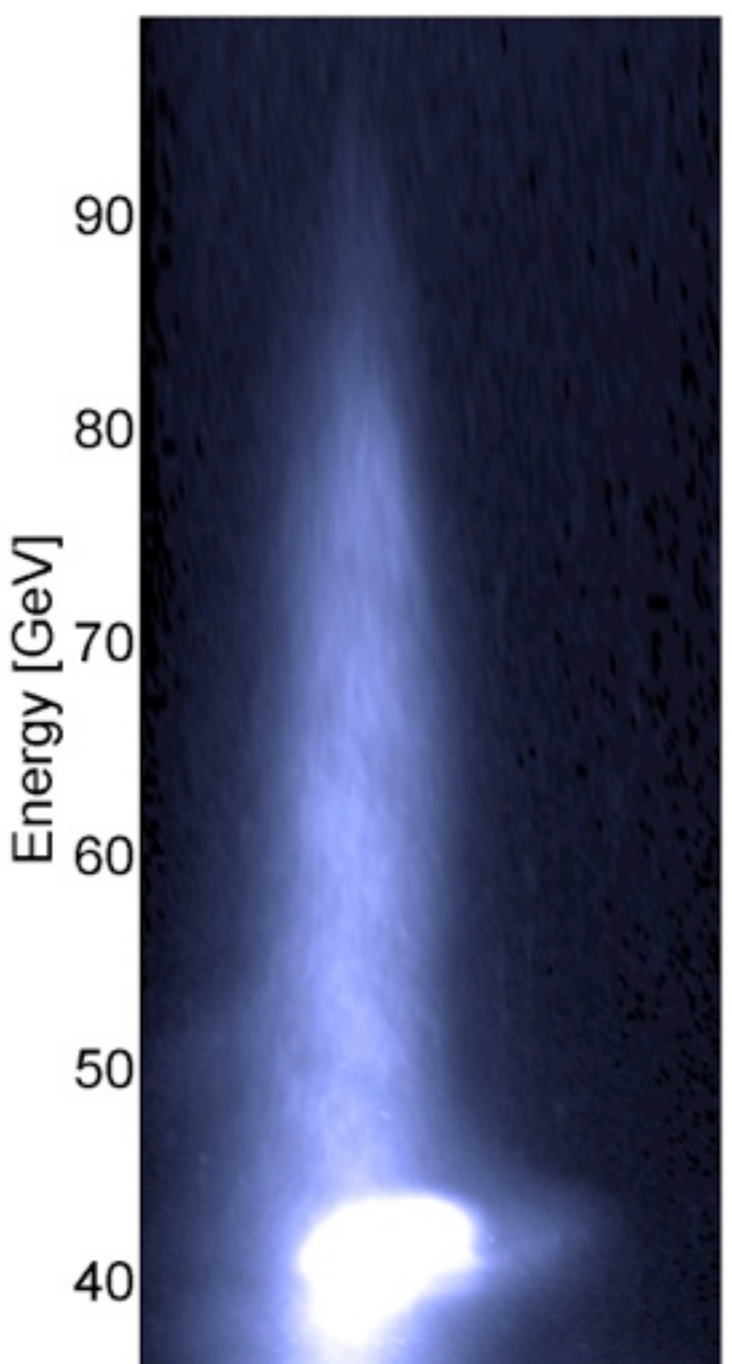

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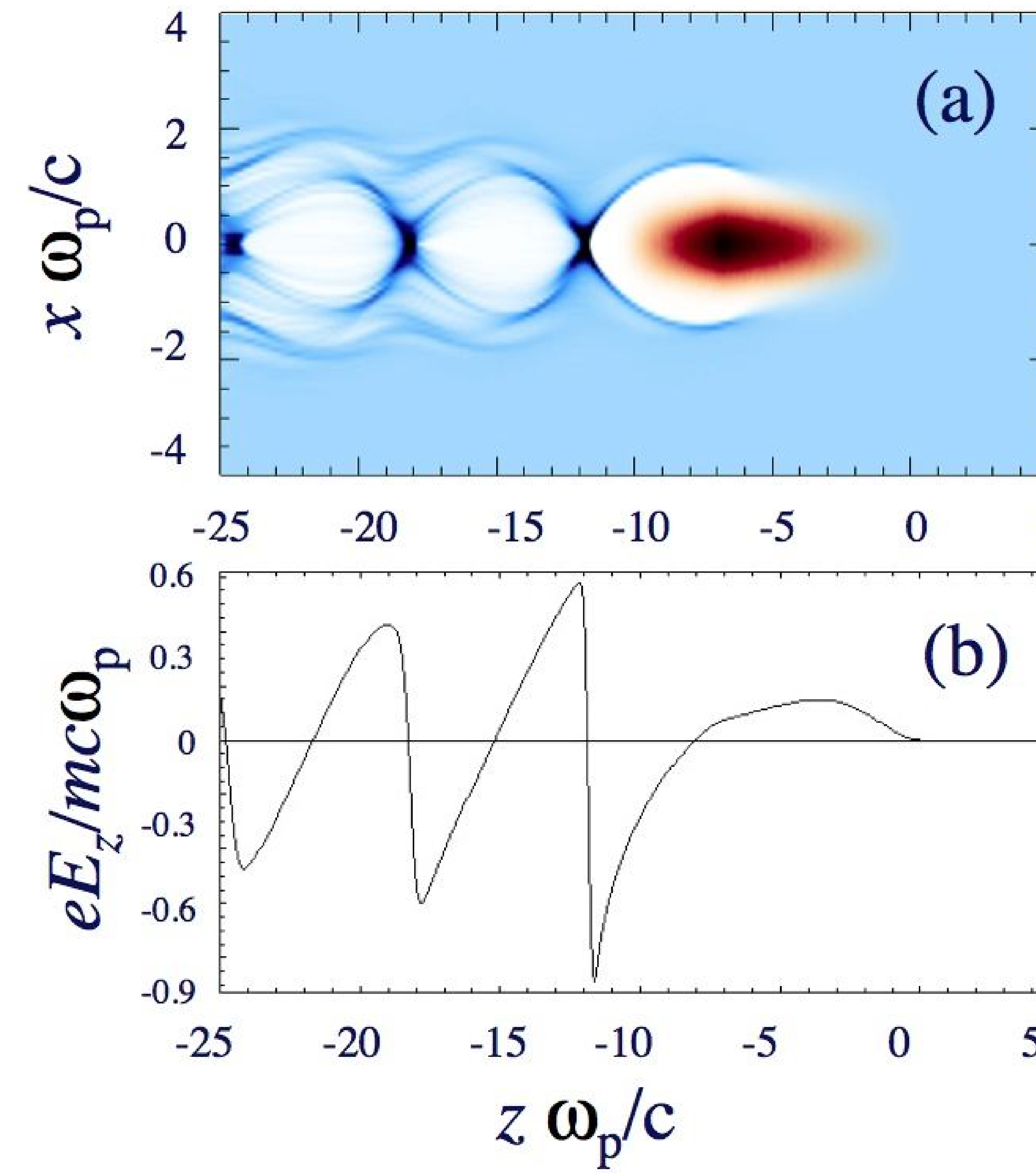

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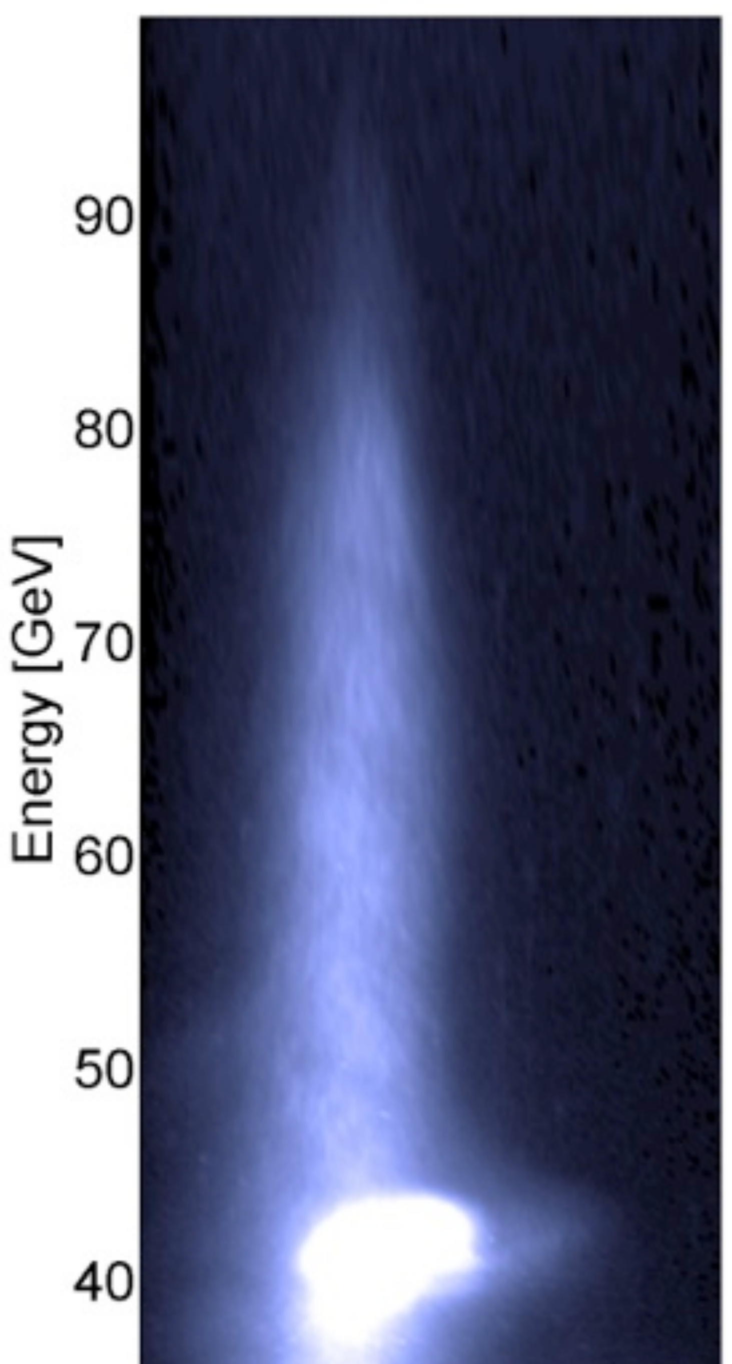

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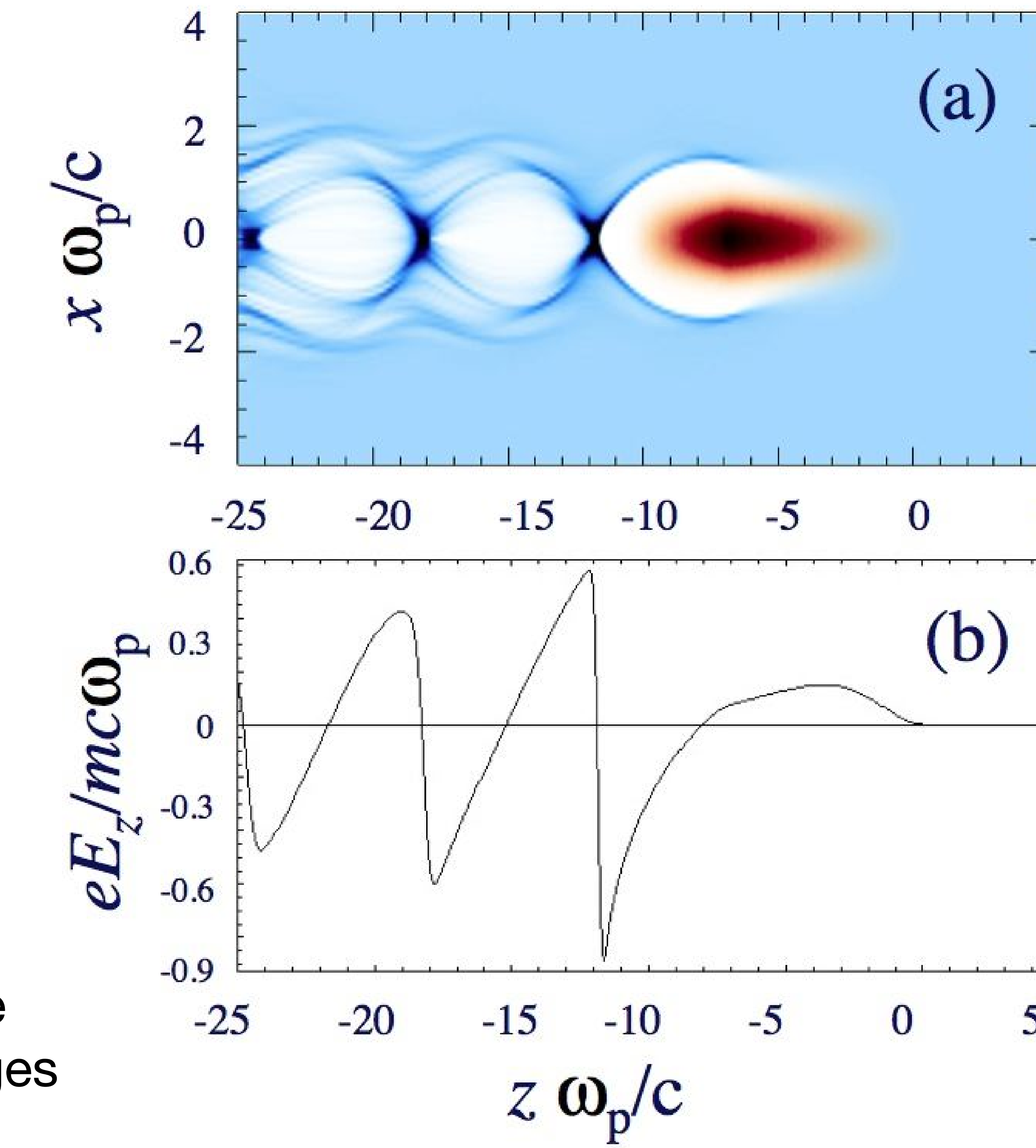
> Accelerators at the energy frontier will require large conventional facilities or/and many stages



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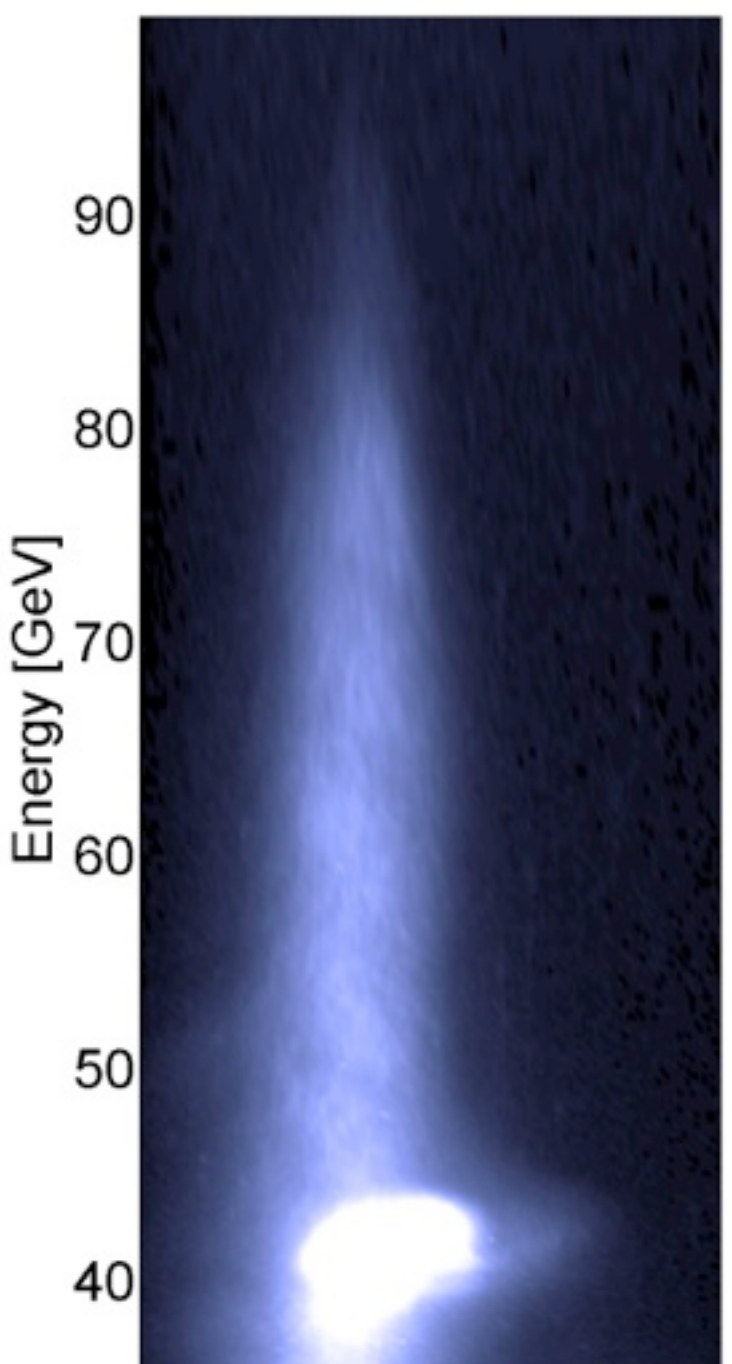
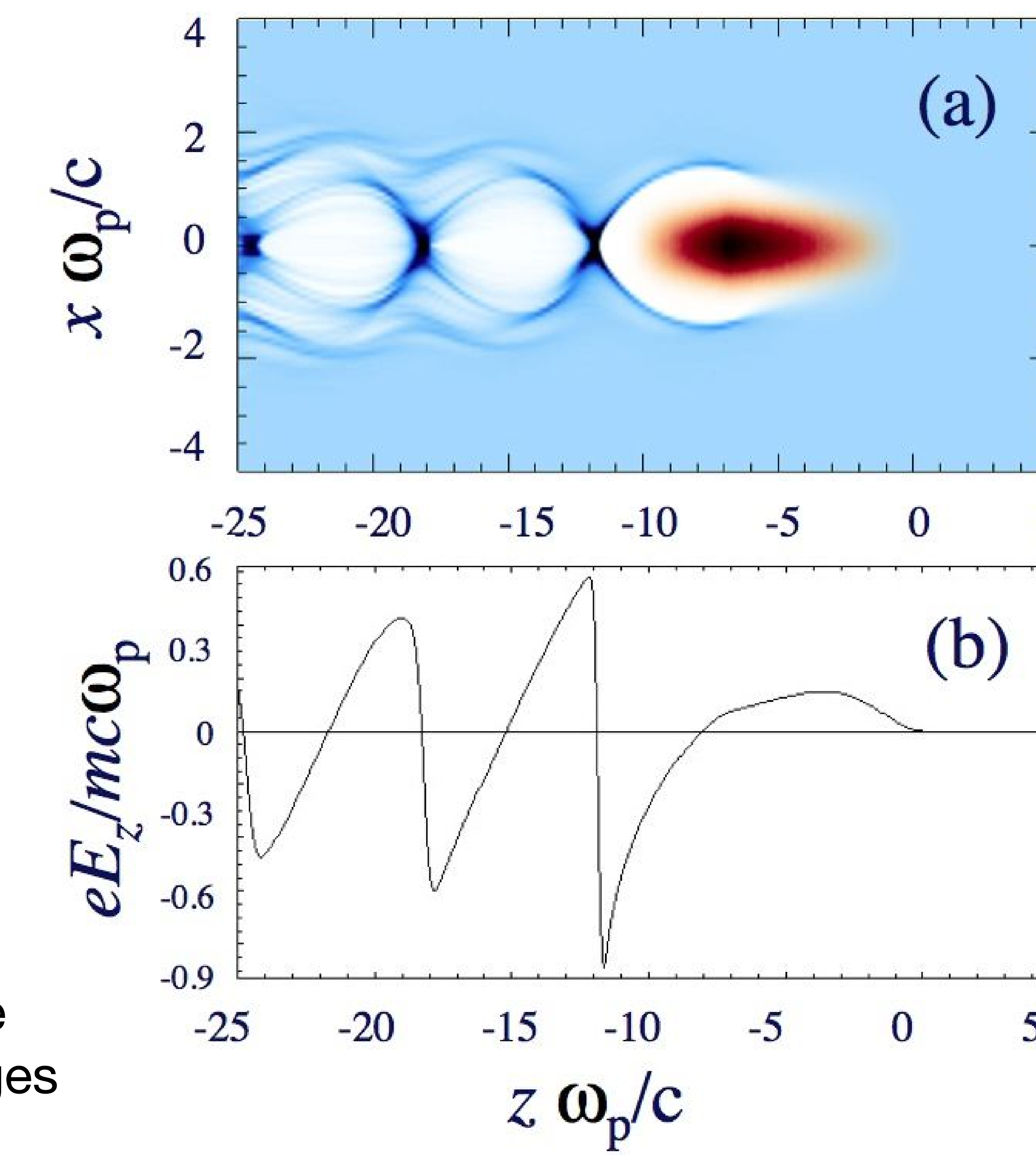
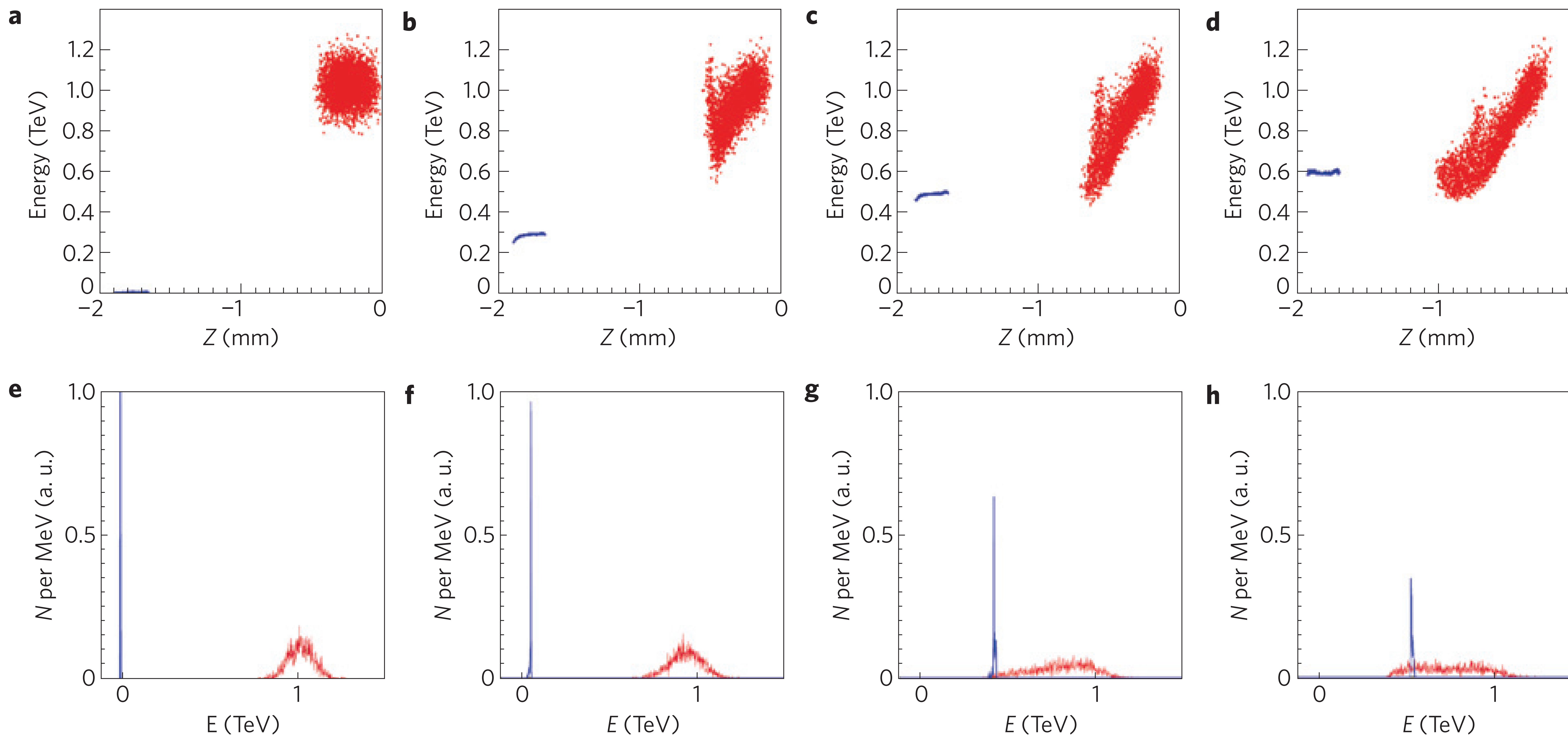




- Limiting issue: transformer ratio ≈ 2 owing to energy conservation
- Accelerators at the energy frontier will require large conventional facilities or/and many stages
- …or the use of heavier particles as drivers that can be prepared in ring accelerators

Particle-driven plasma wakefield schemes: proton beams



- Idea: use a 1 TeV proton beam (e.g. from LHC) to drive a single TeV electron-acceleration stage in plasma
- First pre-studies are planned with the SPS beam to start in 2015/16

Summary and conclusions

- Plasma-based wakefield acceleration can provide electric fields in excess of 10 GV/m, about three orders of magnitude above what conventional technology can deliver today
- It is a young and dynamic field with plenty of challenges that require in-depth scientific research and solutions to allow for reliable applications
- The success of plasma acceleration and applications at the particle-energy frontier will depend on
  - the development of efficient, high-peak power, high-average power lasers
  - the development of a compact staging technique
- First applications in photon science likely within the next 10 years, e.g. driving an FEL
- First particle physics applications will take significantly longer…

Contributions and scientific collaborators

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