RWTH Aachen (January 31st, 2011)

PROSPECTS OF LASER-PLASMA ACCELERATION

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United Kingdom

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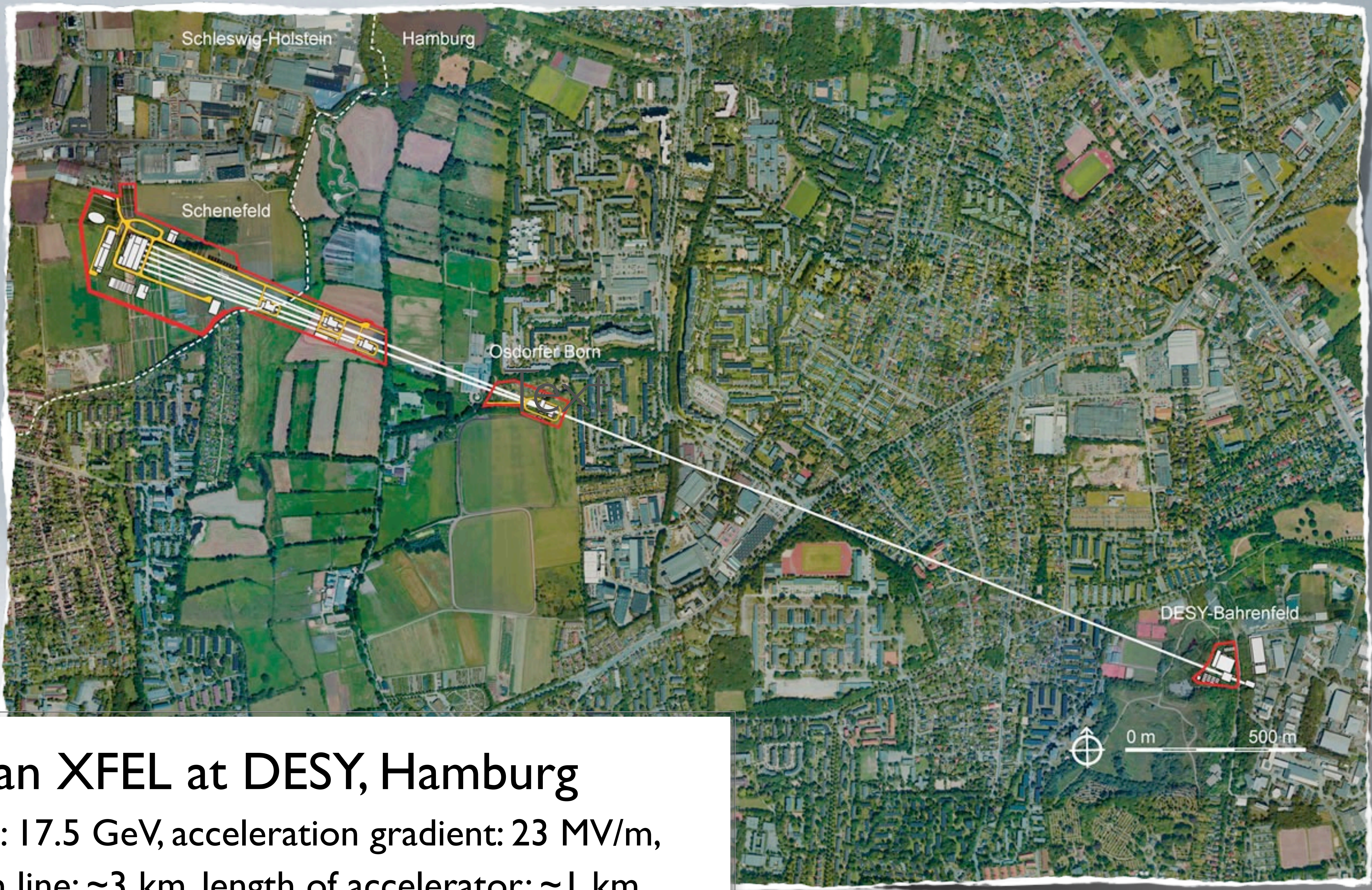
Modern accelerators are large-scale machines



European XFEL at DESY, Hamburg

Electron energy: 17.5 GeV, acceleration gradient: 23 MV/m,
length of beam line: ~3 km, length of accelerator: ~1 km

Plasma accelerators allow for extreme electric fields

LOASIS TREX at LBNL, Berkeley

Laser-driven plasma accelerator for electrons with 1.0 GeV

Length: 3.3 cm, average acceleration gradient: 30 GV/m

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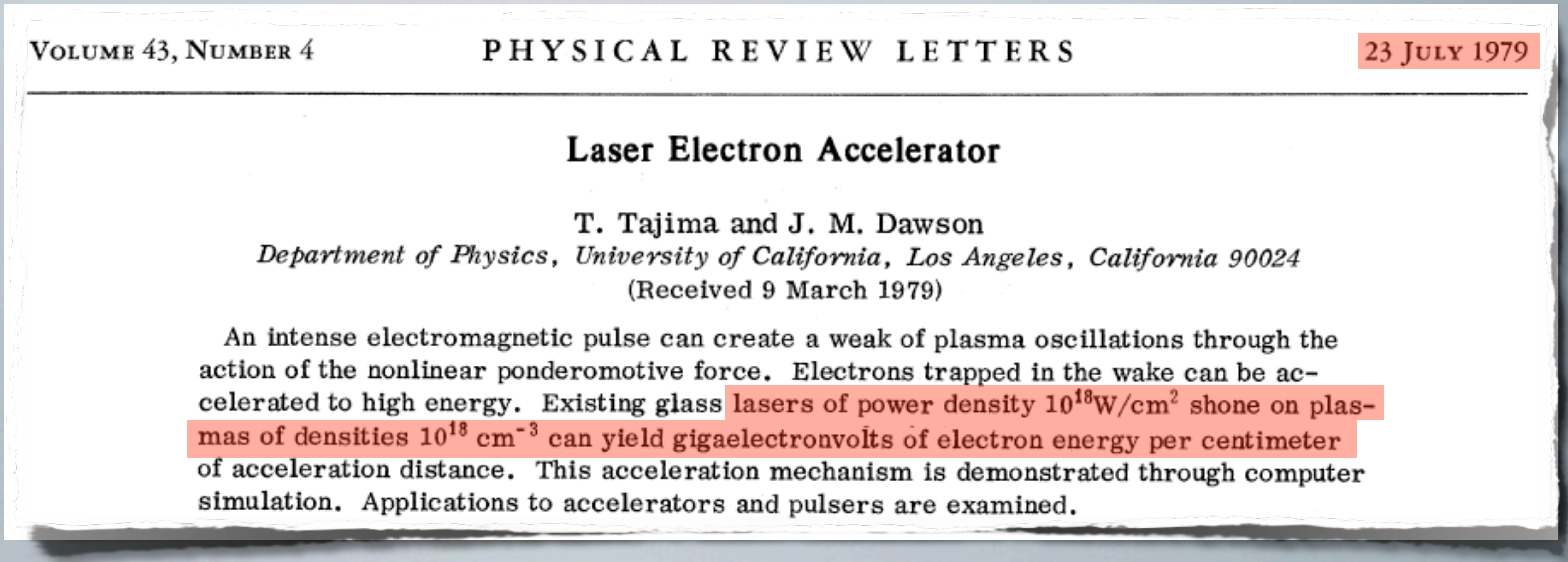
10^3 times larger than in conventional accelerators

Plasma accelerators allow for extreme electric fields



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.

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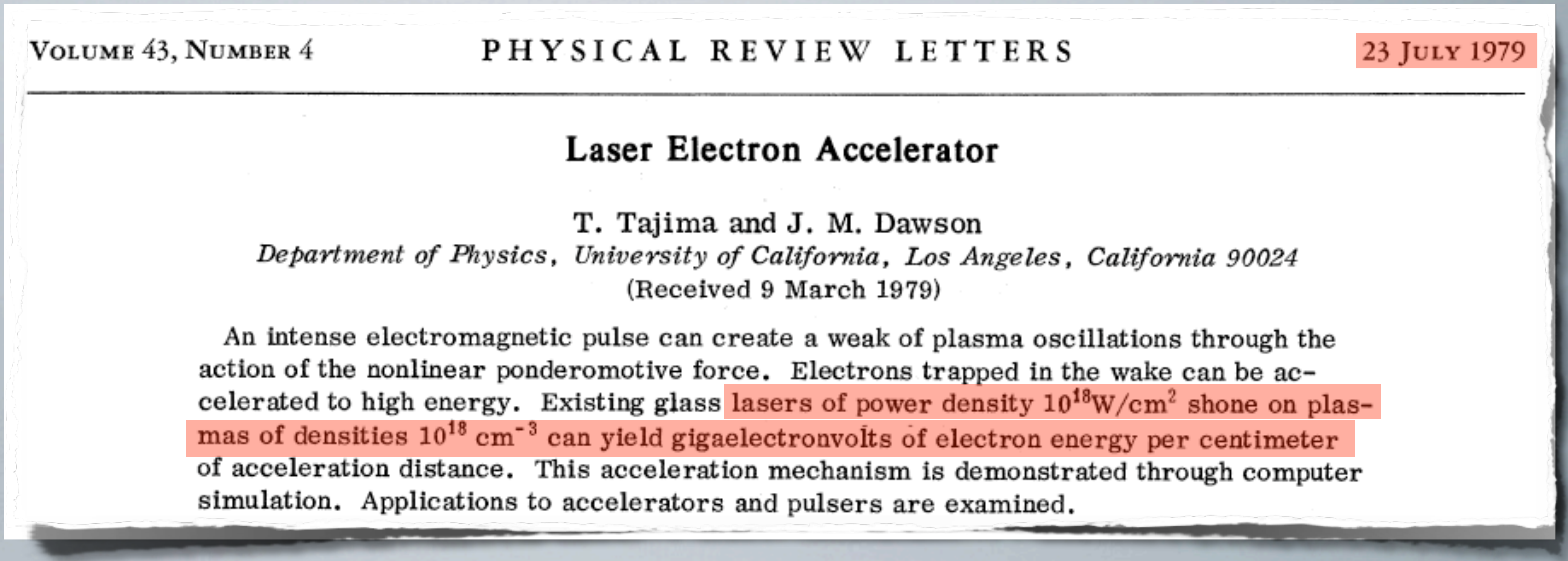

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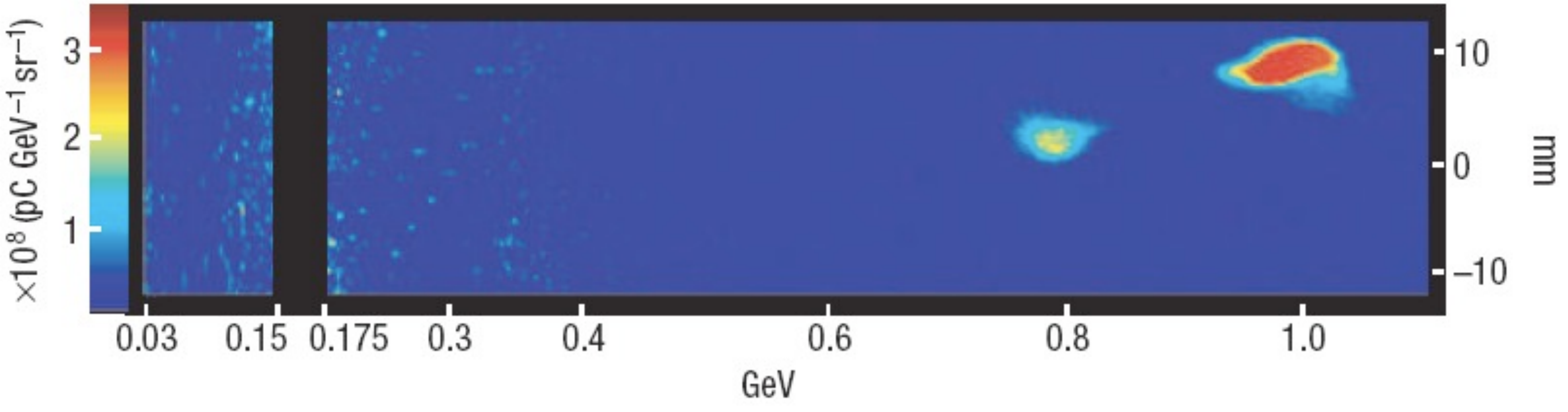
40 TW laser pulse (3×10^{18} W/cm^2)
inside plasma with $n_e = 4.3\times10^{18}$ cm^{-3}

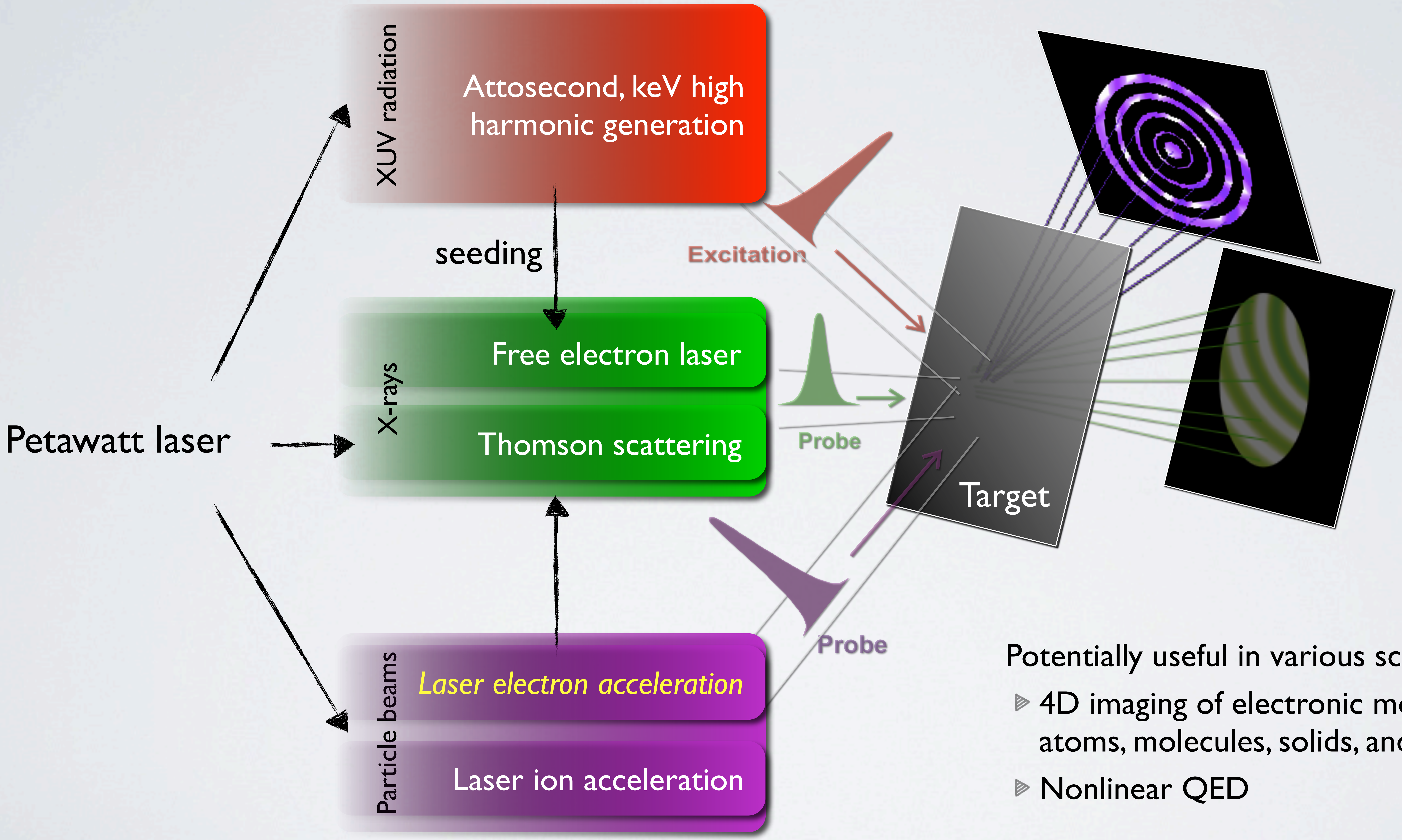
→ 30 pC of electrons at 1 GeV

accelerated over a distance < 3 cm
(with > 33 GV/m fields)



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

Lasers provide sub-femtosecond synchronization



Petawatt laser

XUV radiation

Attosecond, keV high harmonic generation

seeding

X-rays

Free electron laser

Thomson scattering

Particle beams

Laser electron acceleration

Laser ion acceleration

Potentially useful in various scientific fields:

- 4D imaging of electronic motion in atoms, molecules, solids, and plasmas
- Nonlinear QED

Laser-plasma accelerator basics

Wake excitation

Electron injection

High-intensity lasers can drive large plasma wakes

Background plasma

Laser pulse

Electron-depleted cavity

Laser pulse propagates into a plasma-density ramp, electrons get trapped

3D particle-in-cell (PIC) simulation

osiris v2.0

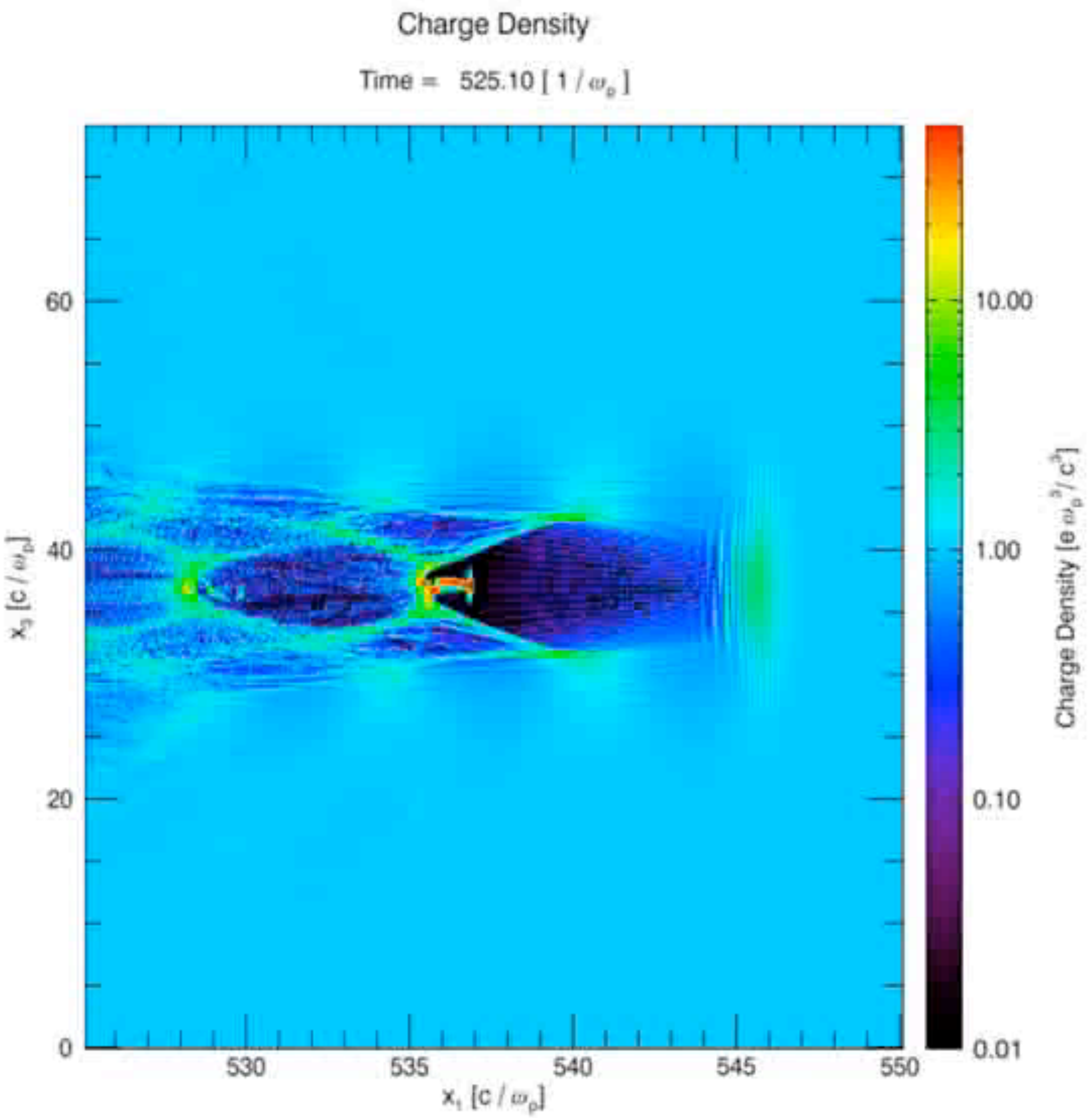
Laser pulse properties

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

Plasma background density

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

High-intensity lasers can drive large plasma wakes



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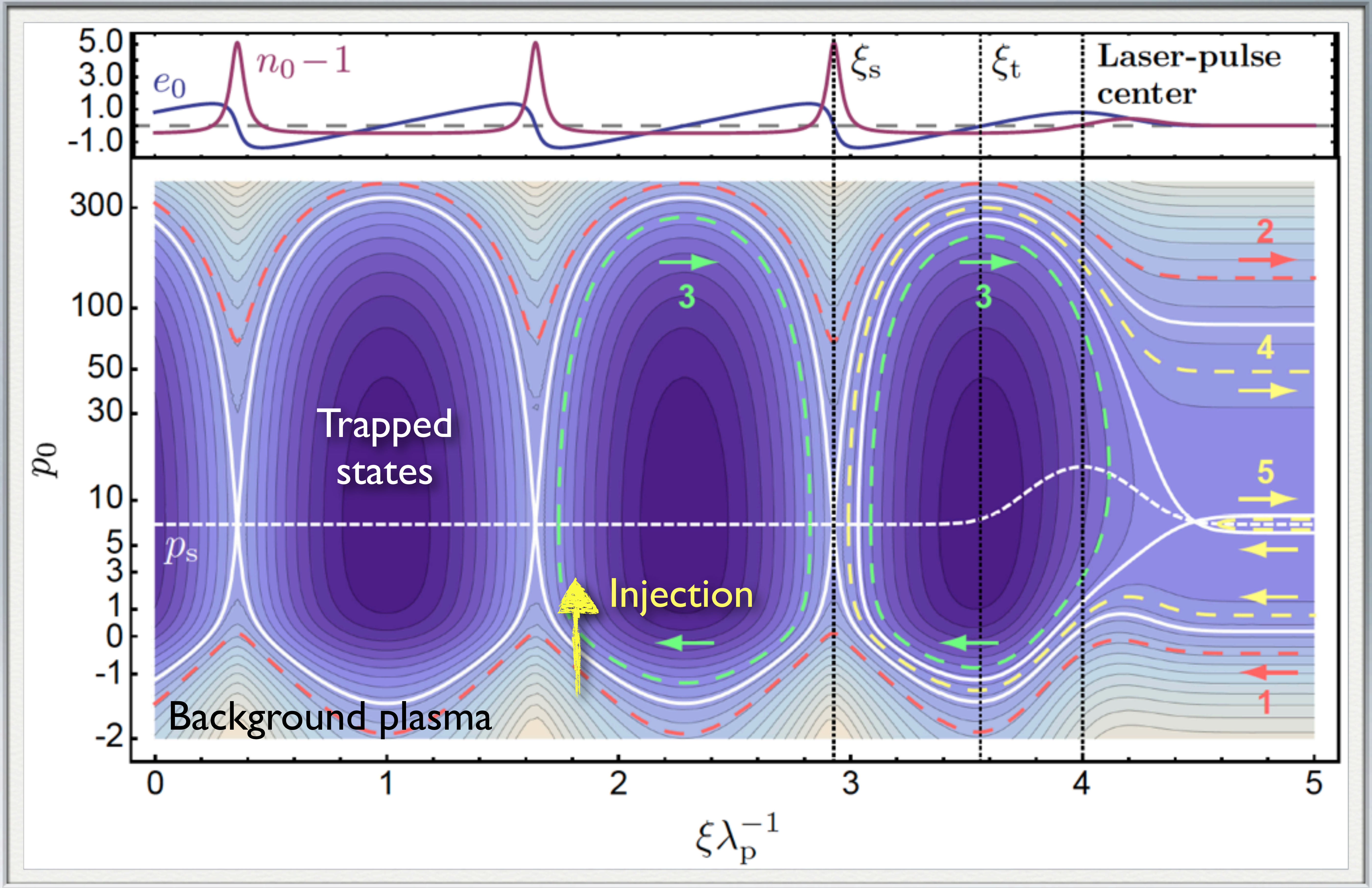
INSTITUTO SUPERIOR TÉCNICO

USC

UCLA

3D particle-in-cell (PIC) simulation

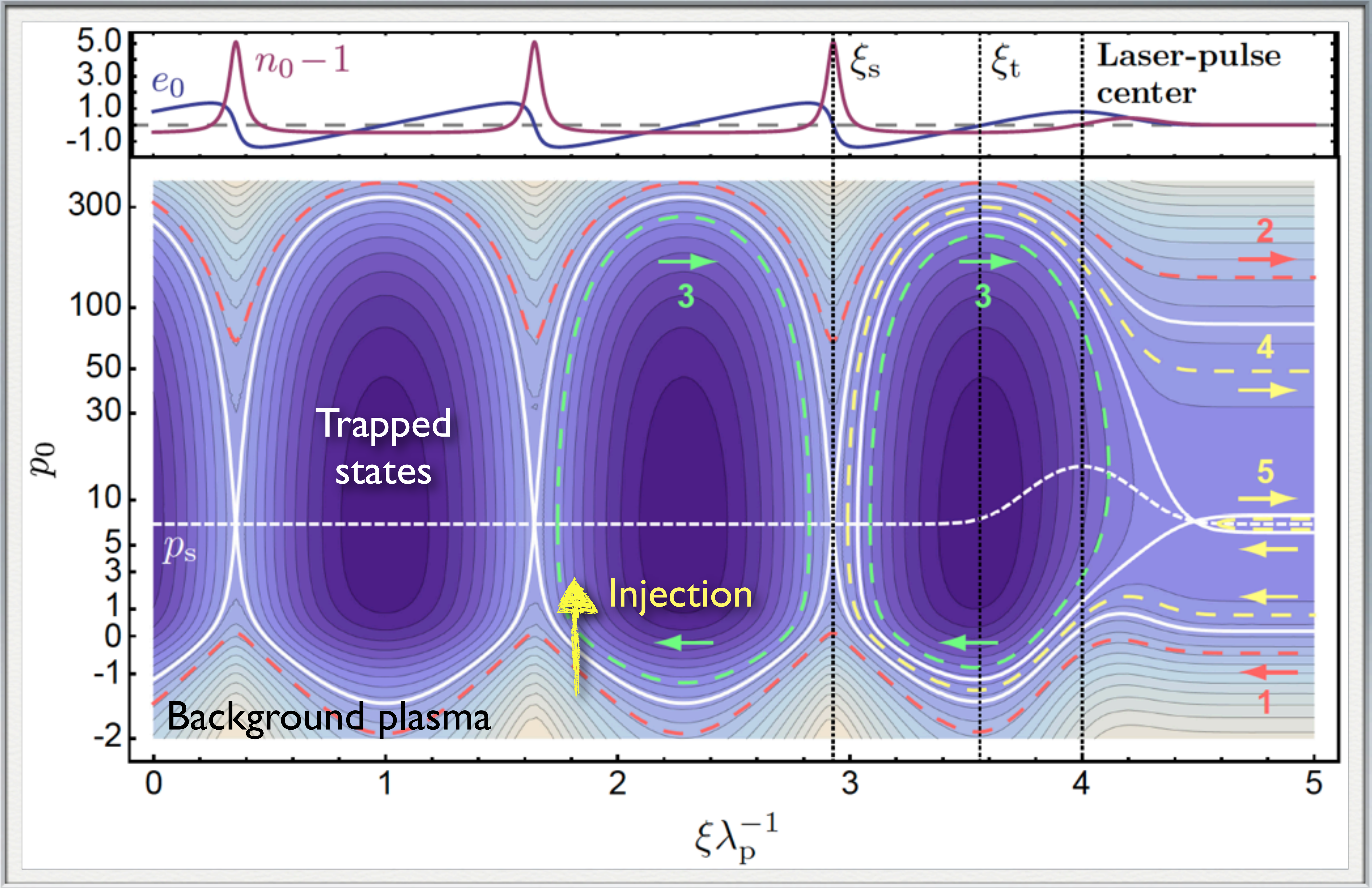
Injection controls charge, energy spread, emittance



Injection controls charge, energy spread, emittance

Self-injection (or wave-breaking):
hard to control, stability issues
→ undesirable

Controlled injection:
control over accelerated charge,
bunch energy spread, and
emittance, less fluctuations



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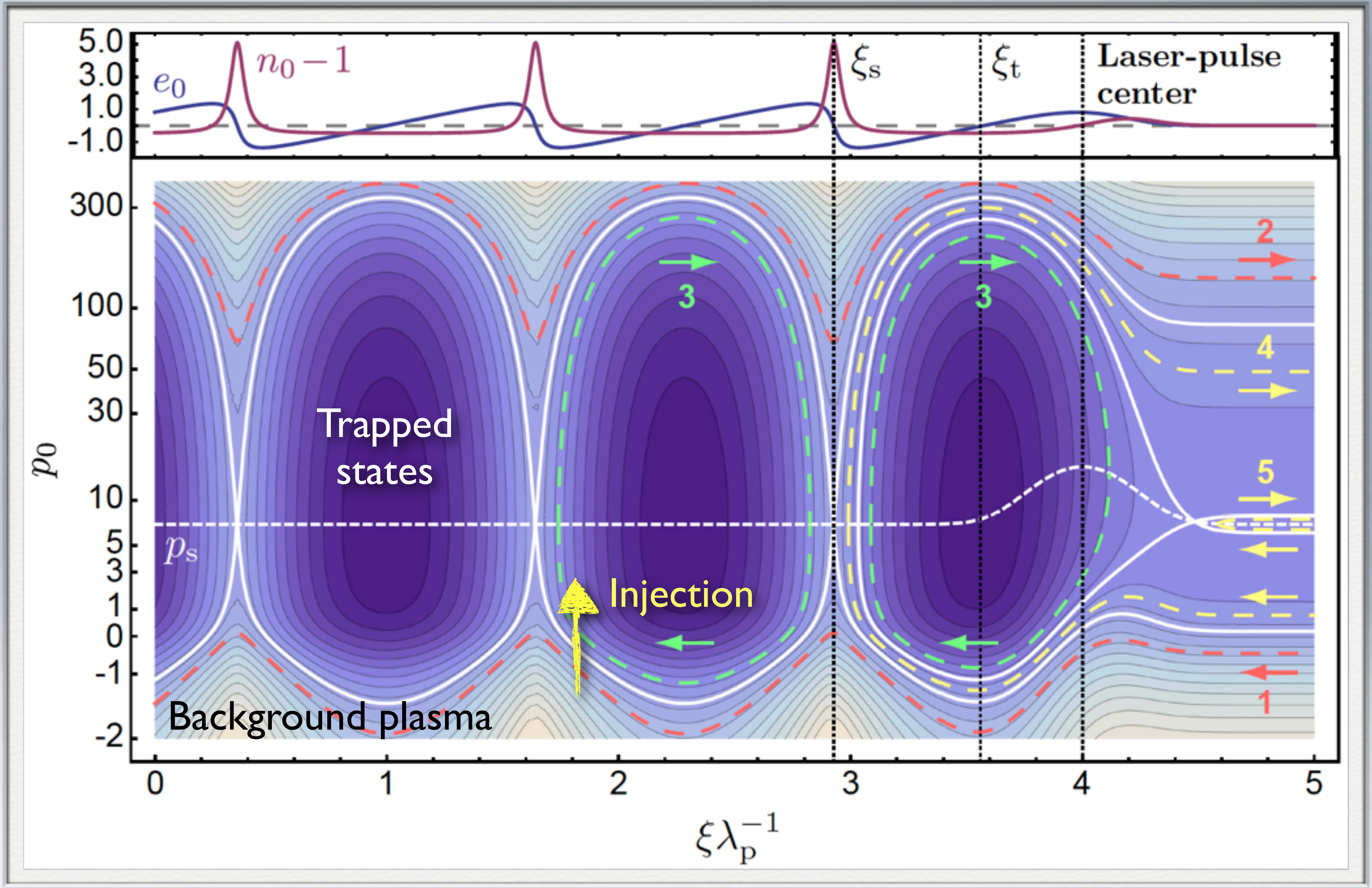

In principle, triggered injection into a plasma wave could achieve beam quality (low emittance) beyond state-of-the-art photocathodes (due to space-charge shielding provided by ions, rapid acceleration)

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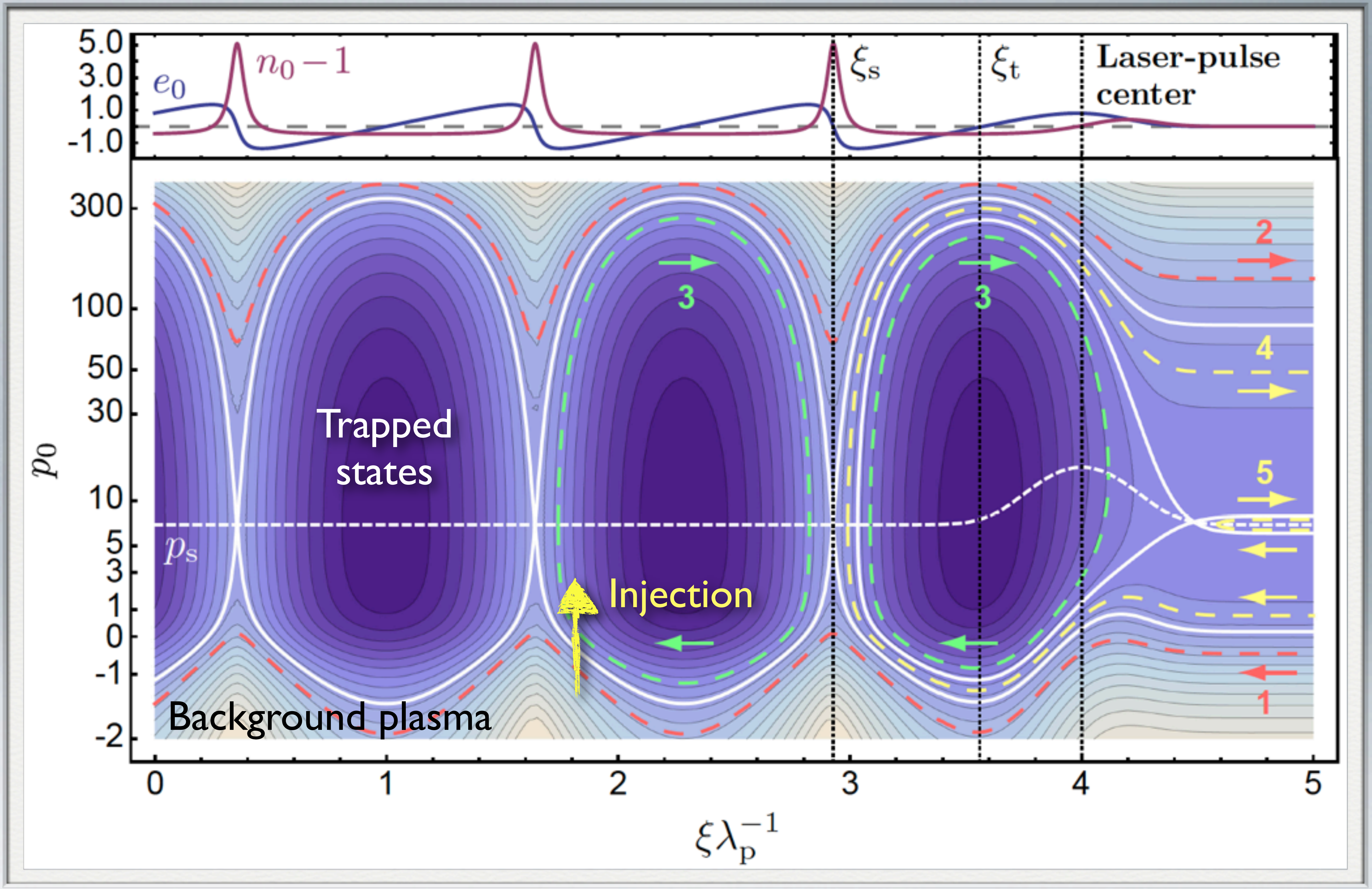
Methods for controlled injection:

- Density down-ramp injection
  [Bulanov *et al.*, Phys. Rev. E 58, R5257 (1998);
  Geddes *et al.*, Phys. Rev. Lett. 100, 215004 (2008)]
- Laser-triggered injection
  [Esarey *et al.*, Phys. Rev. Lett. 79, 2682 (1997);
  Faure *et al.*, Nature 444, 737 (2006)]
- Ionization injection
  [Umstadter *et al.*, Phys. Rev. Lett. 76, 2073 (1996);
  Pak *et al.*, Phys. Rev. Lett. 104, 025003 (2010)]
- External beam injection
  [Dewa *et al.*, Nucl. Instrum. & Methods Phys. Res. A 410, 357 (1998); Dorchies *et al.*, Phys. Plasmas 6 2903 (1999)]



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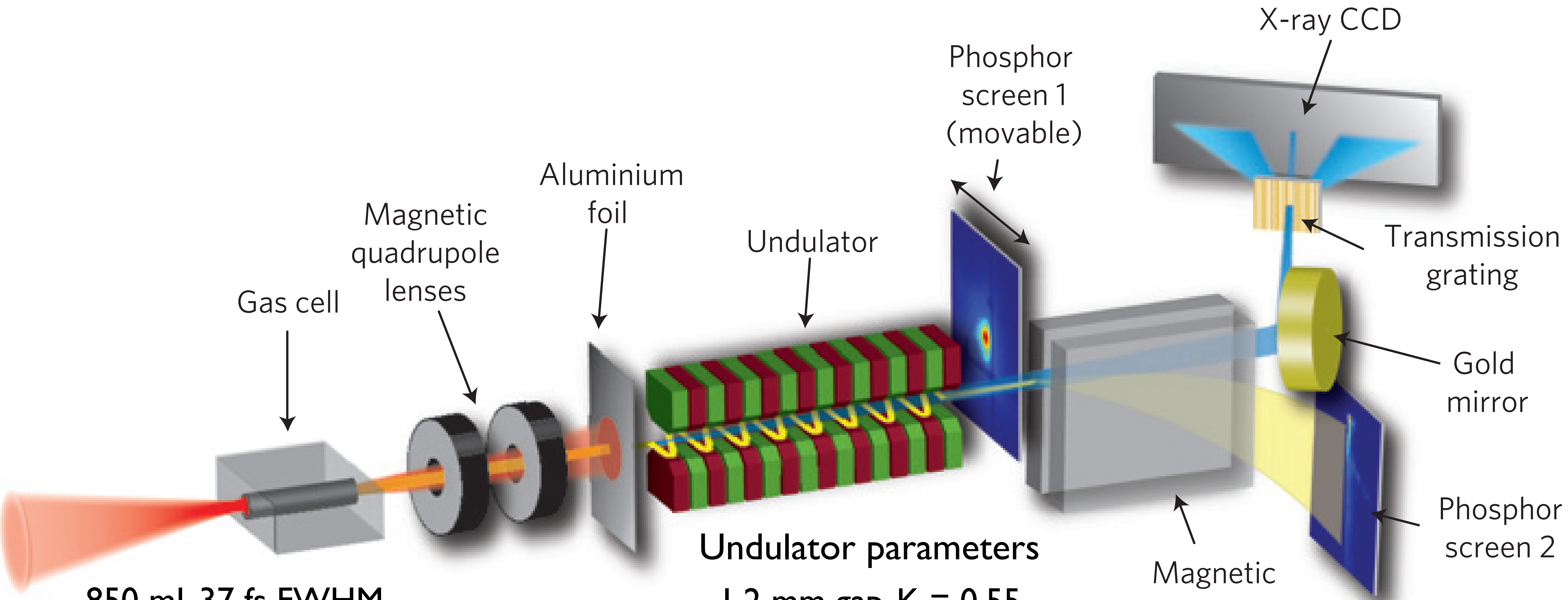
Generation of soft-X-rays from an LPA driven undulator

Fuchs *et al.*, Nature Physics 5, 826 (2009)



Undulator parameters

1.2 mm gap, K = 0.55

λ_u = 5 mm, 60 periods

Laser pulse parameters

850 mJ, 37 fs FWHM

23 μm focus FWHM

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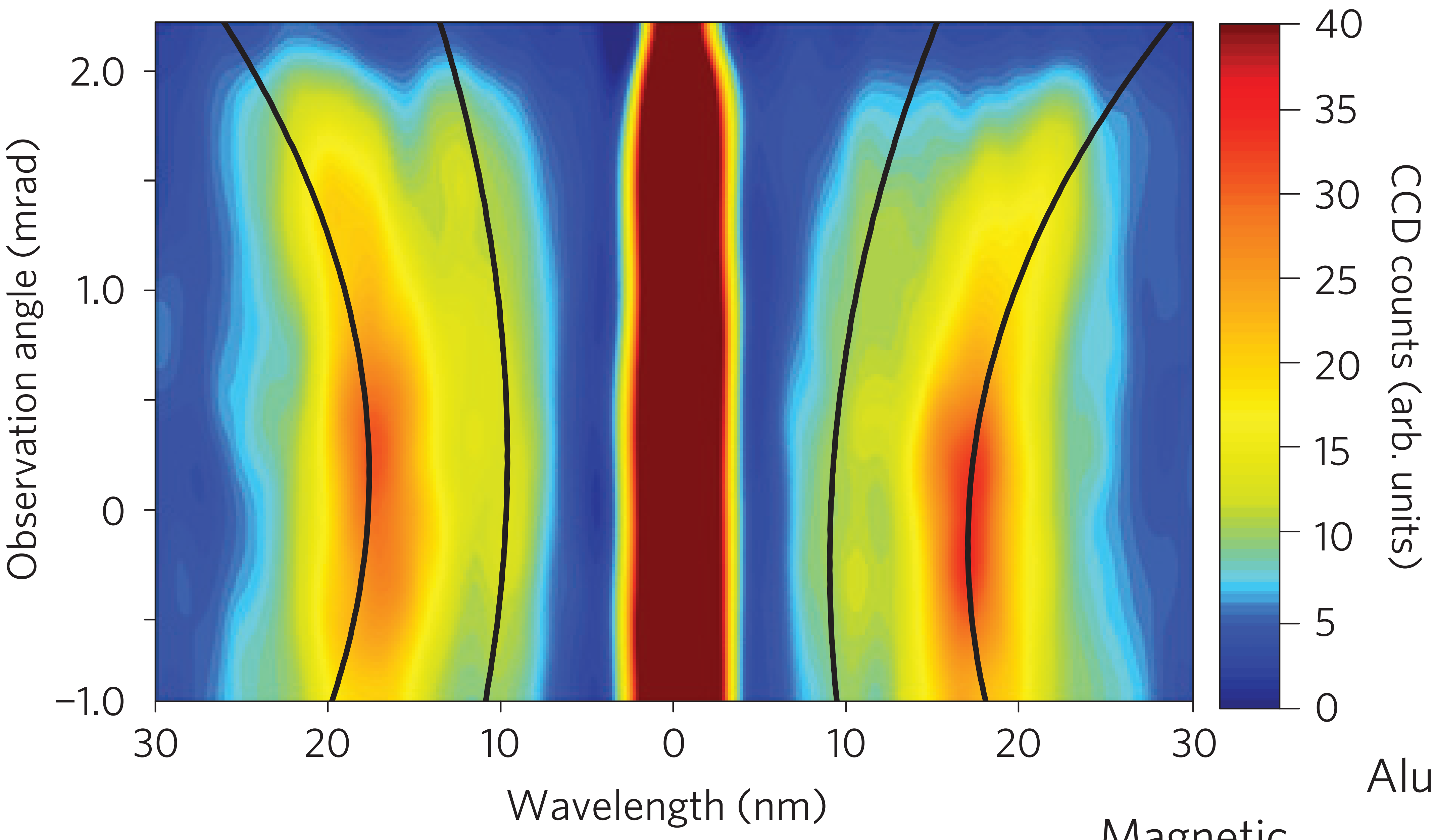
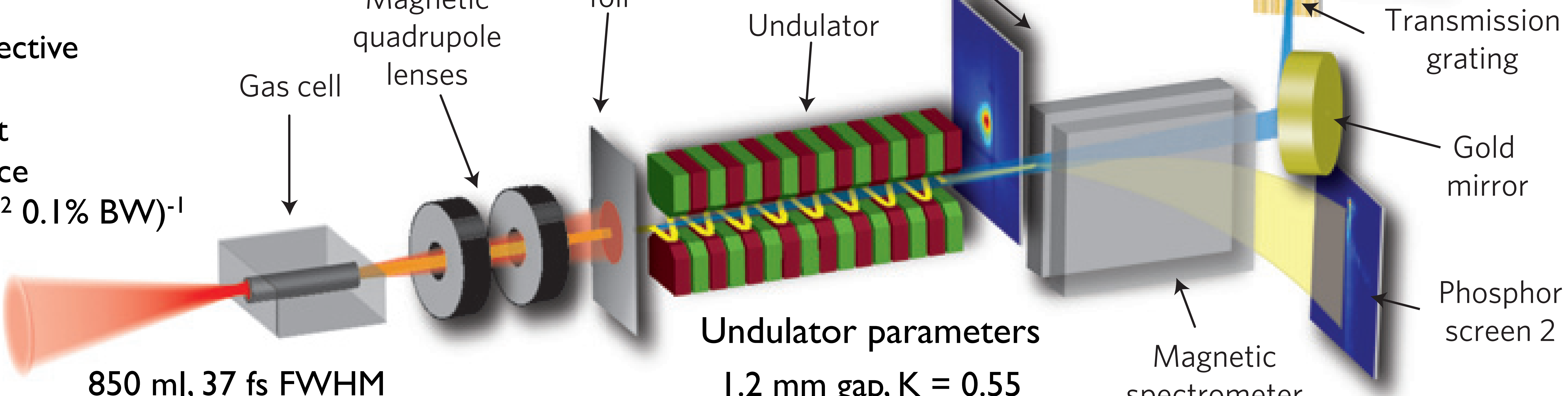


Resonance condition:

$$\lambda = \frac{\lambda_u}{2n\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\Theta^2\right)$$

- ~1 pC of charge in effective electron spectrum
- ~10^5 photons per shot
- Estimated peak brillance 1.3×10^{17} (s mrad^2 mm^2 0.1% BW)$^{-1}$



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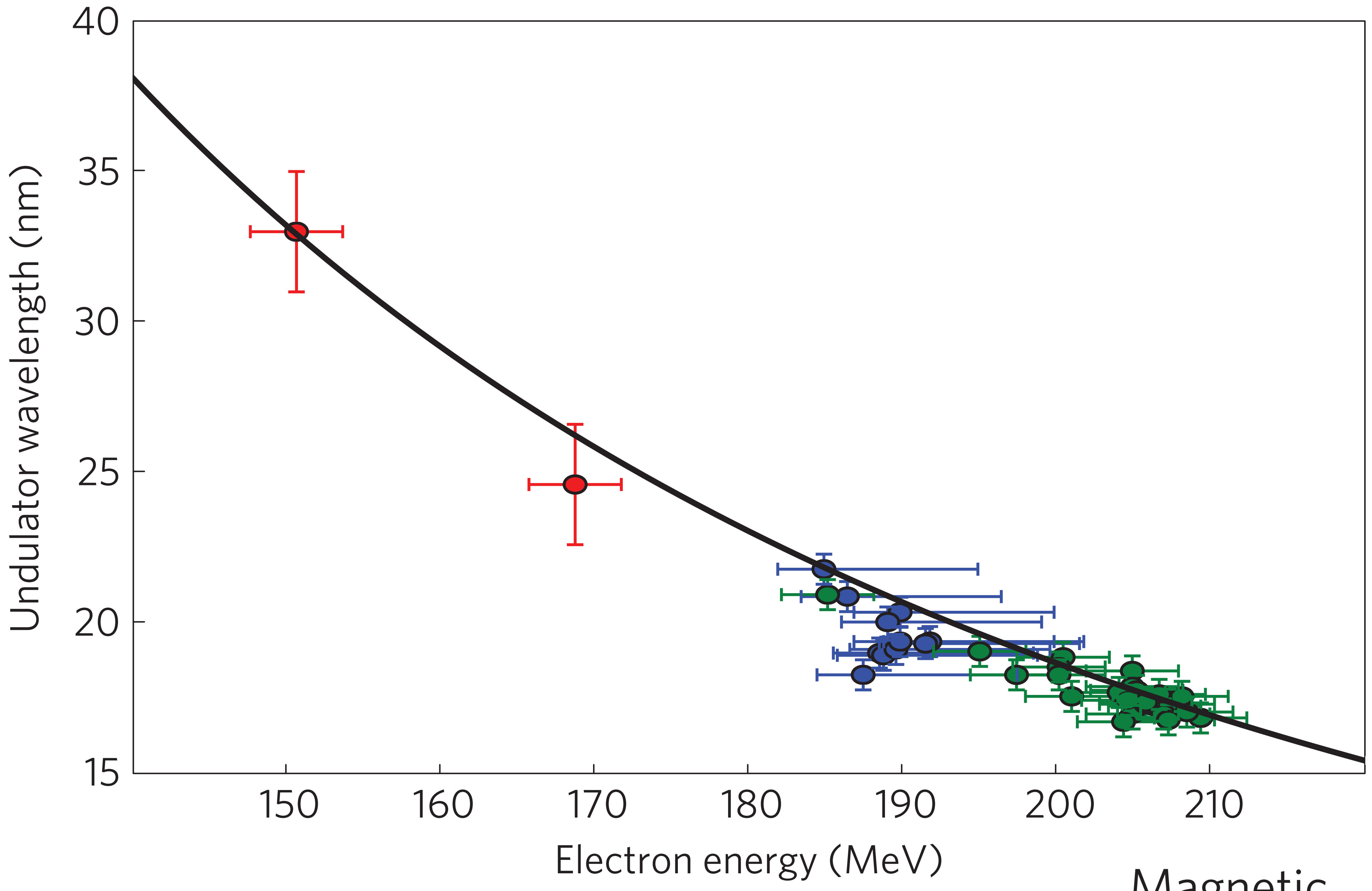

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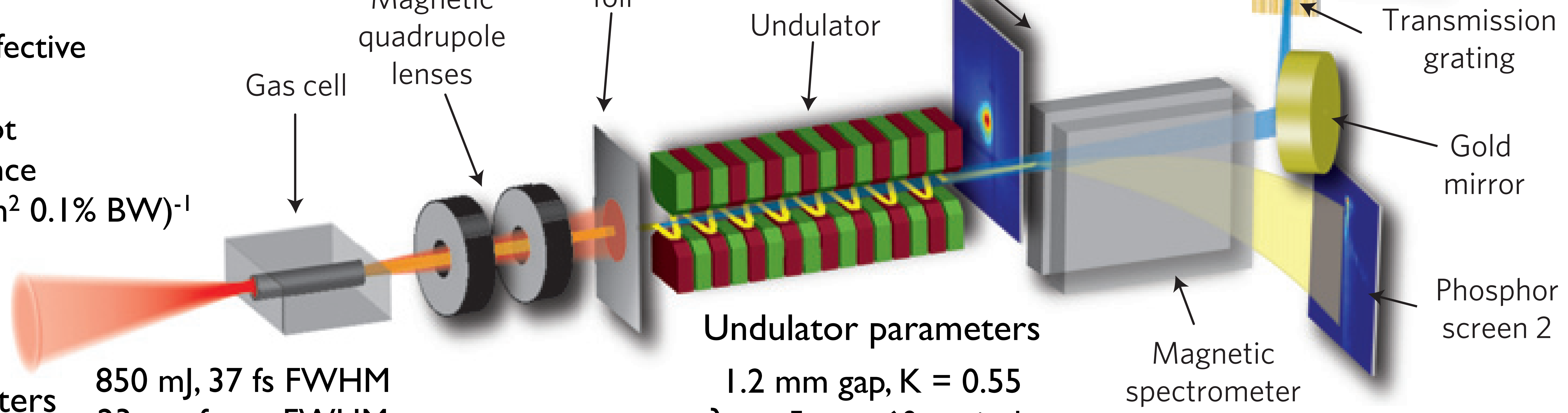

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Phase-space characterization of LPA beams needed

Many properties of electrons beams from laser-wakefield accelerators
have only been insufficiently characterized:

- Pulse duration
  upper limit ~50 fs RMS with electrooptic sampling [van Tilborg, Leemans *et al.*, Phys. Rev. Lett. 96, 014801 (2006)]

- Slice energy spread
  inferred from PIC simulations

- Longitudinal and transverse beam density modulations (e.g. at λ / 2)
  inferred from PIC simulations

- Transverse beam emittance and source size
  inferred from PIC simulations, old pepper pot measurements [Fritzler *et al.*, Phys. Rev. Lett. 92, 165006 (2004)]

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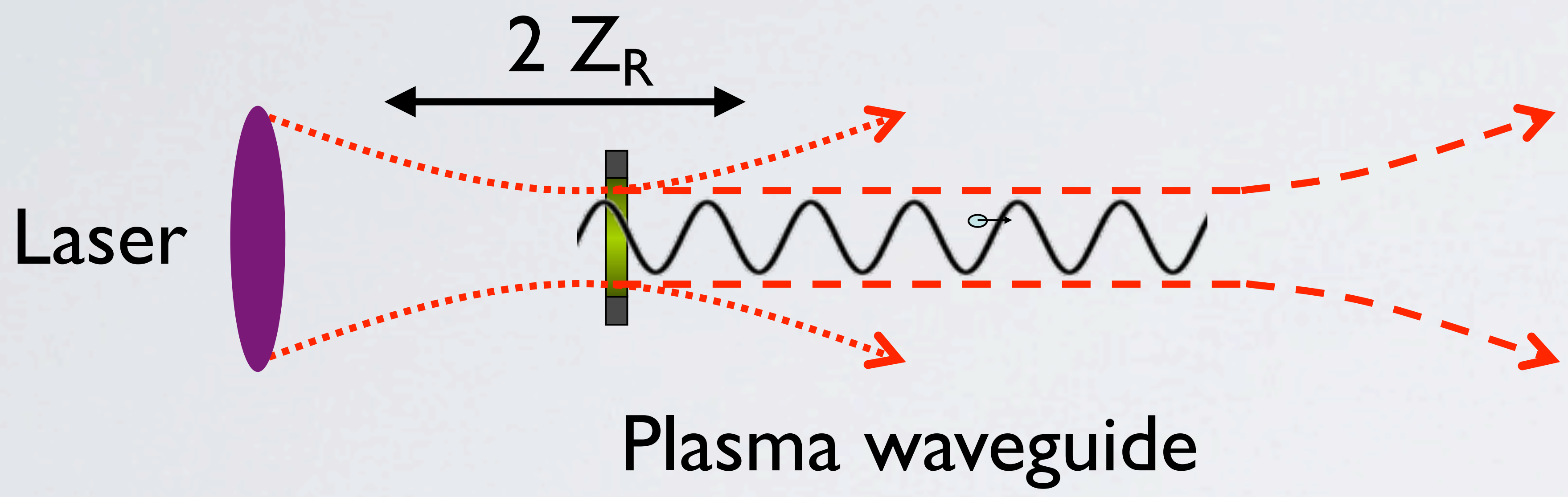
Know how at established accelerator facilities would help to analyze LPA beams more thoroughly:

(C)OTR, IR/THz spectrometry, transverse deflection cavities,
characterization of XUV/x-ray emission from undulators, characterization of betatron emission

Also important: beam position measurements (BPMs), transport and imaging (magnetic beam transport systems)

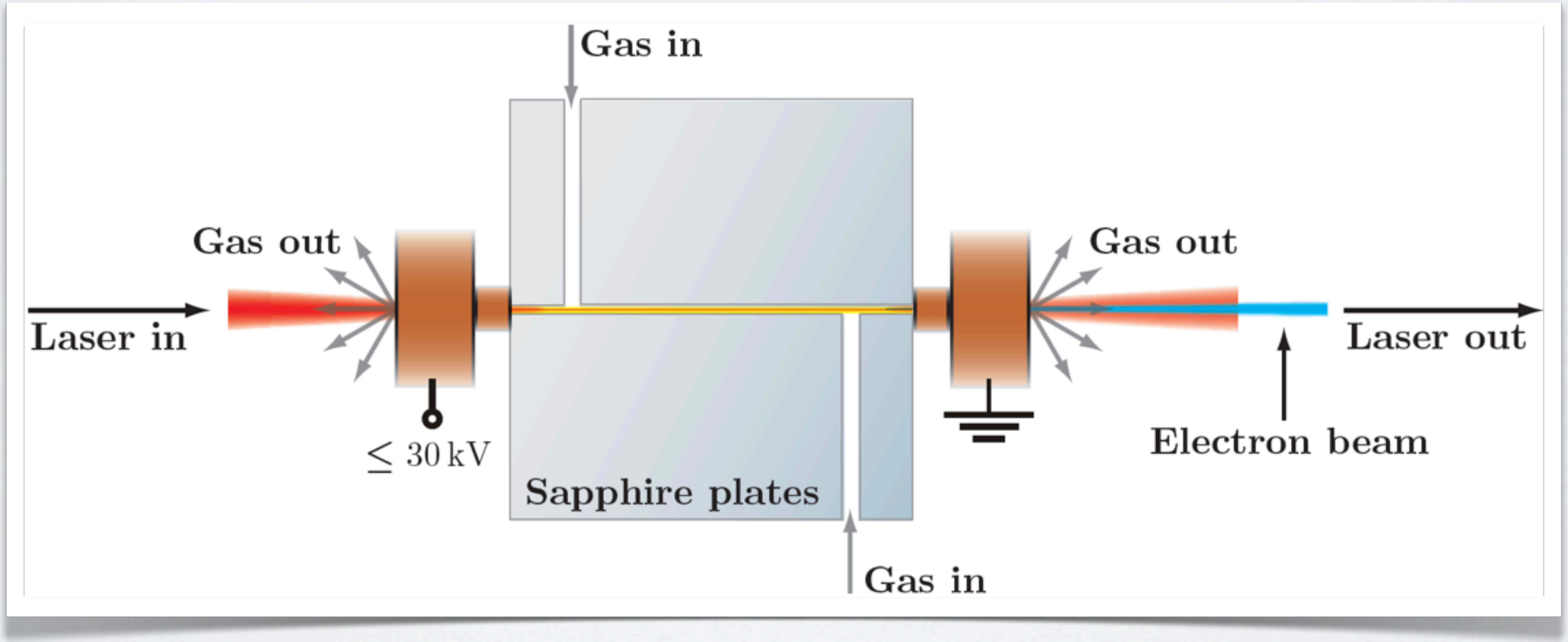
Energy gain scalings and single-stage limitations

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



<u>Capillary discharge plasma waveguides</u>

- 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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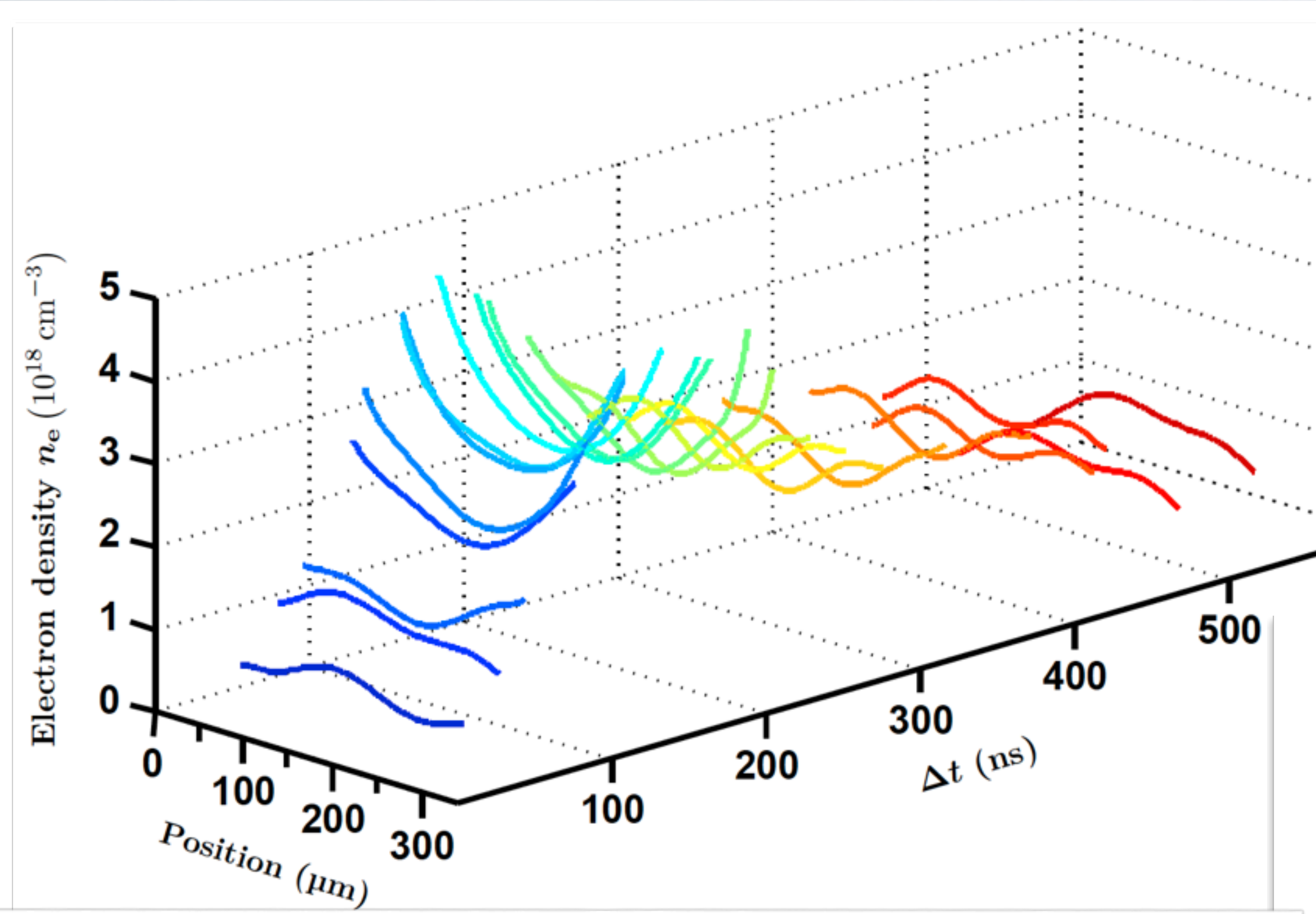

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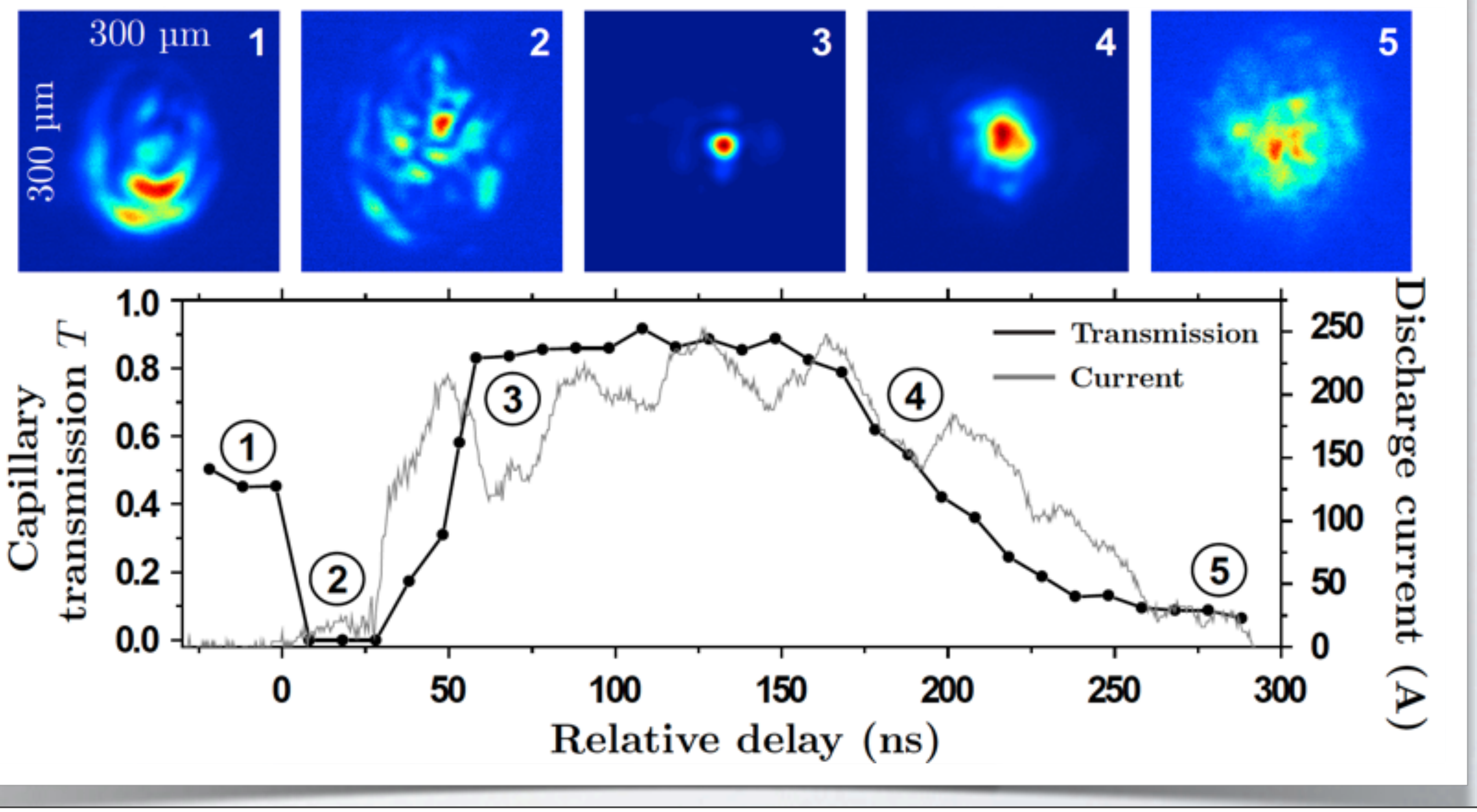
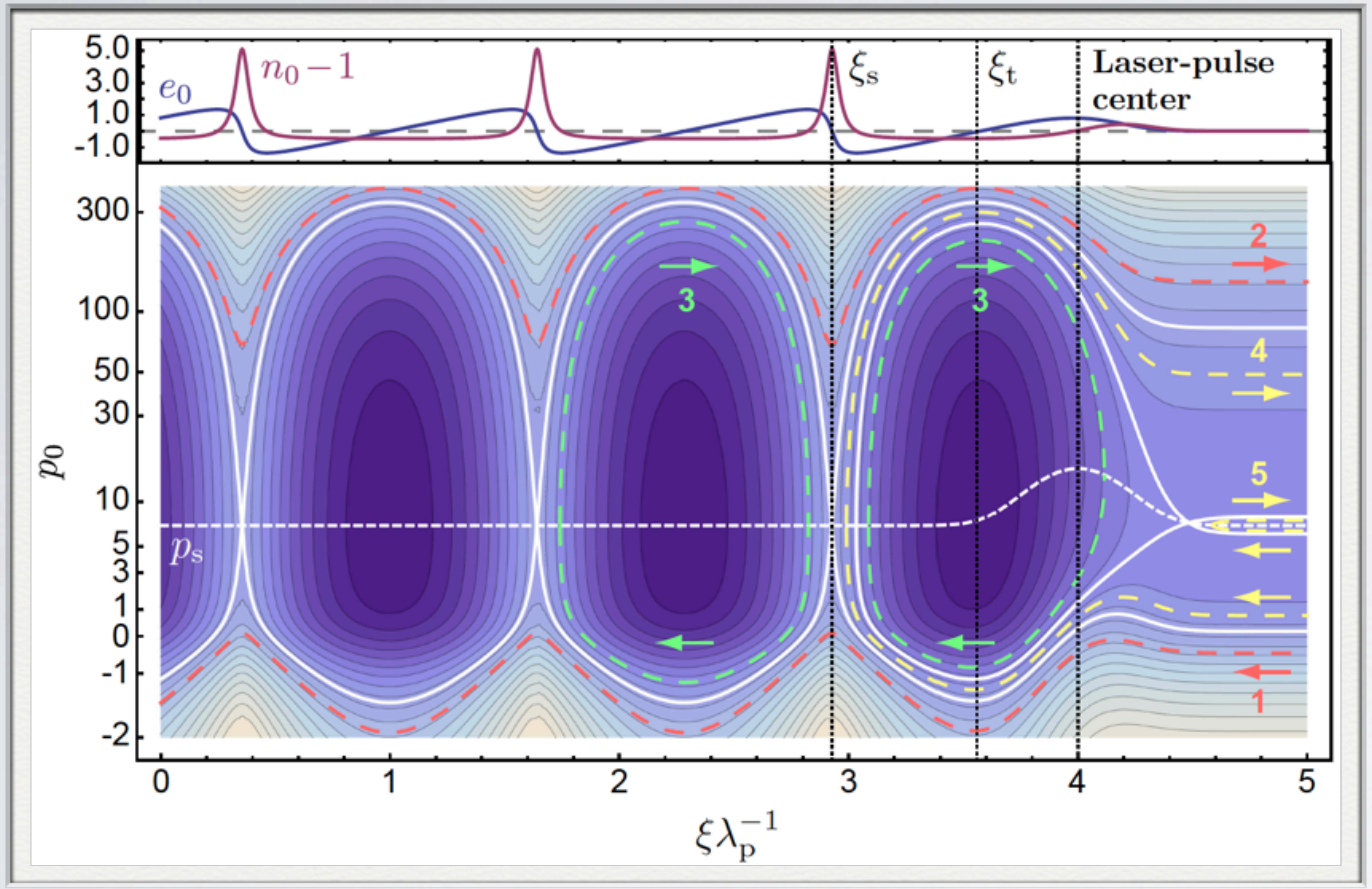


In this example:
Z_R = 2 mm, guiding over 16 mm, guiding efficiency > 90 %

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 $v_e \approx c > v_{wave}$

⇒ they outrun the accelerating field structure

Energy gain scalings and single-stage limitations

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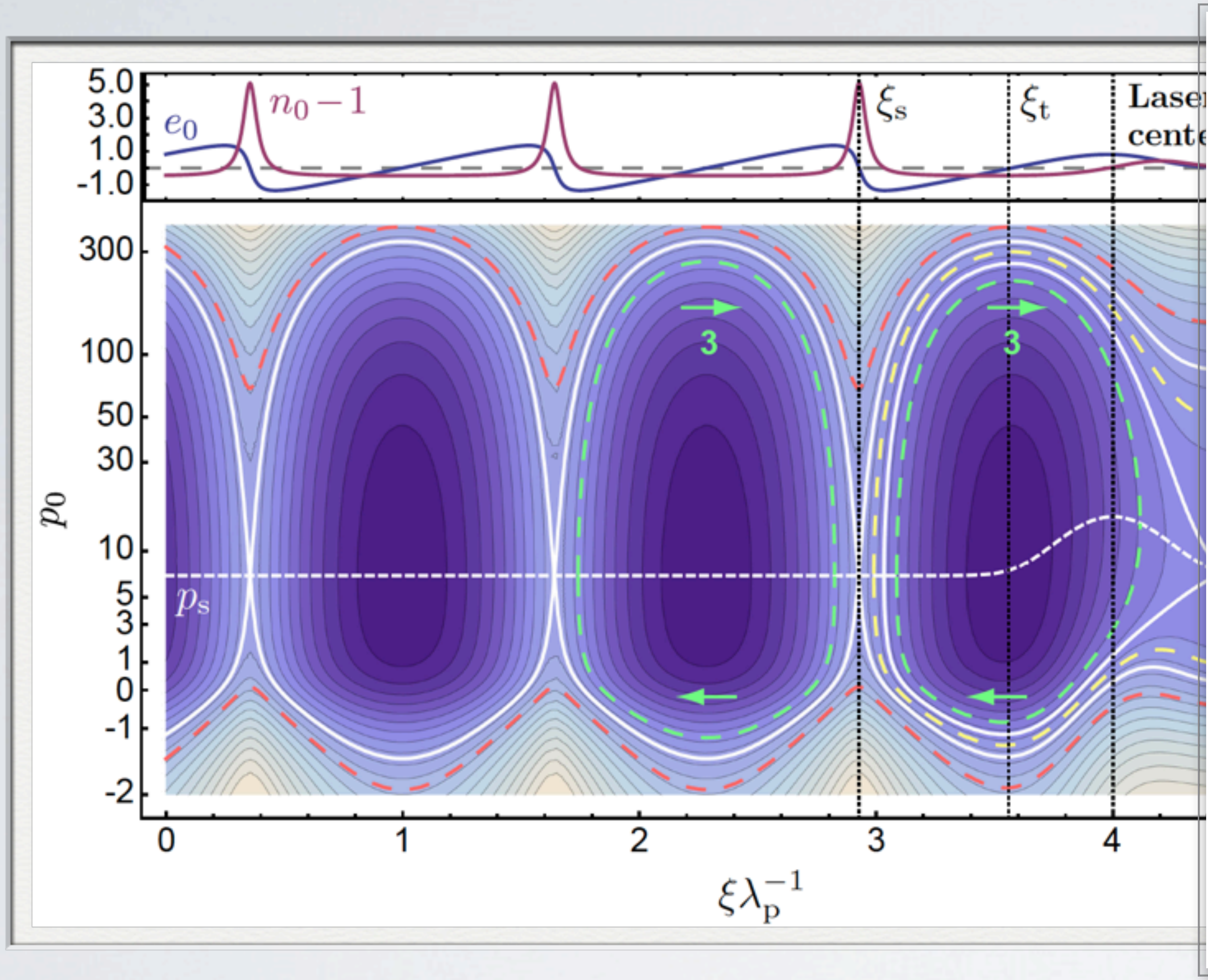

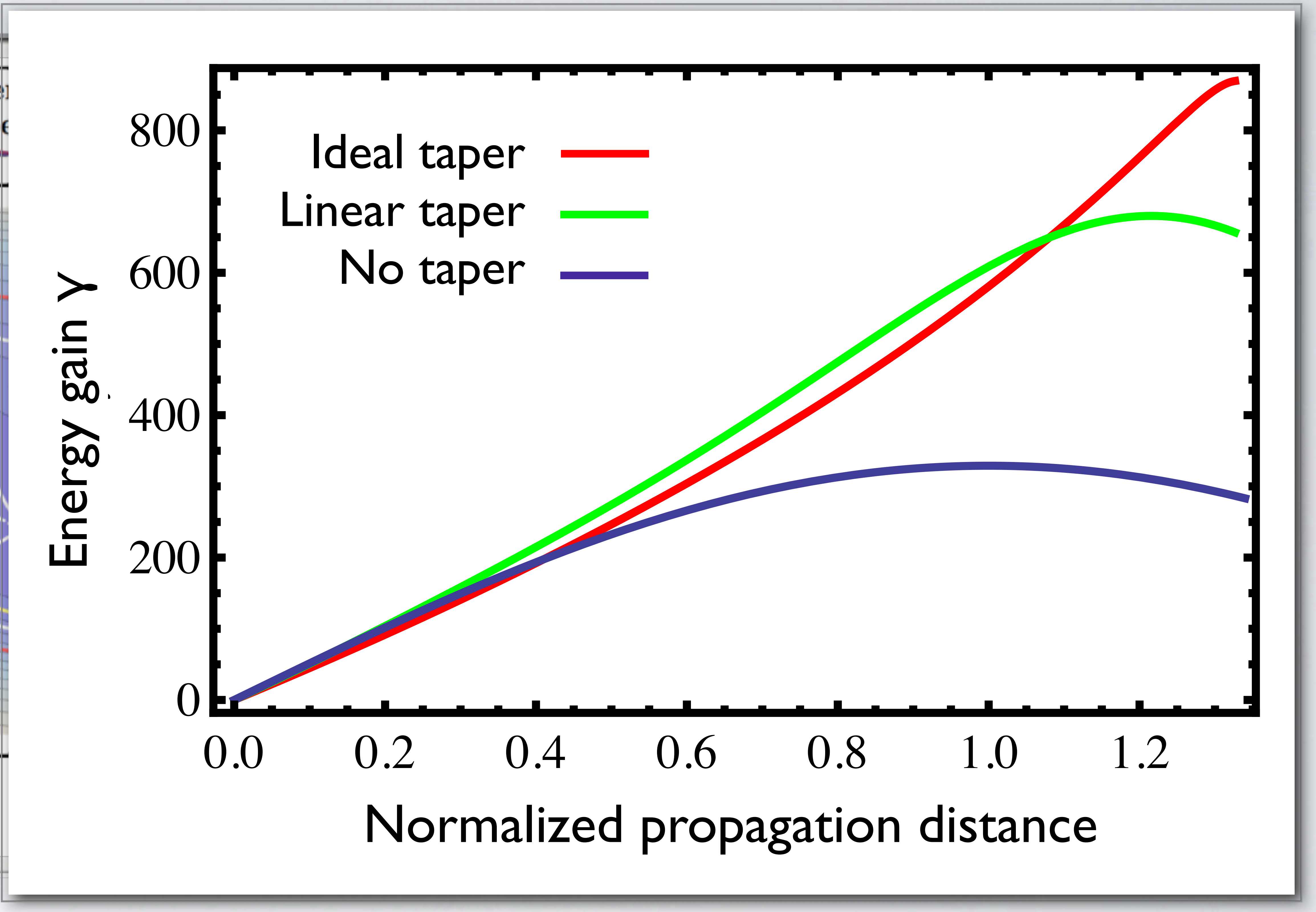

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Laser pulse, plasma wave travel with $v_{wave} = v_g < c$

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

⇒ they outrun the accelerating field structure

<u>Rising density plasma</u>

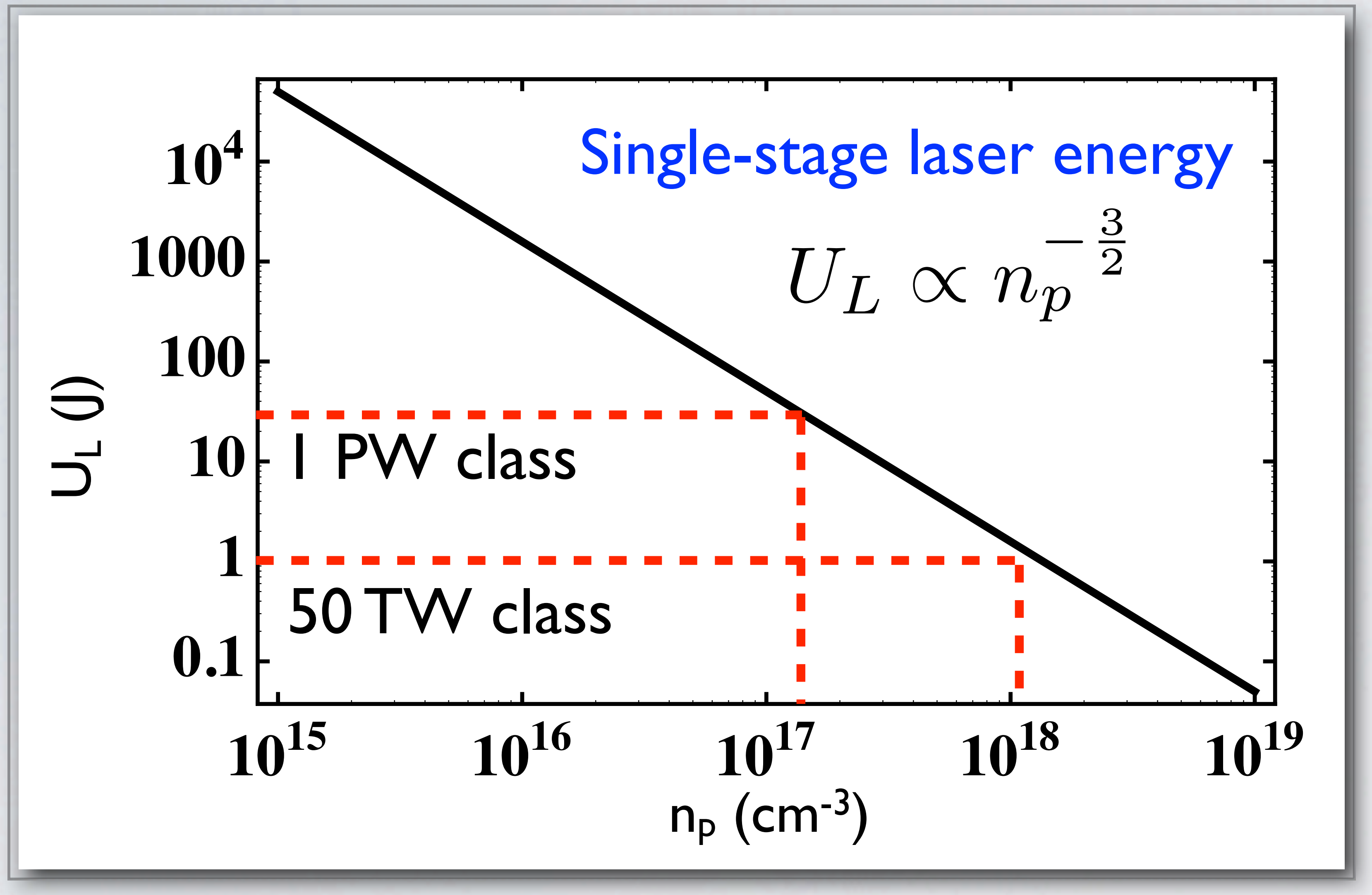
Plasma wave phase velocity v_{wave} may be set to v_e

⇒ 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.*, Proceedings of Advanced Accelerator Concepts Workshop (2010)

Energy gain scalings and single-stage limitations

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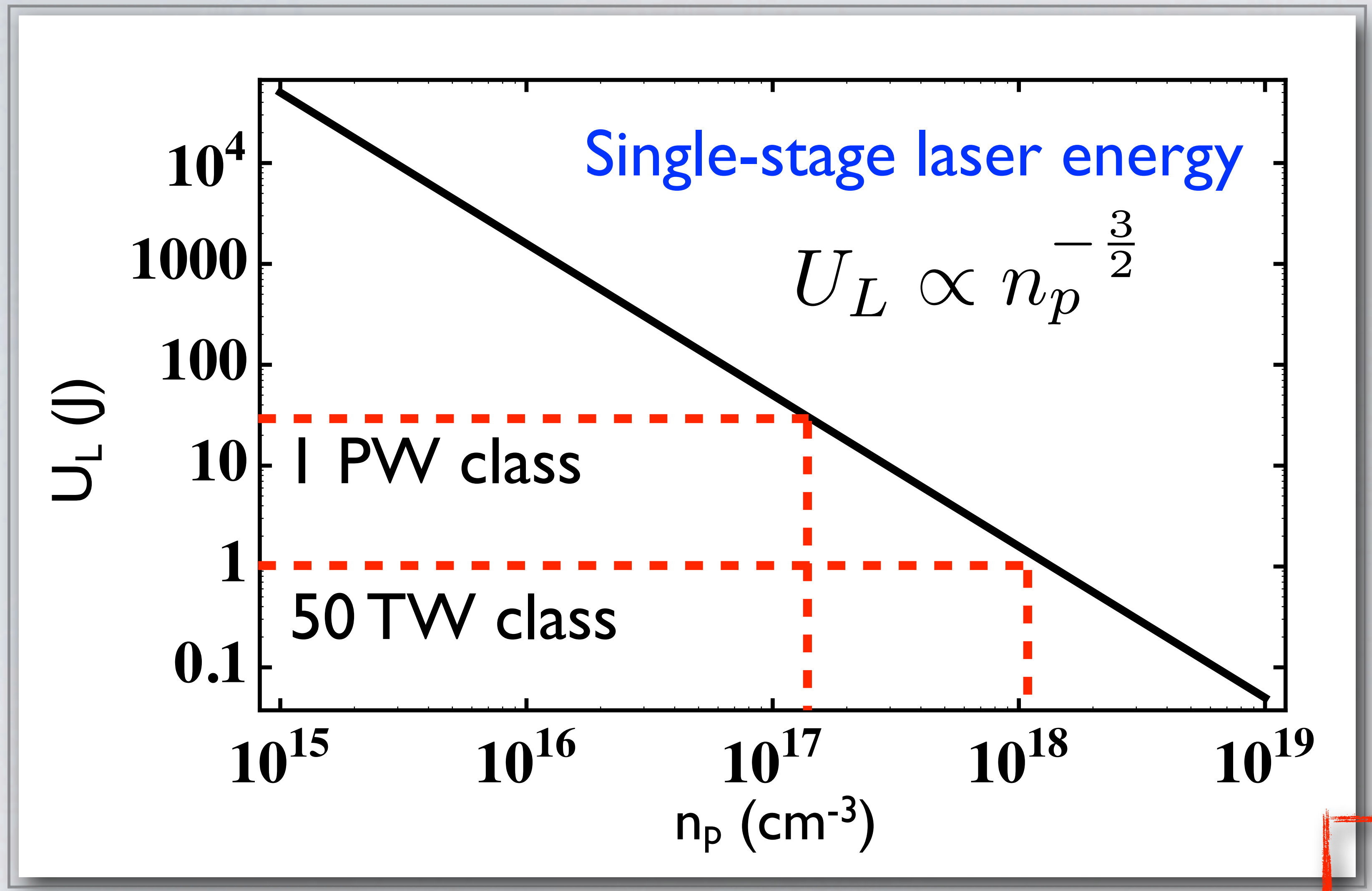

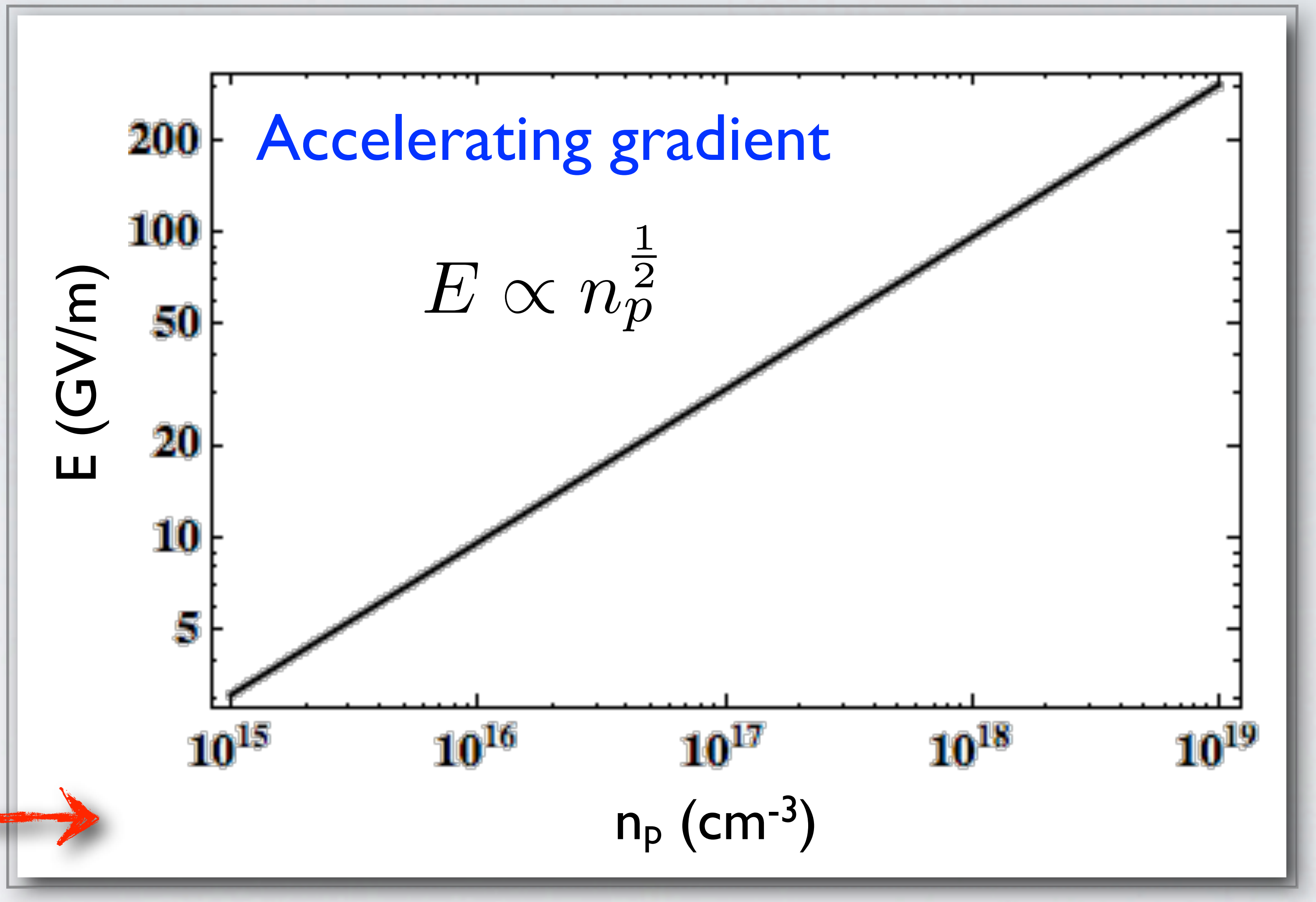

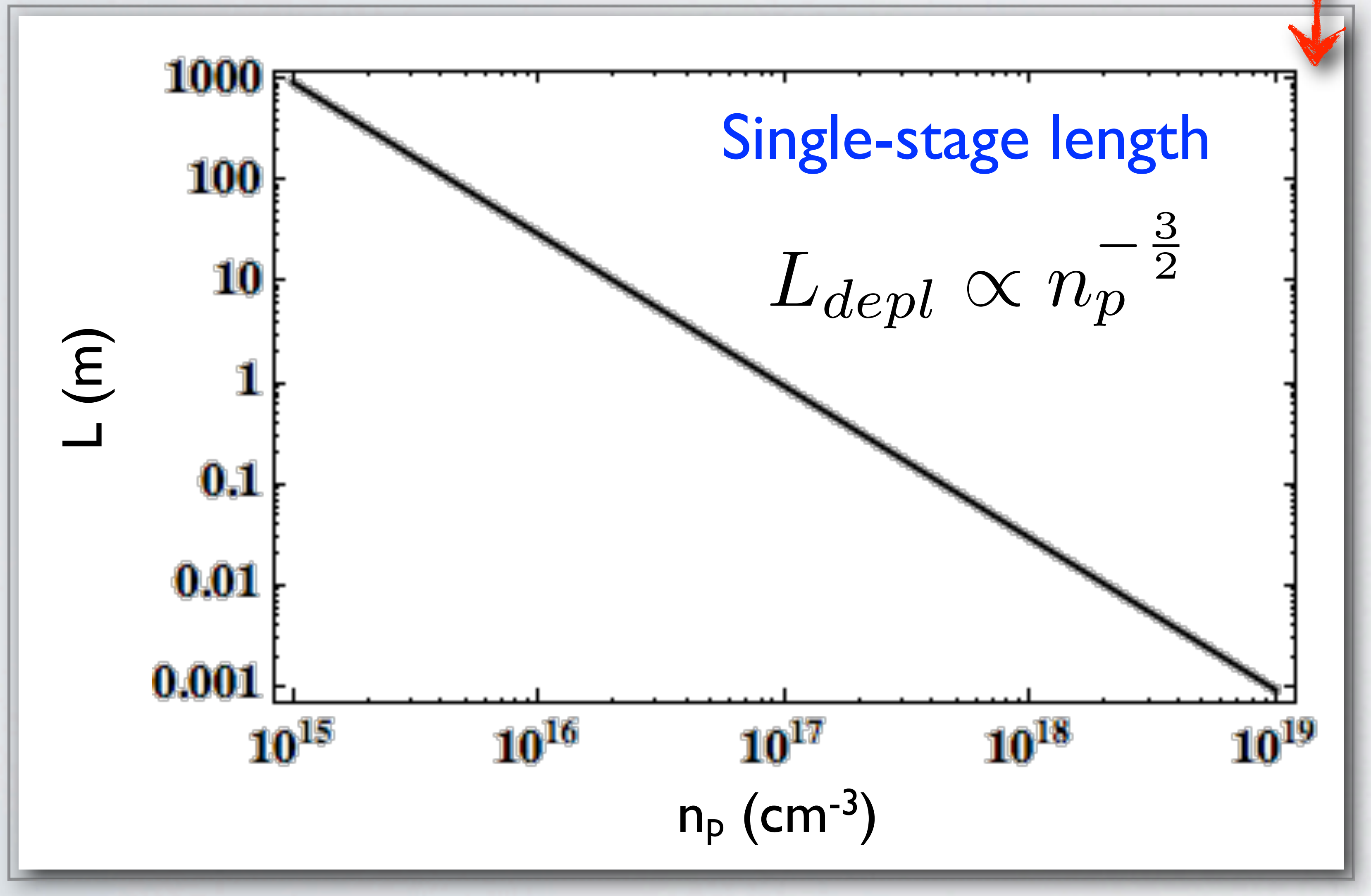

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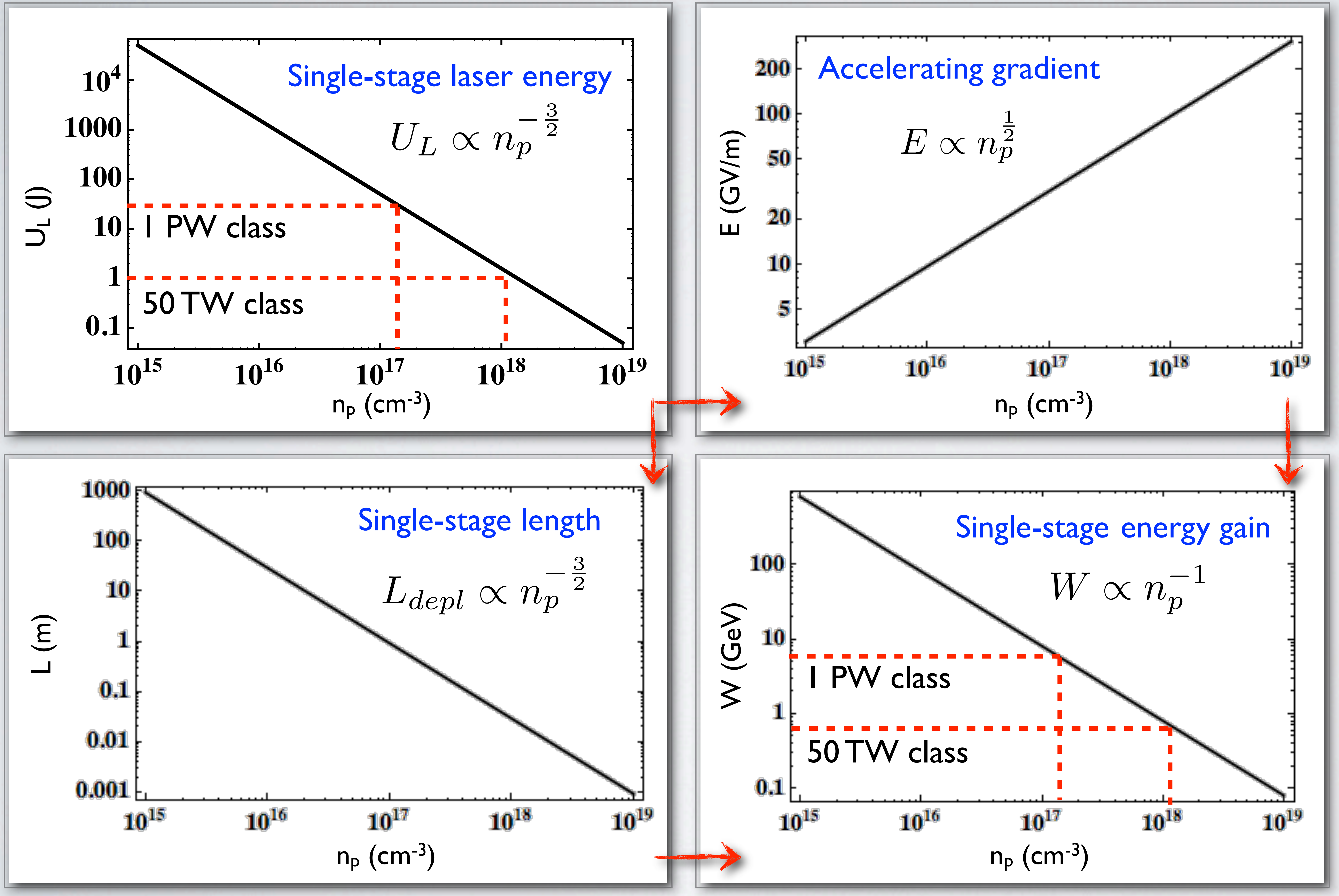

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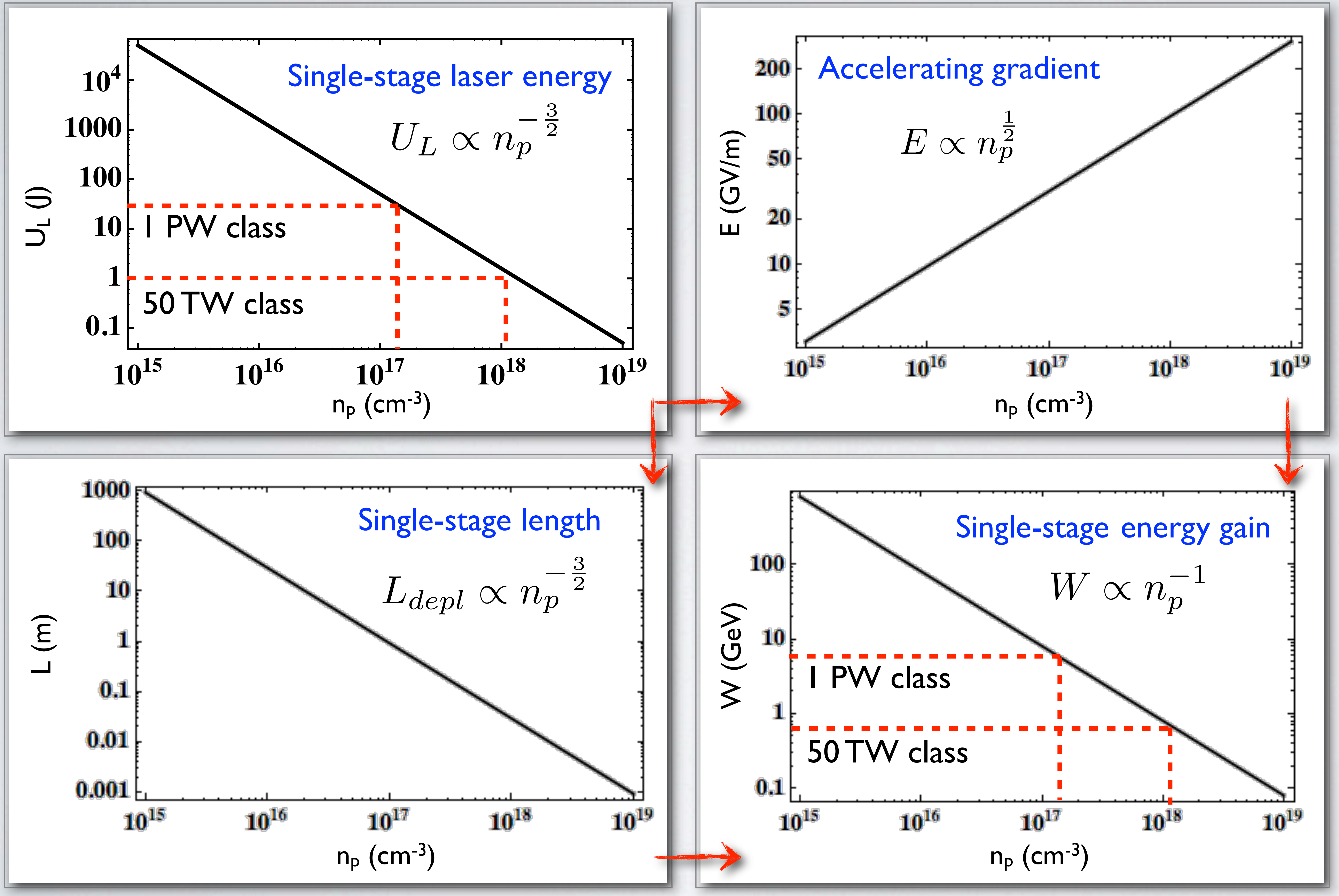

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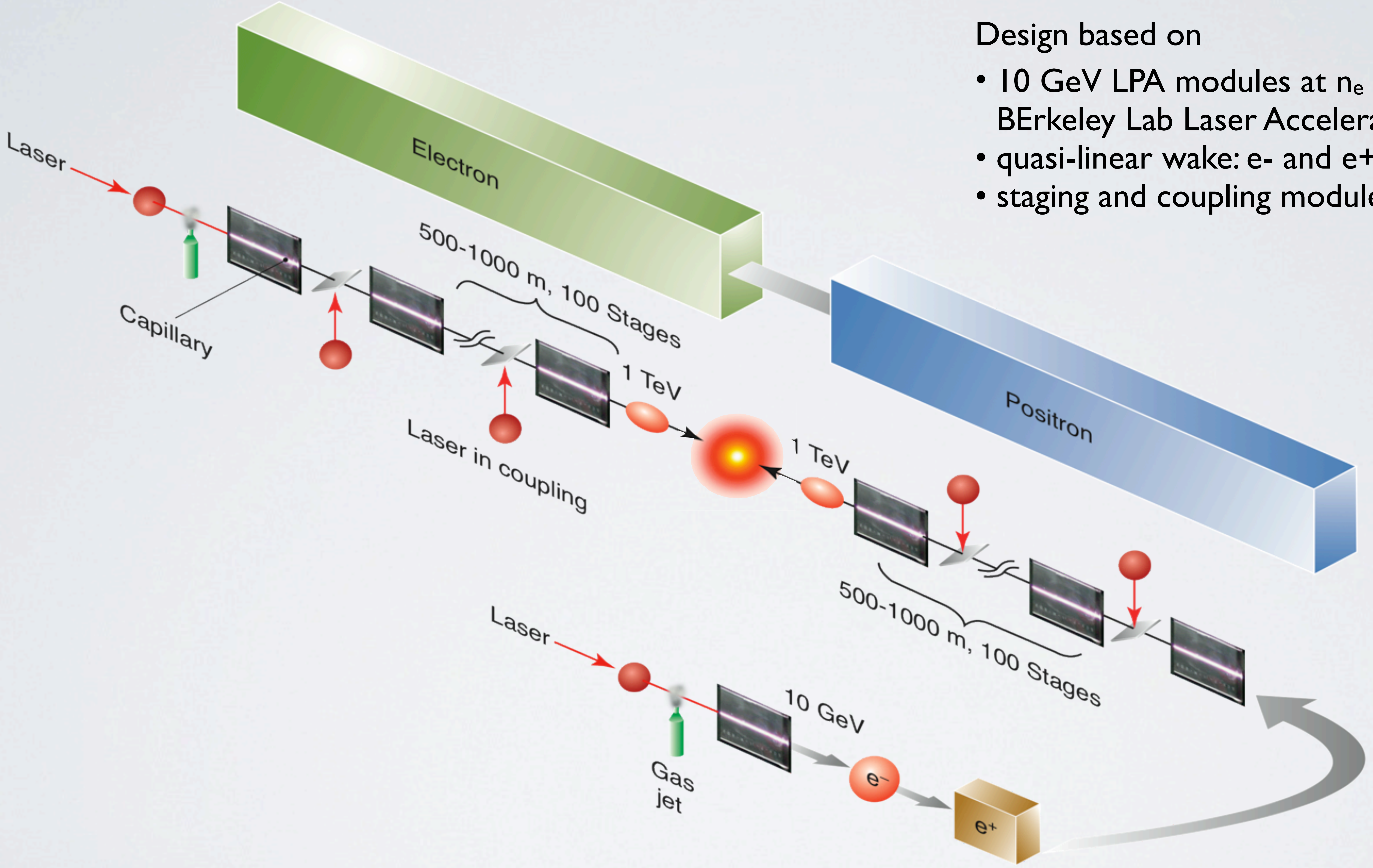
<u>Staging necessary for higher electron energies</u>

by courtesy of C. B. Schroeder *et al.*, Proceedings of Advanced Accelerator Concepts Workshop (2010)

Constructing a TeV-class LPA-based linear collider



Design based on

- 10 GeV LPA modules at $n_e \approx 10^{17}$ cm^{-3} BErkeley Lab Laser Accelerator (BELLA)
- 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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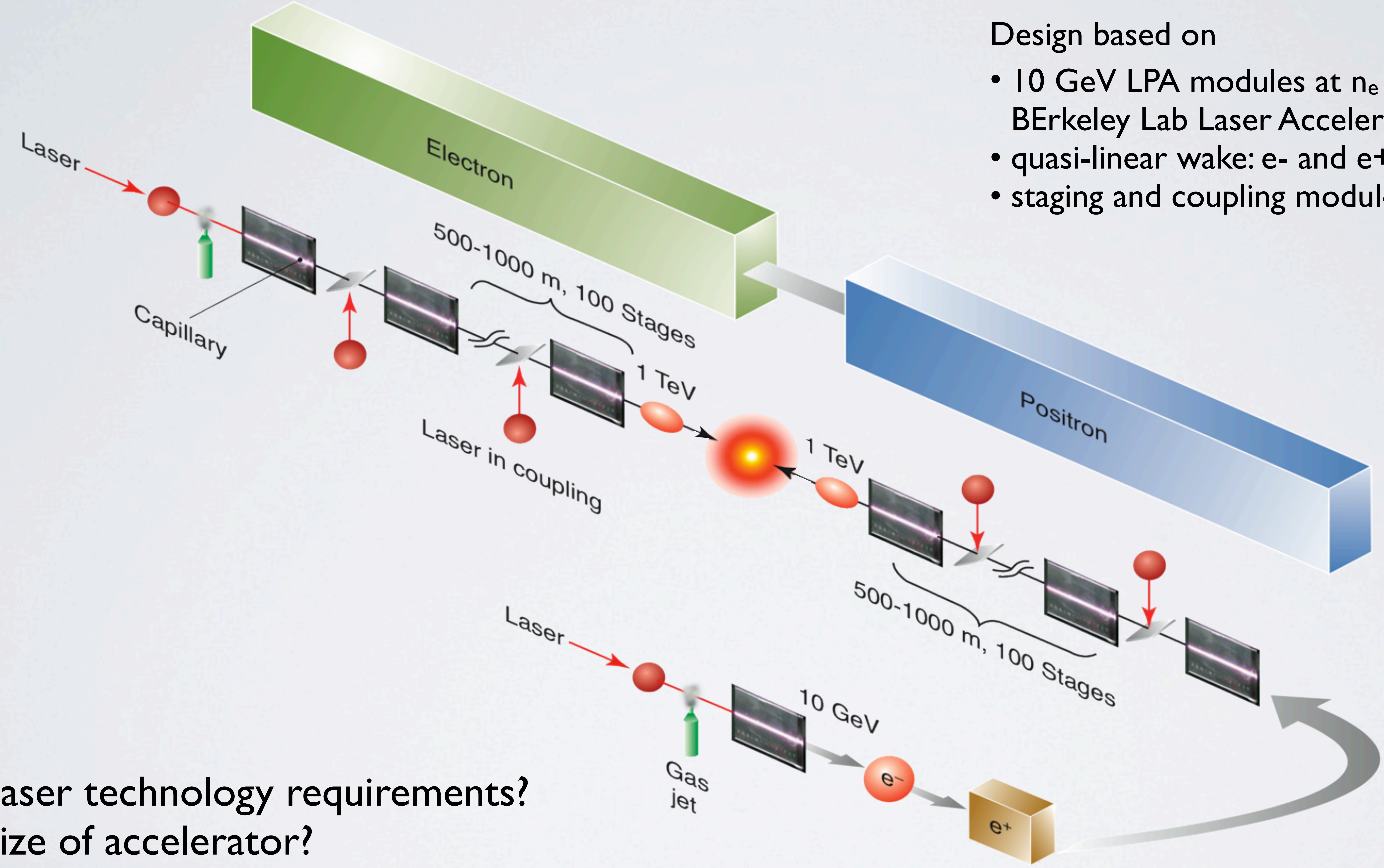

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- Laser technology requirements?
- Size of accelerator?

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

Future user facilities require beam parameter stability

Laser-plasma accelerators have suffered from low shot-to-shot reproducibility

<u>Ways to improve electron beam stability</u>

- Minimizing variations in laser and plasma parameters
  see Osterhoff *et al.,* Phys. Rev. Lett. 101, 085002 (2008)

- Improved control over crucial laser parameters
  e.g., pulse-front tilt (Popp, Osterhoff *et al.*, Phys. Rev. Lett. 105, 215001 (2010)),
  laser pointing (Gonsalves, Osterhoff *et al.*, Phys. Plasmas 17, 056706 (2010))

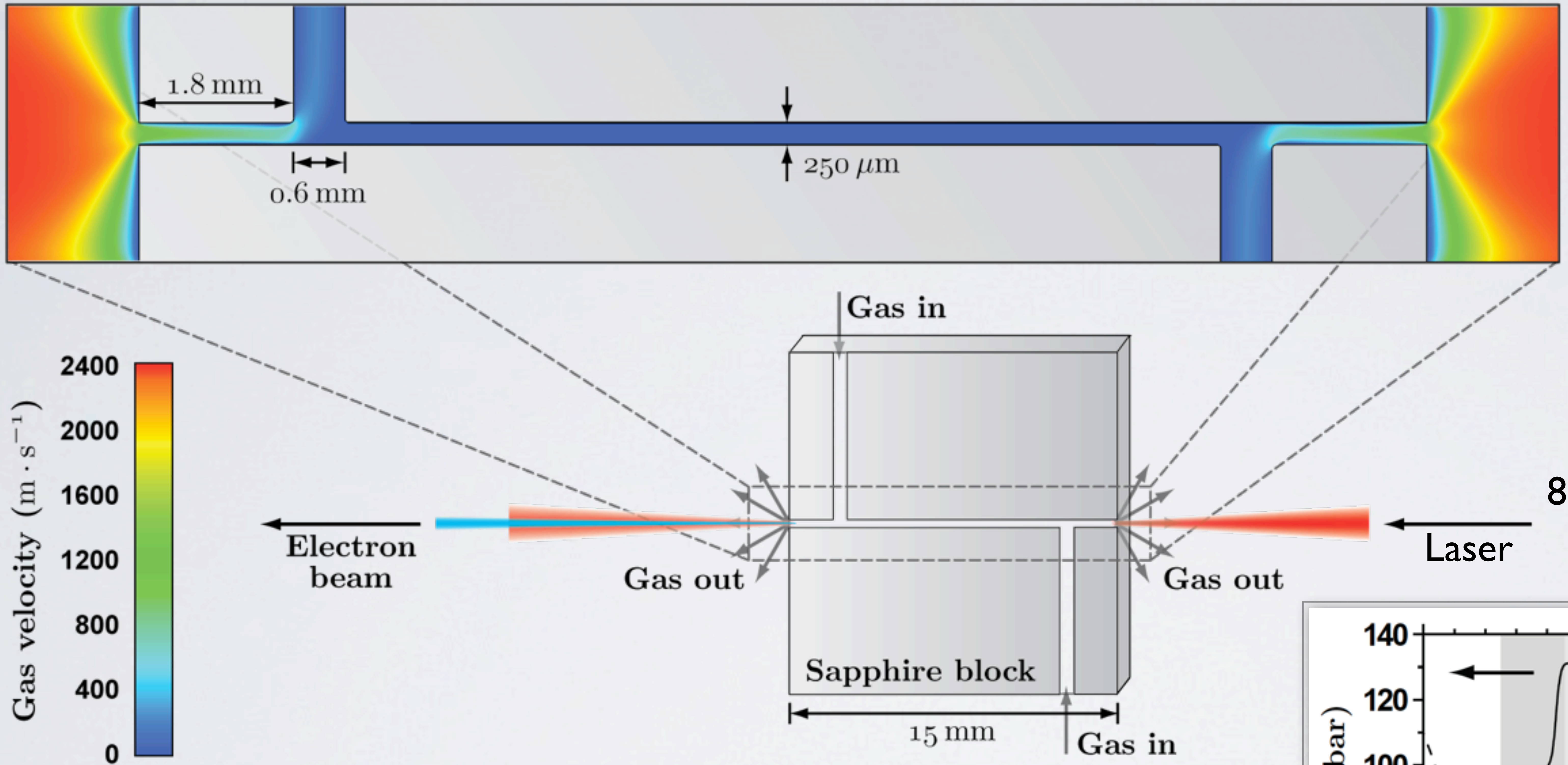
- Employing laser pulses matched to plasma conditions $\tau_L \approx \frac{\lambda_p}{2c}$

- Driving acceleration process in the quasi-linear regime, no dark currents $a \approx 1$

- Separating injection & acceleration stages, controlling injection, no wavebreaking

A steady-state-flow gas cell stabilizes plasma conditions

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



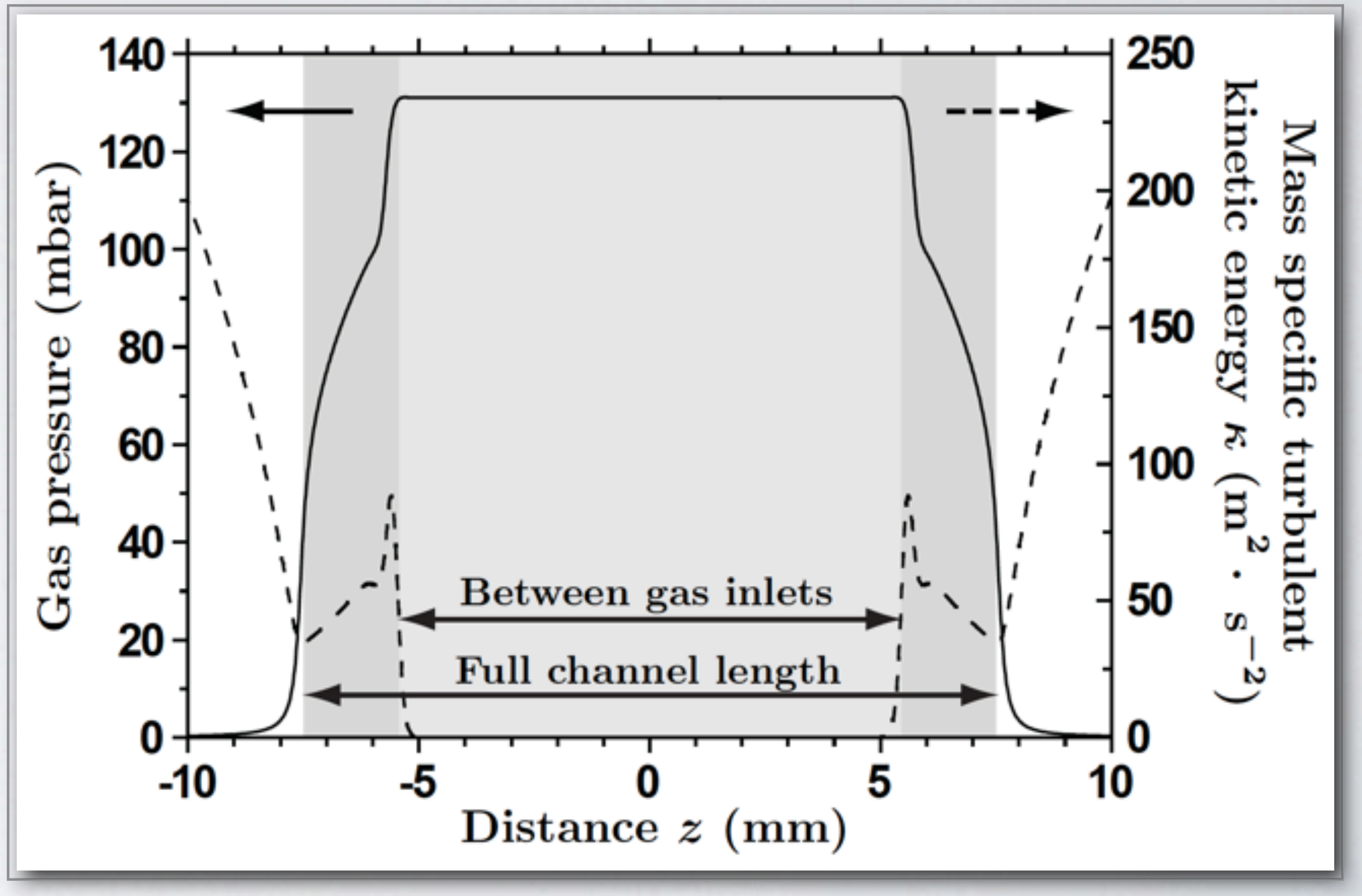
FLUENT simulation

Pulse parameters

850 mJ ± 2%, 37 fs FWHM
23 μm focus FWHM

Steady-state-flow gas cell advantages over gas jets

- Allows for high repetition rates (10’s of kHz)
- Lasts > 10^5 shots
- Virtually no gas flow in the interaction region
- No turbulence or shocks (compared to jets)



A steady-state-flow gas cell stabilizes plasma conditions

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

Osterhoff *et al.*,
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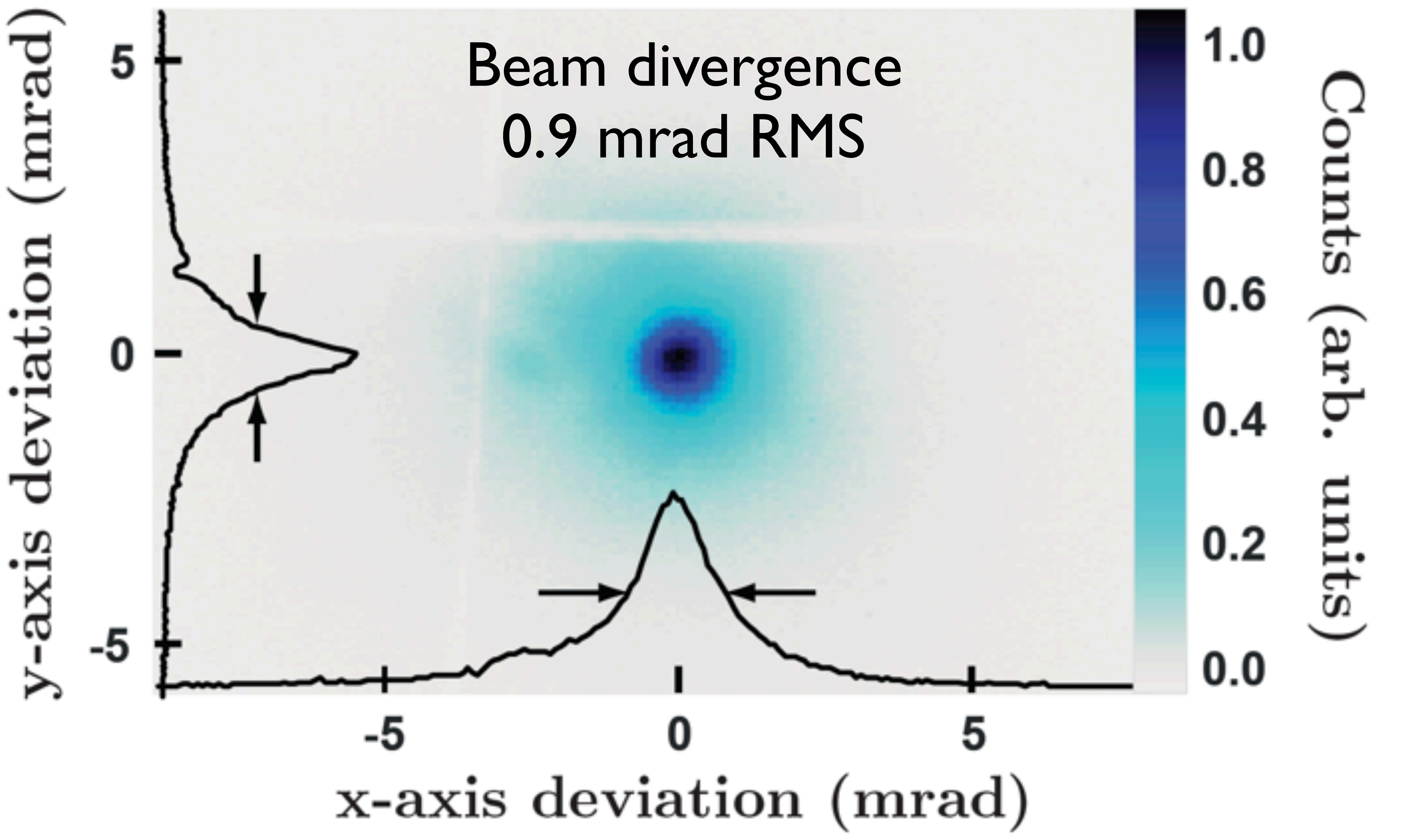

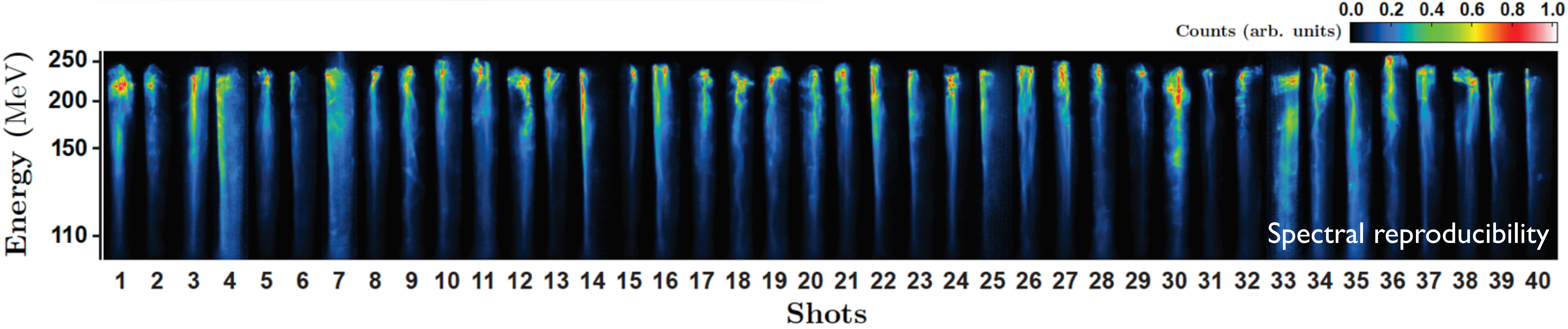

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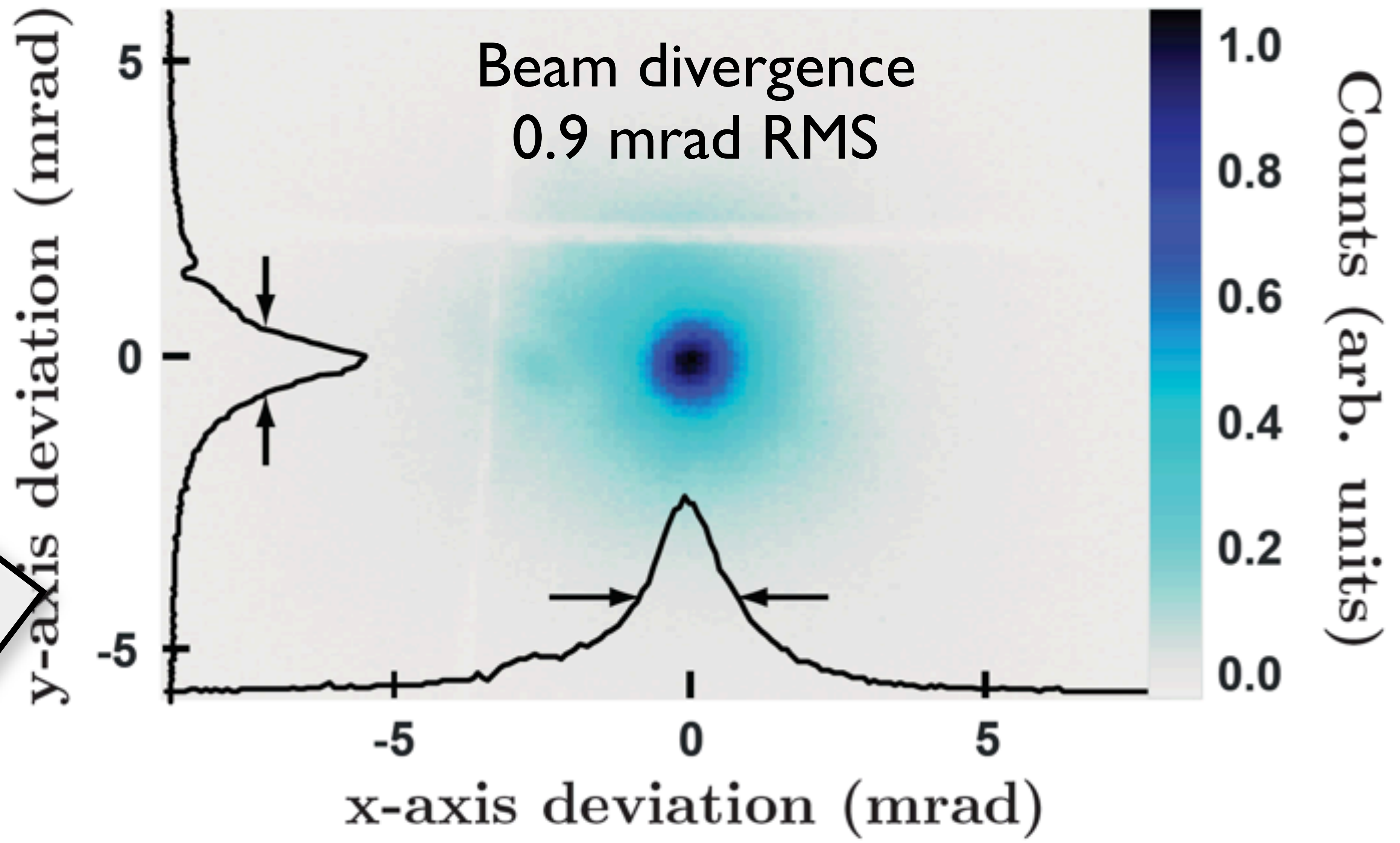
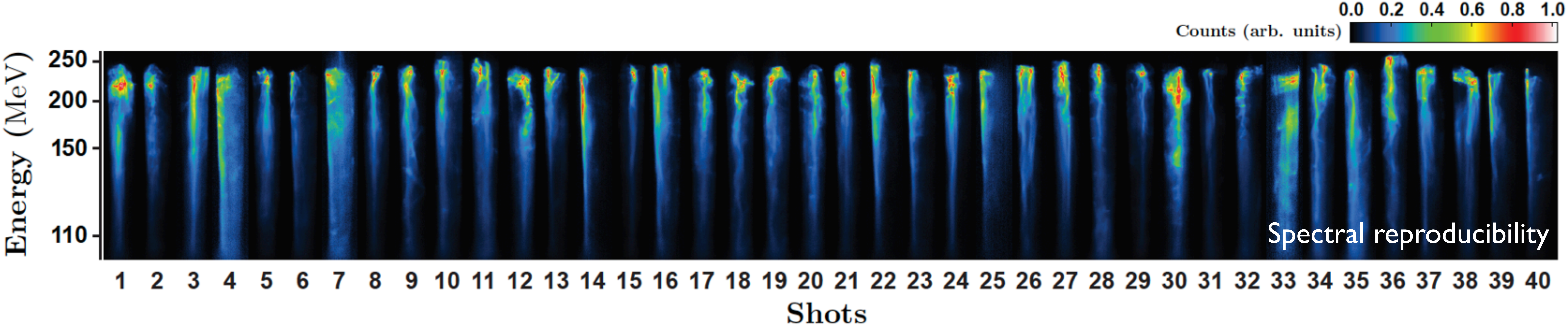
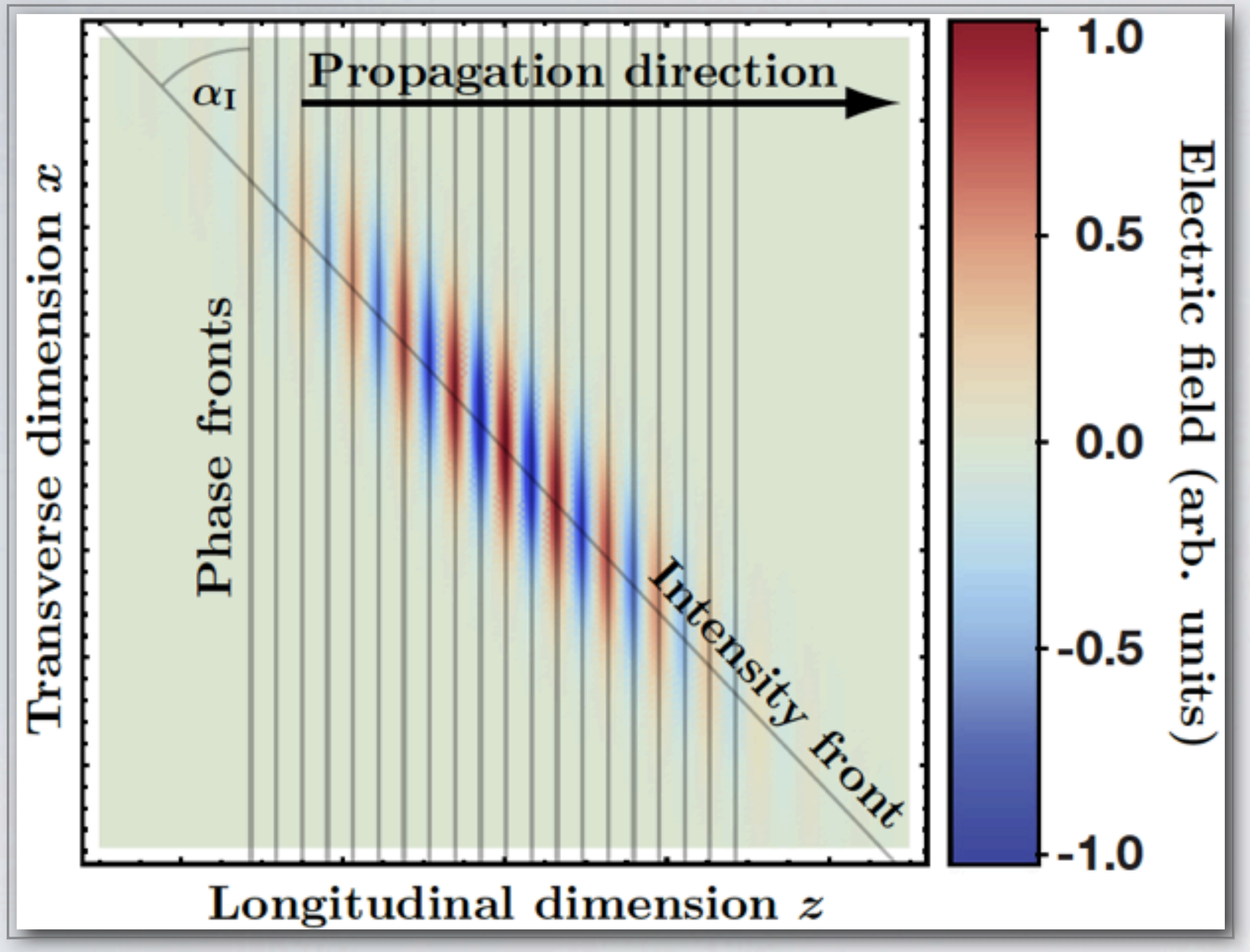
Injection	~ 100 %	

…in 2008!


Beam divergence
0.9 mrad RMS


Spectral reproducibility

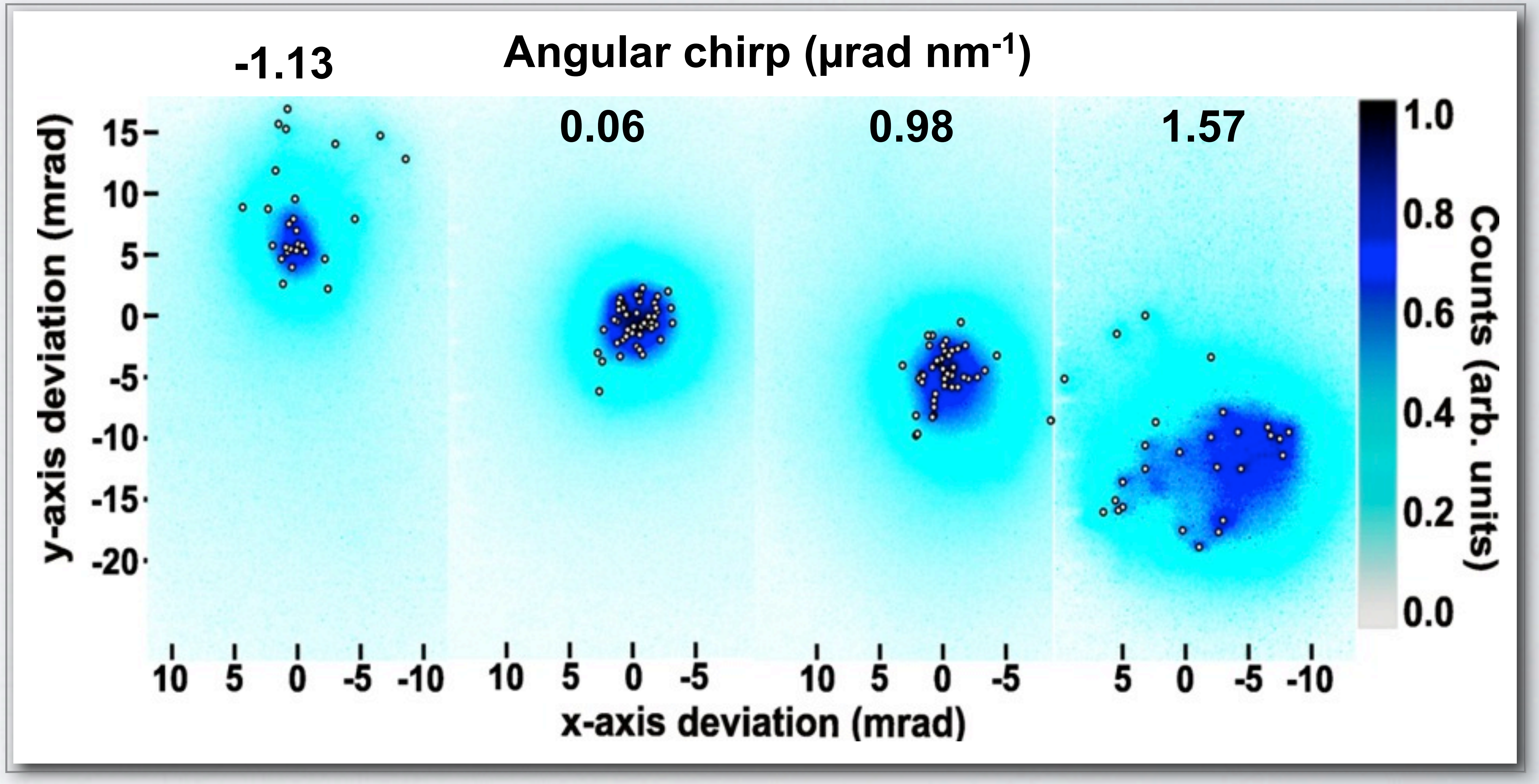
Eliminating laser intensity-front tilt increases stability



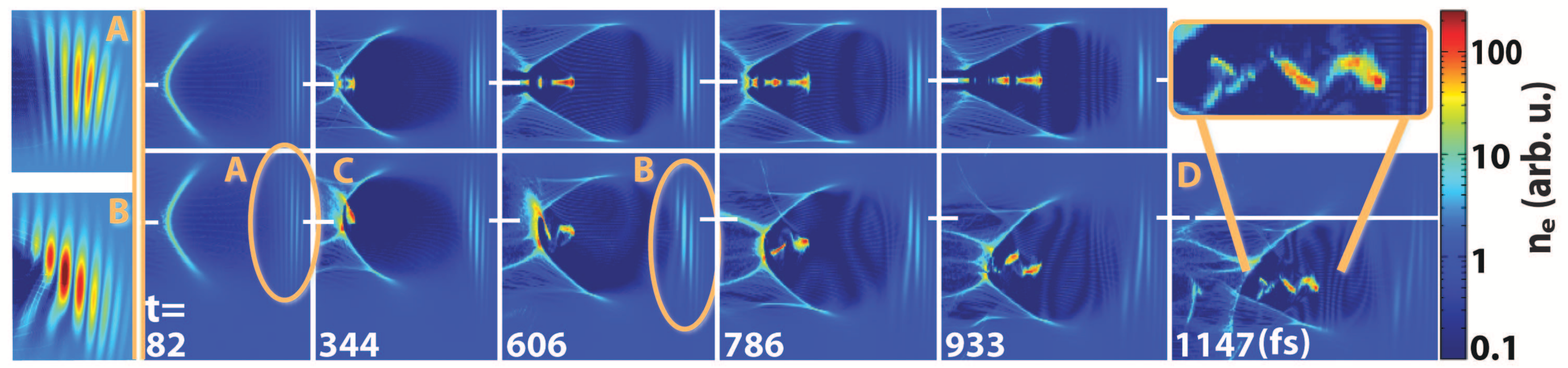
A. Popp *et al.*, Phys. Rev. Lett. 105, 215001 (2010)

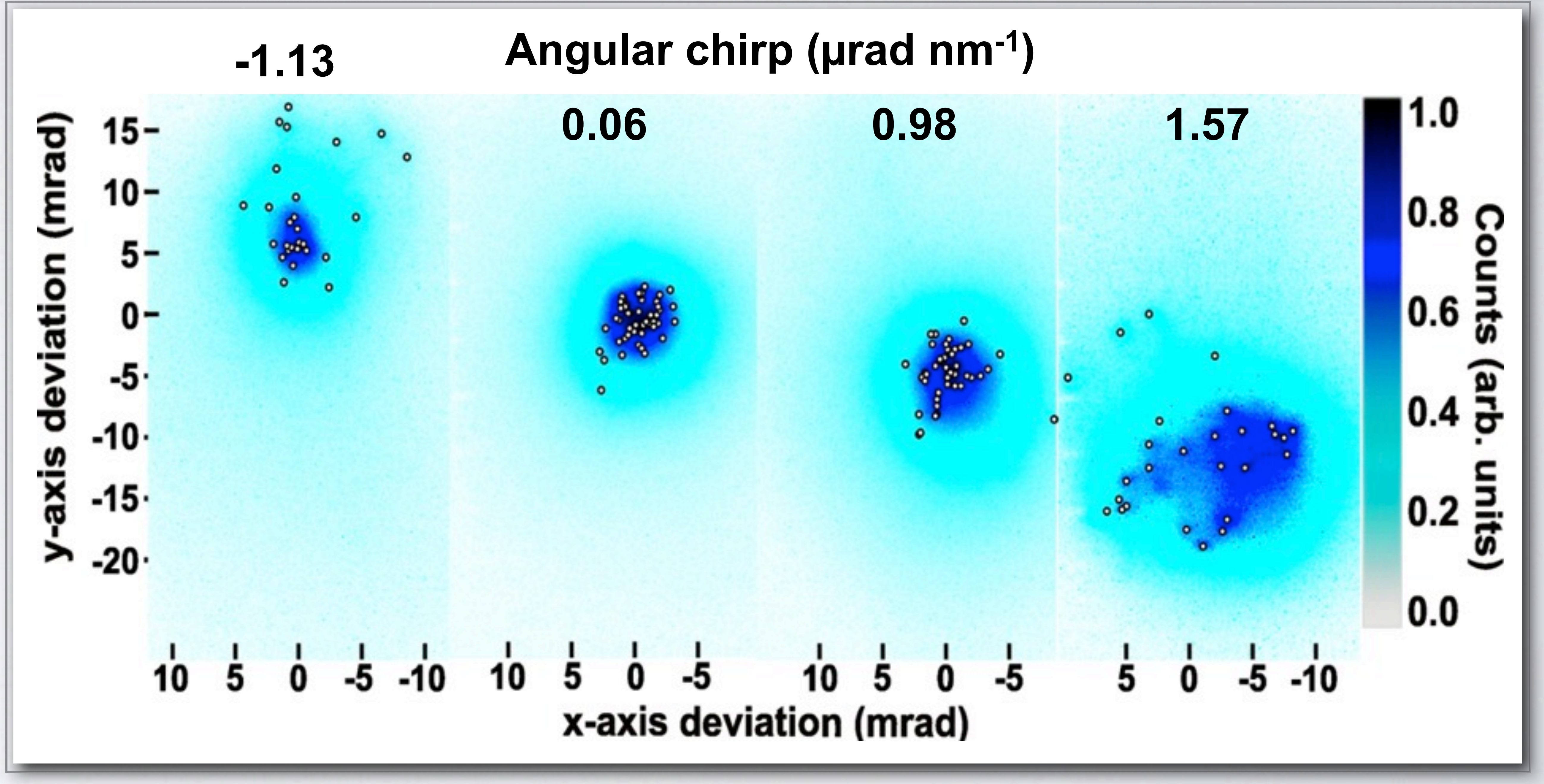
Intensity or pulse-front tilt usually originates from laser angular chirp (AC) caused by an imperfect stretcher/compressor alignment

- hard to diagnose
- small amounts of AC have large effect on the stability of LPAs

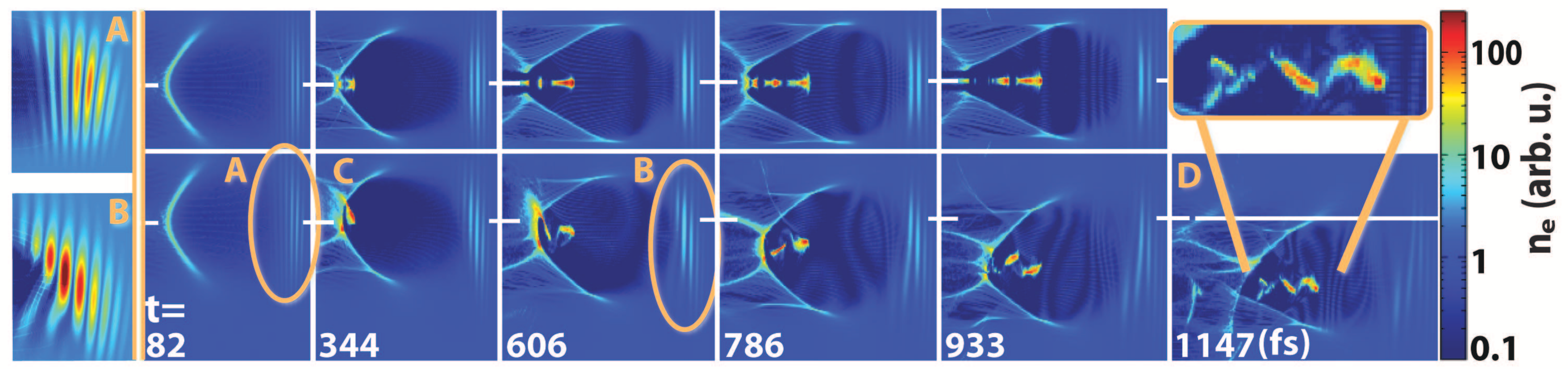


Eliminating laser intensity-front tilt increases stability





Eliminating laser intensity-front tilt increases stability



Collective beam oscillations
→ way to tailor betatron radiation?
→ useful for beam cooling?

Summary

Laser-plasma accelerator technology has advanced quickly in recent years

Milestone experiments: quasi-monoenergetic beams, plasma guiding and GeV electron energies, controlled injection, stability enhancements, soft-X-ray undulator radiation

Lots of research still to be done for compact photon source or collider applications

Milestone experiments needed: emittance measurements, slice energy spread characterization, FEL, 10 GeV accelerator module, staging, positron capturing, advancements in laser technology (luminosity requirements)

Plasma accelerators may have the potential to revolutionize accelerator technology and could make them much more compact, affordable, and therefore accessible

Thanks for your attention!