Deutsches Elektronen-Synchrotron Zeuthen (September 30th, 2010)

LASER-PLASMA ACCELERATION

A SENSIBLE TECHNOLOGY FOR ACTUAL APPLICATIONS?

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Contributions

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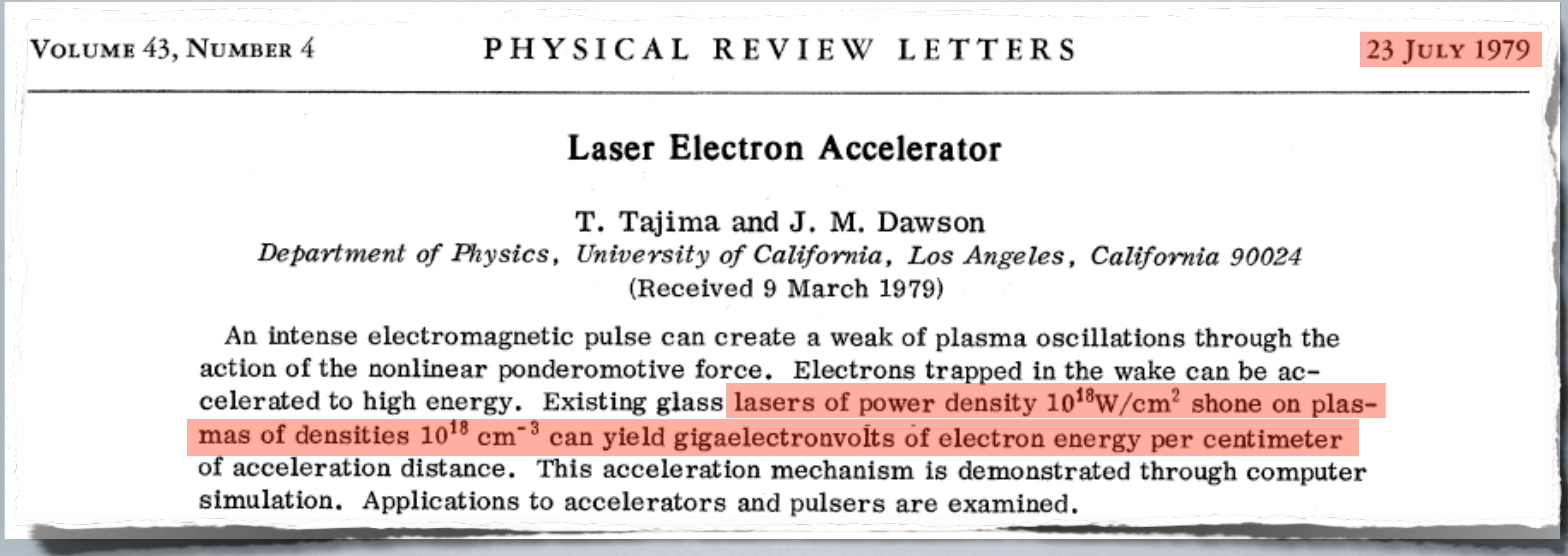
Plasma accelerators allow for extreme electric fields



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

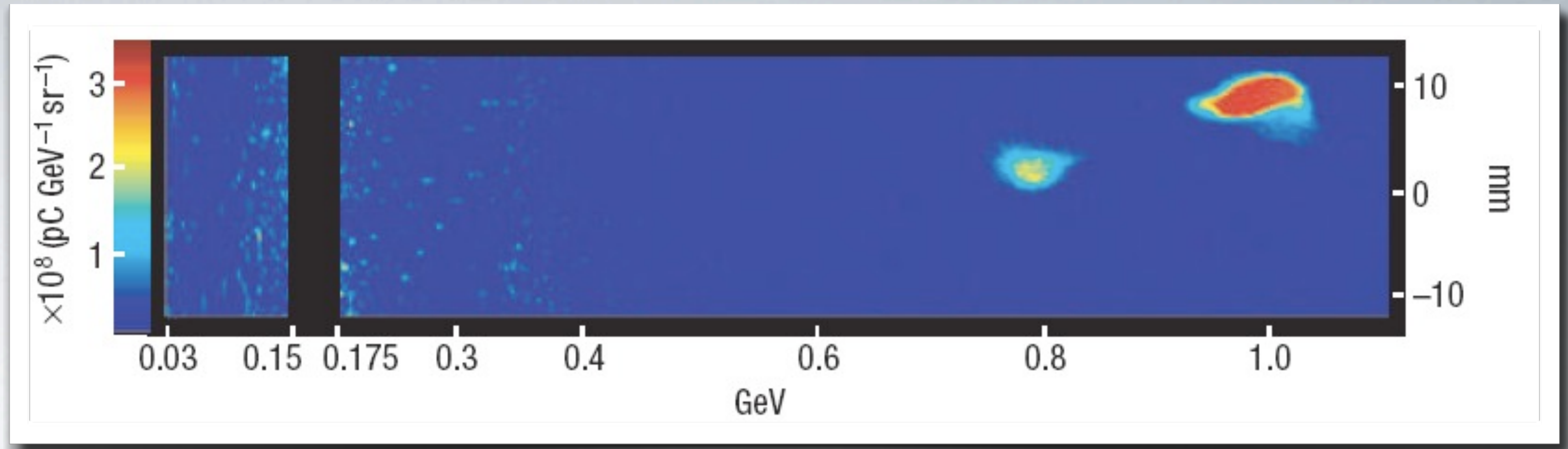
(Received 9 March 1979)

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.

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

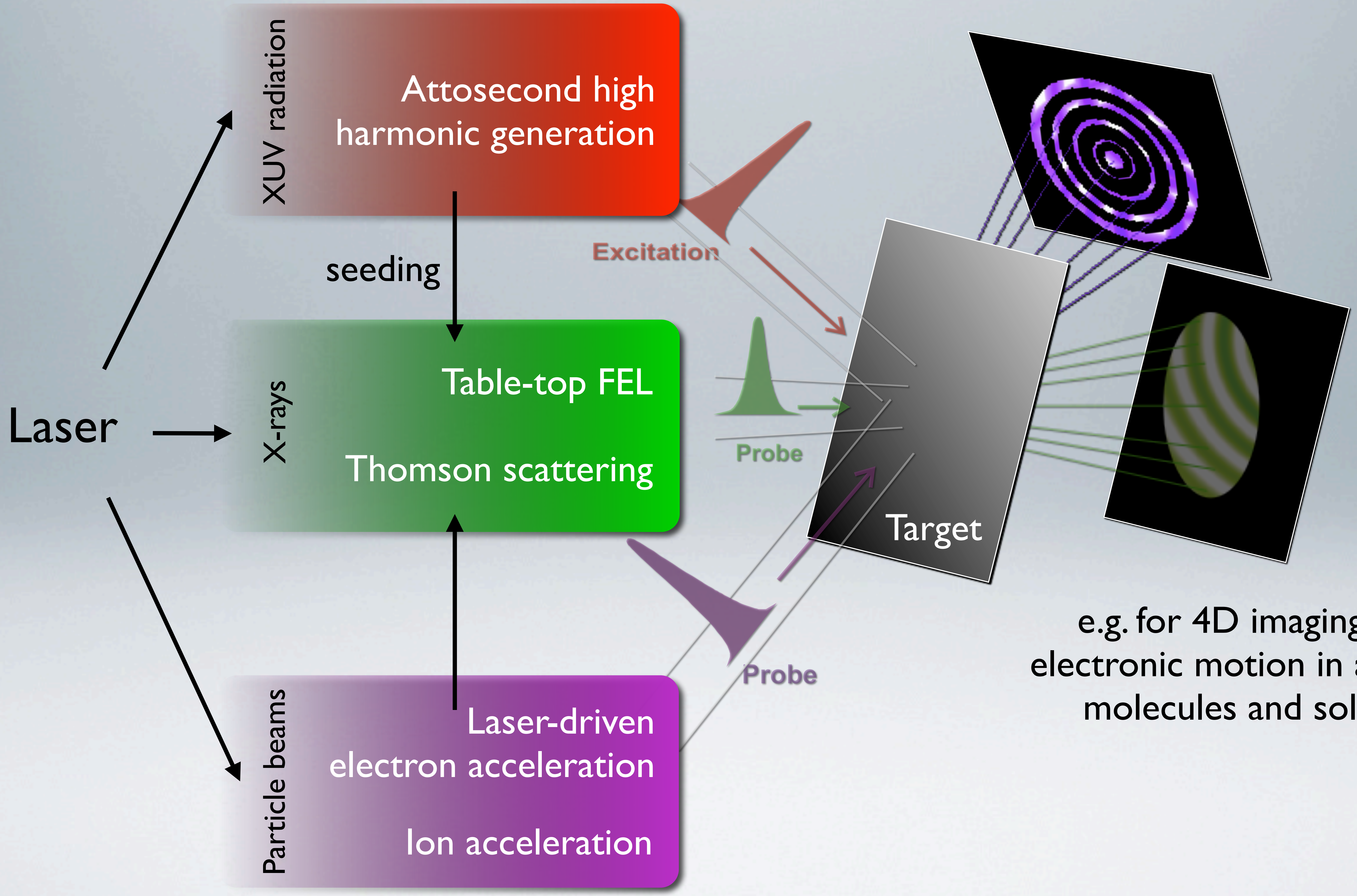
→ 30 pC of electrons at 1 GeV

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



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

Lasers provide sub-femtosecond synchronization



e.g. for 4D imaging of electronic motion in atoms, molecules and solids

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, wake forms

Laser pulse properties

$a = 2$

$\lambda_c = 800$ nm

$\Delta\tau = 25$ fs FWHM

$w_0 = 23$ μm FWHM

Plasma background density

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

osiris v2.0

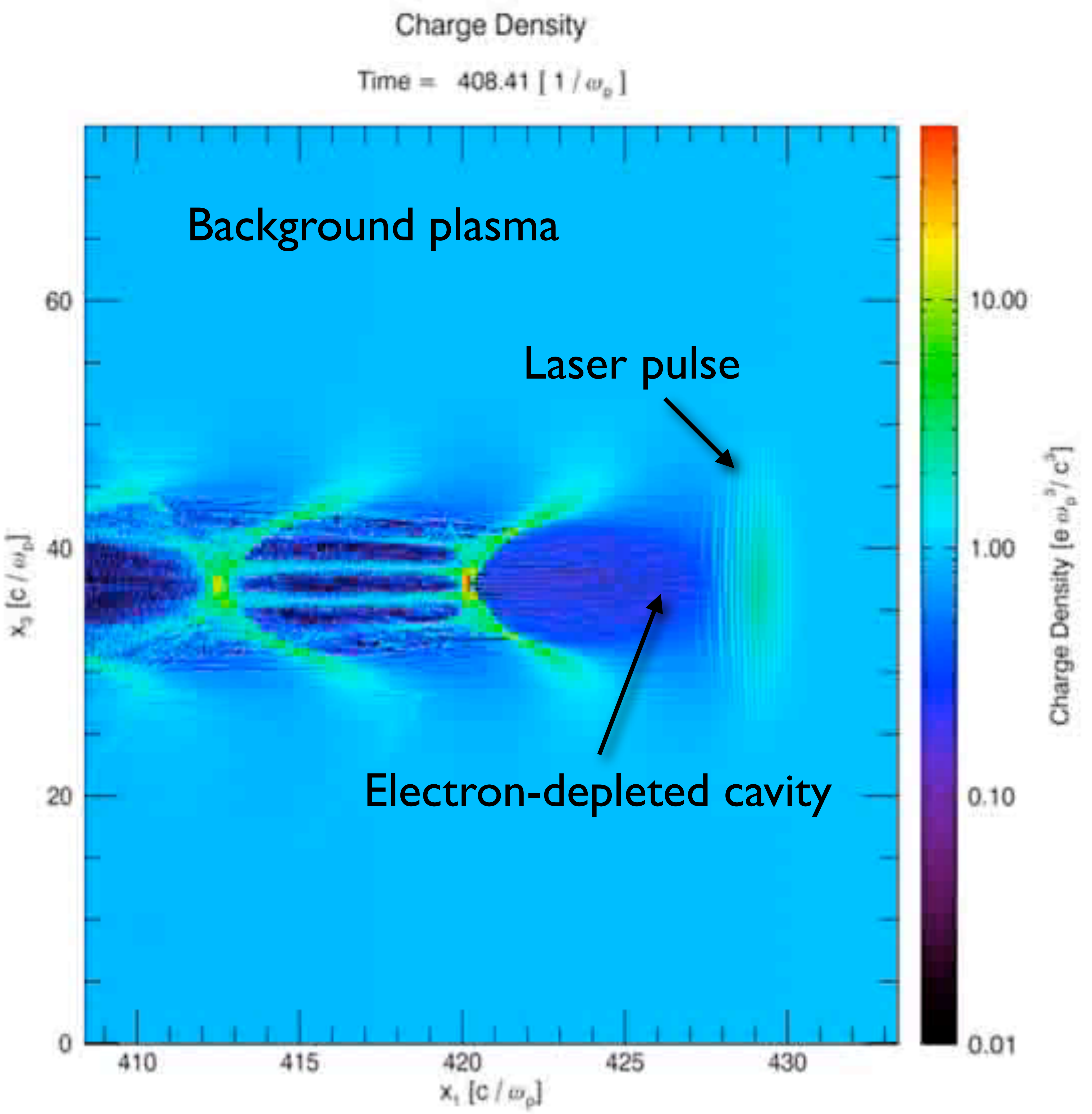
INSTITUTO SUPERIOR TÉCNICO

USC

UCLA

3D particle-in-cell (PIC) simulation

High-intensity lasers can drive large plasma wakes



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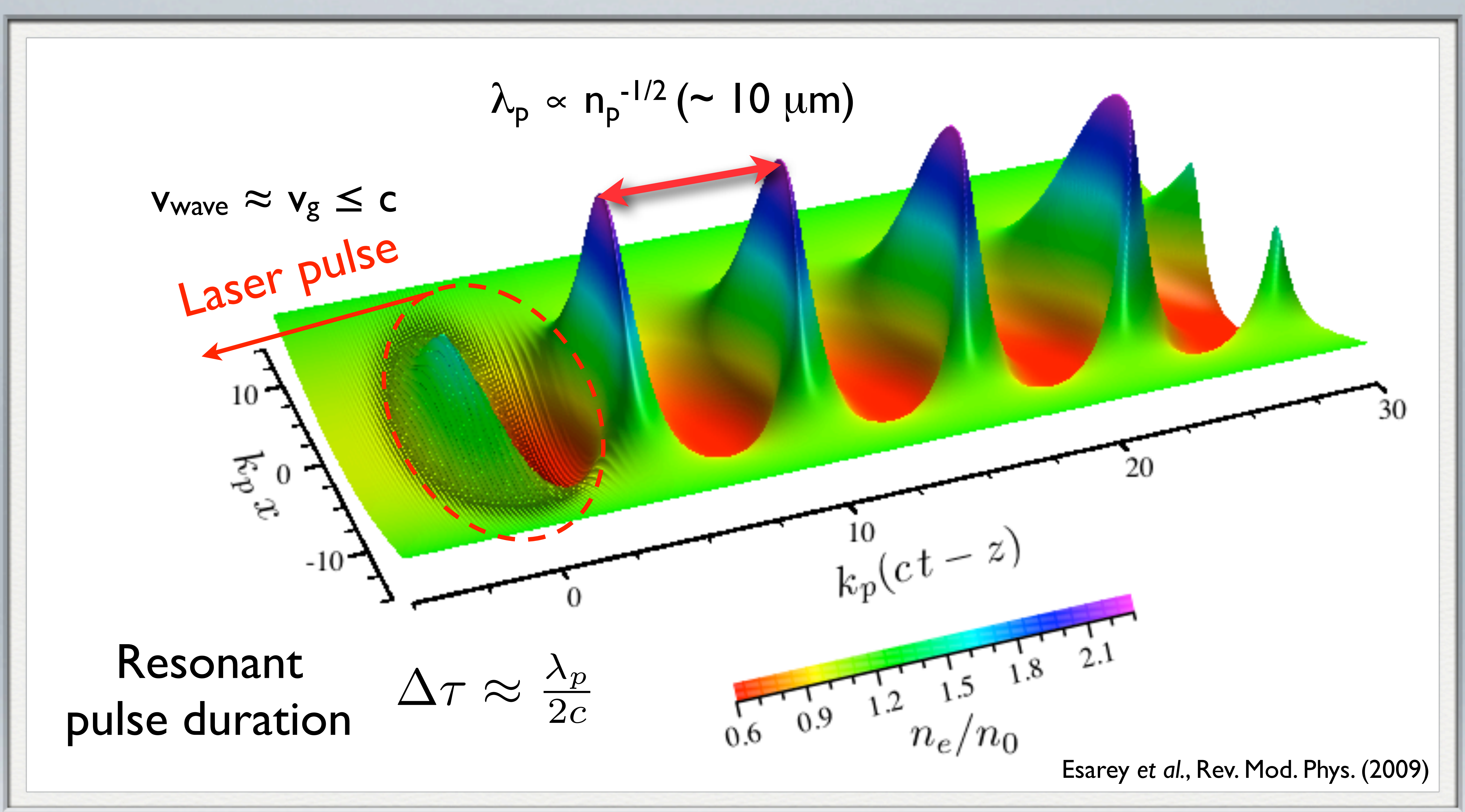

$\lambda_p \propto n_p^{-1/2}$ (~ 10 μm)

$v_{wave} \approx v_g \leq c$

Laser pulse

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

Esarey *et al.*, Rev. Mod. Phys. (2009)

Accelerating electric field strength:

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

E ≈ 100 GV/m

(for $n \approx 10^{18}$ cm^{-3}, $a \approx 1$)

more than 10^3 times larger than in conventional RF accelerators

Plasma wakes may break and electrons get trapped

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

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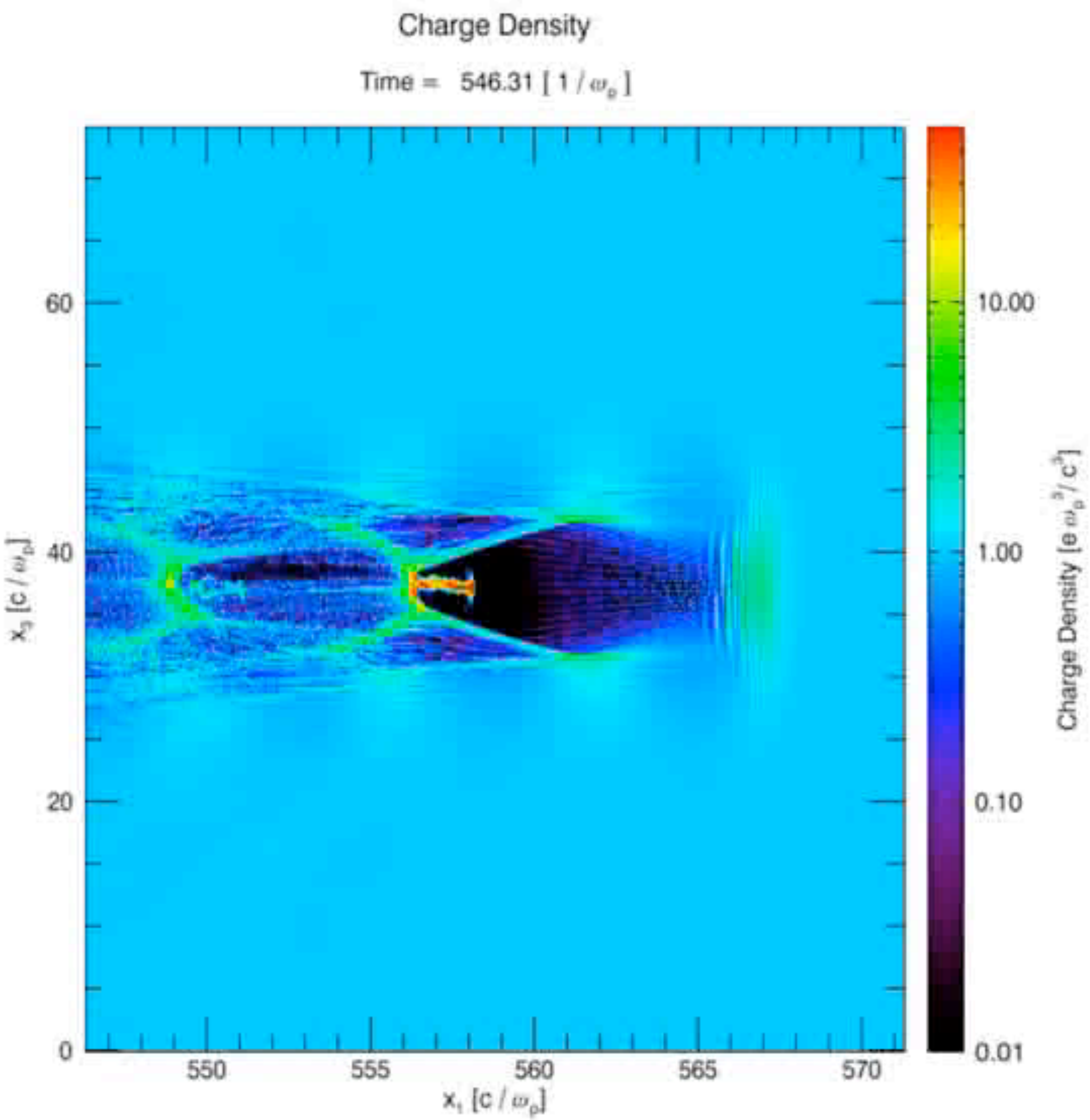

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3D particle-in-cell (PIC) simulation

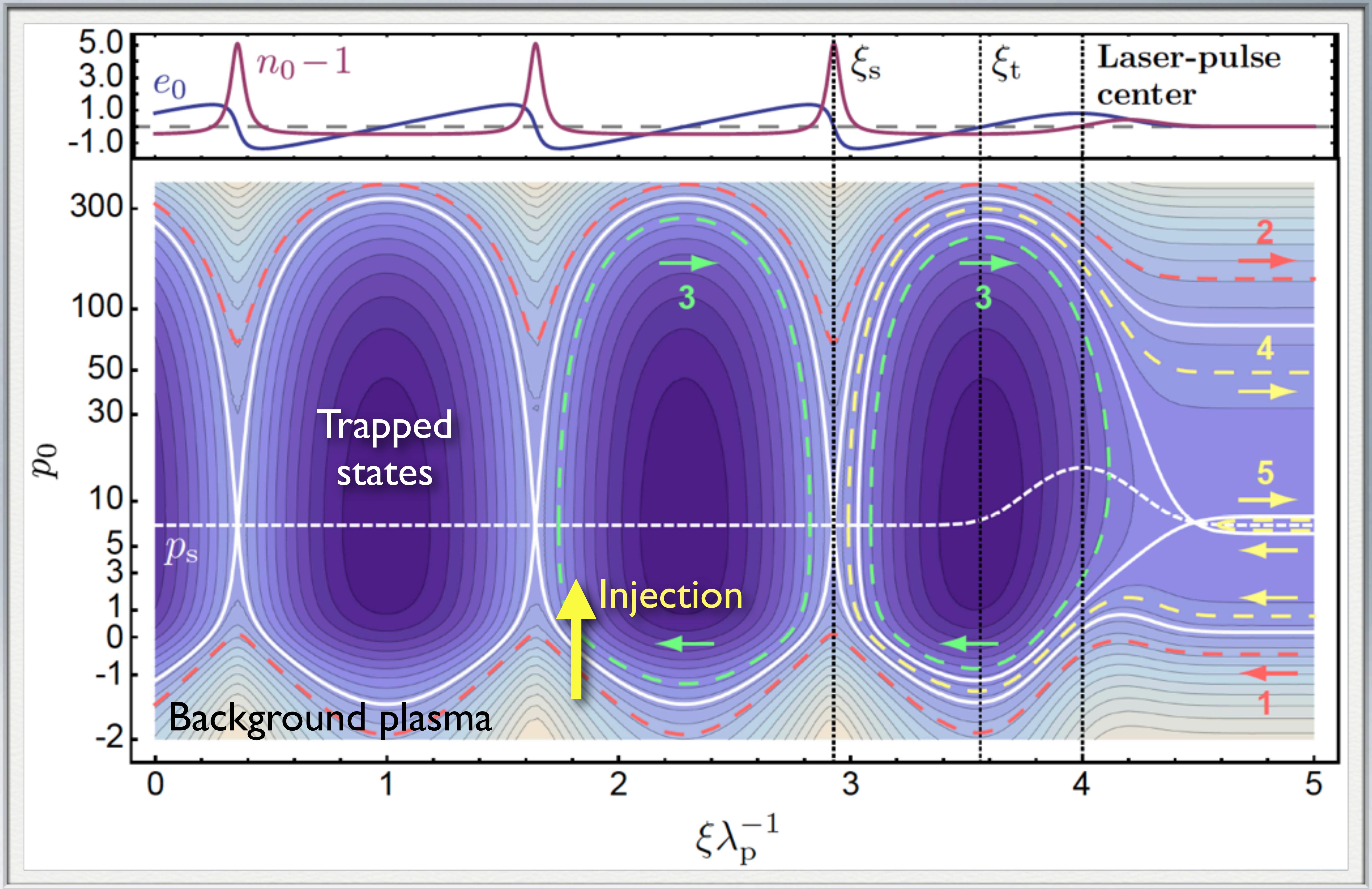
Injection controls charge, energy spread, emittance

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

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

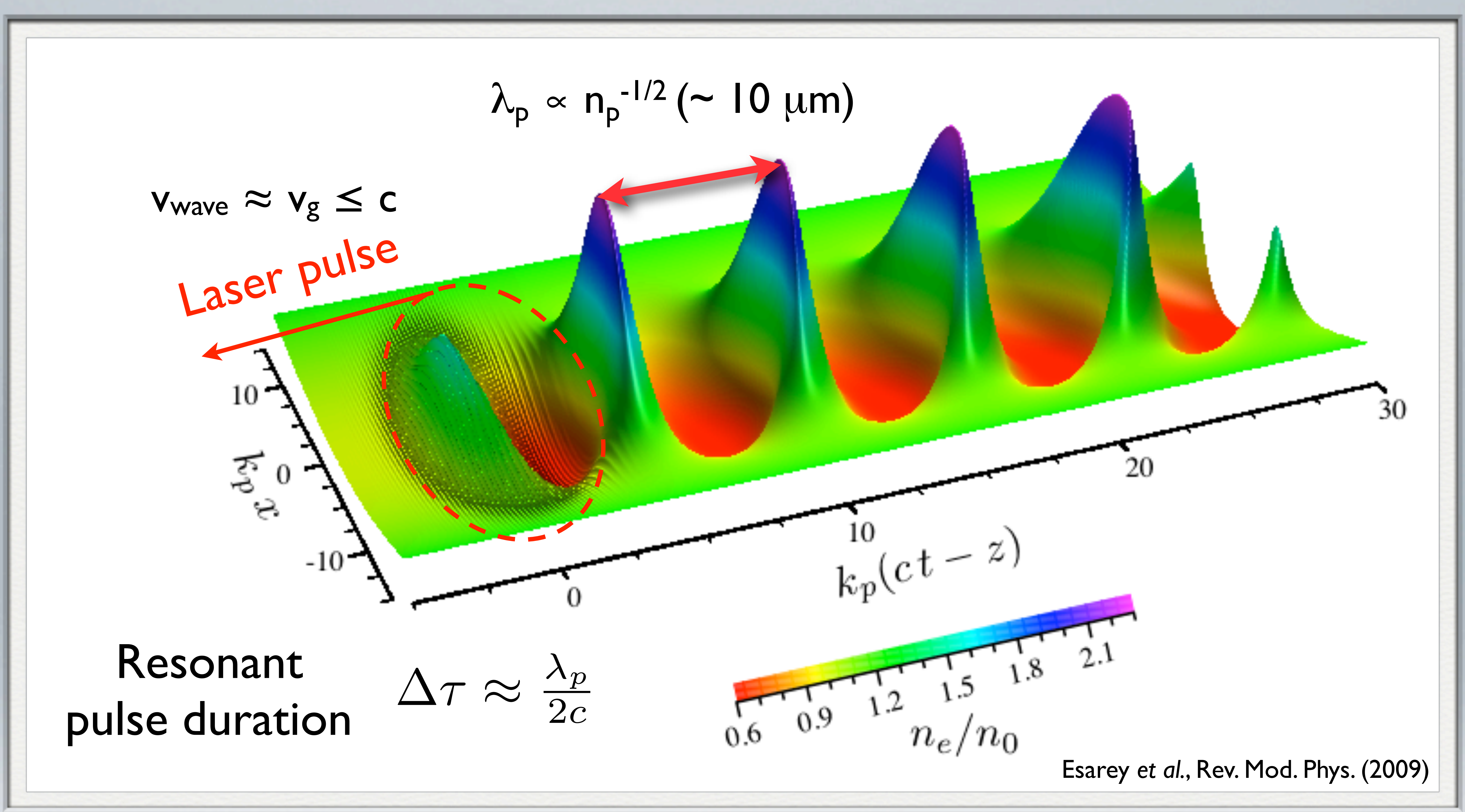
Methods for controlled injection:

- 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)]



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)

Bunch durations from LPAs are inherently short



Esarey *et al.*, Rev. Mod. Phys. (2009)

Laser-plasma based accelerators are intrinsic sources of femtosecond electron beams

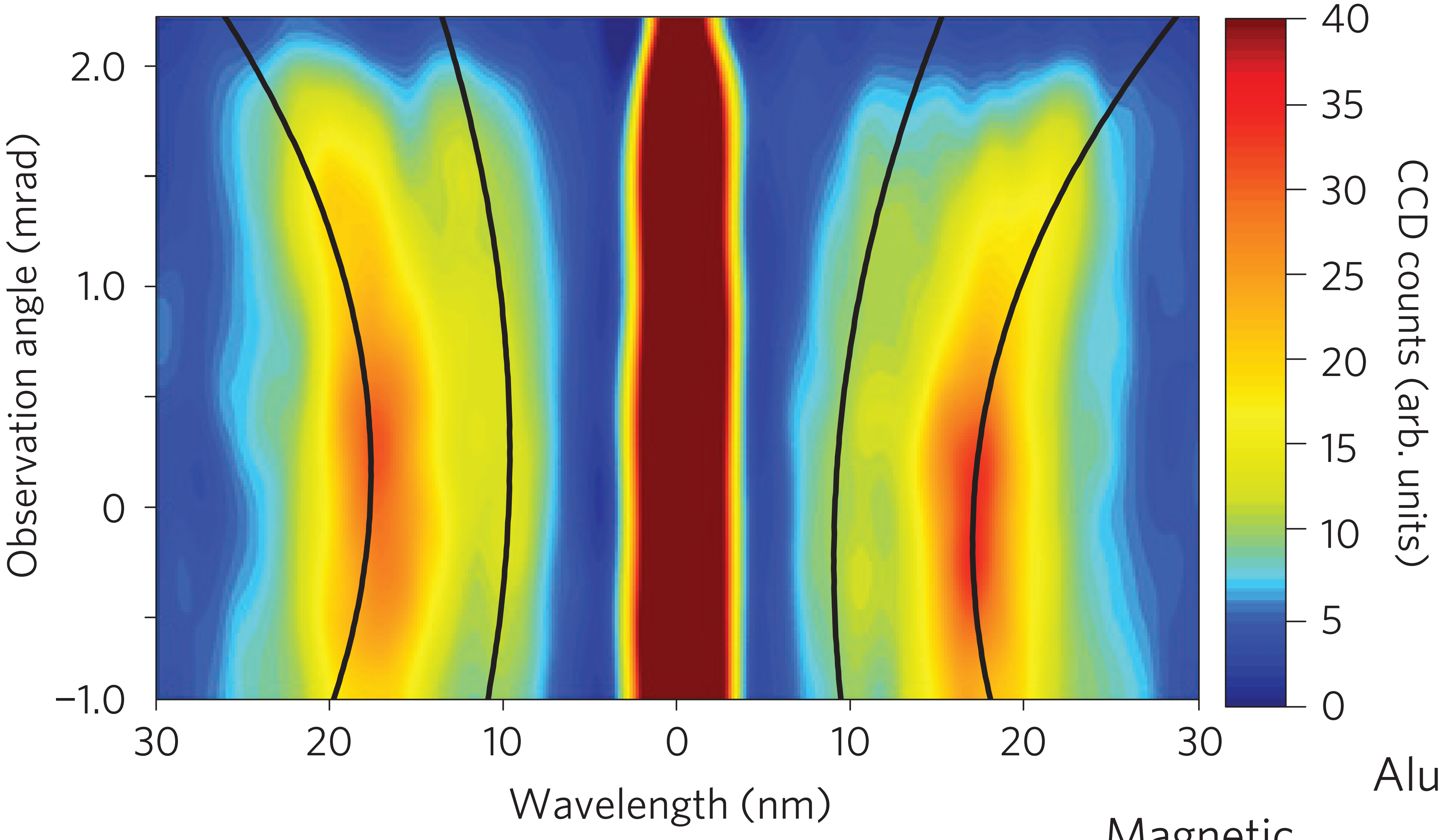
Full width electron bunch duration is a fraction of the plasma wavelength: $\Delta\tau_e \ll \frac{\lambda_p}{c}$

e.g. $\Delta\tau_e \ll$ 50 fs
(for $n \approx 5\times10^{18}$ cm^{-3}, $a \approx 1$)

$\xrightarrow{\text{High peak currents}}$ $I \gtrsim$ 10 kA (for $Q \approx 100$ pC)

→ Drive high peak brightness photon sources

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

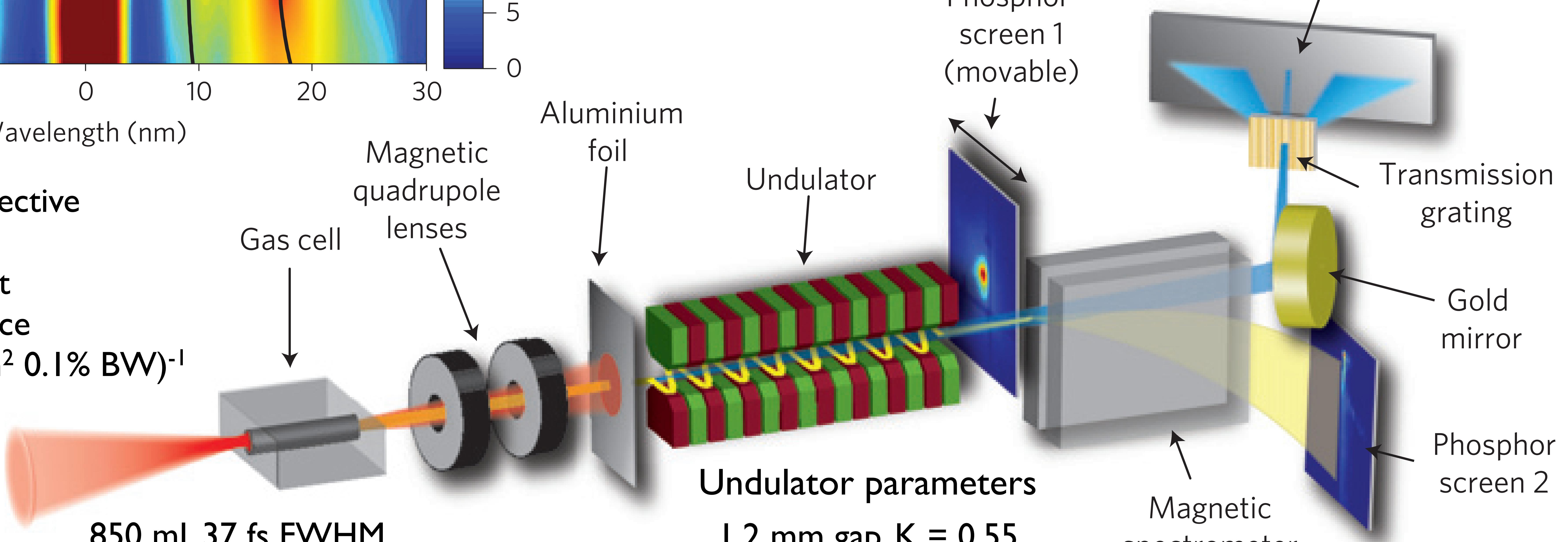


Fuchs *et al.*, Nature Physics 5, 826 (2009)

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)$^{-1}$



X-ray CCD

Phosphor screen 1 (movable)

Aluminium foil

Magnetic quadrupole lenses

Gas cell

Undulator

Transmission grating

Gold mirror

Phosphor screen 2

Magnetic spectrometer

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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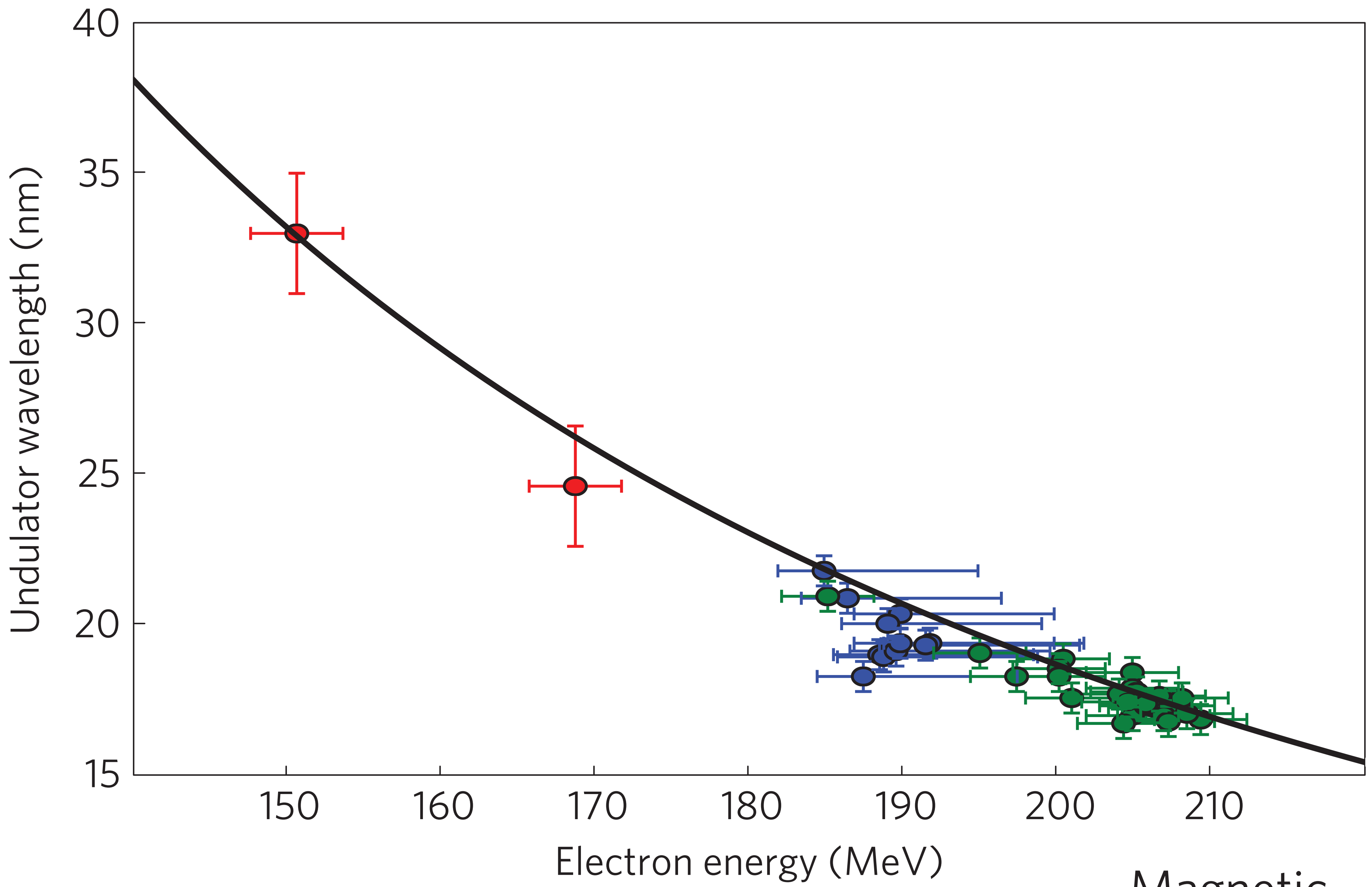

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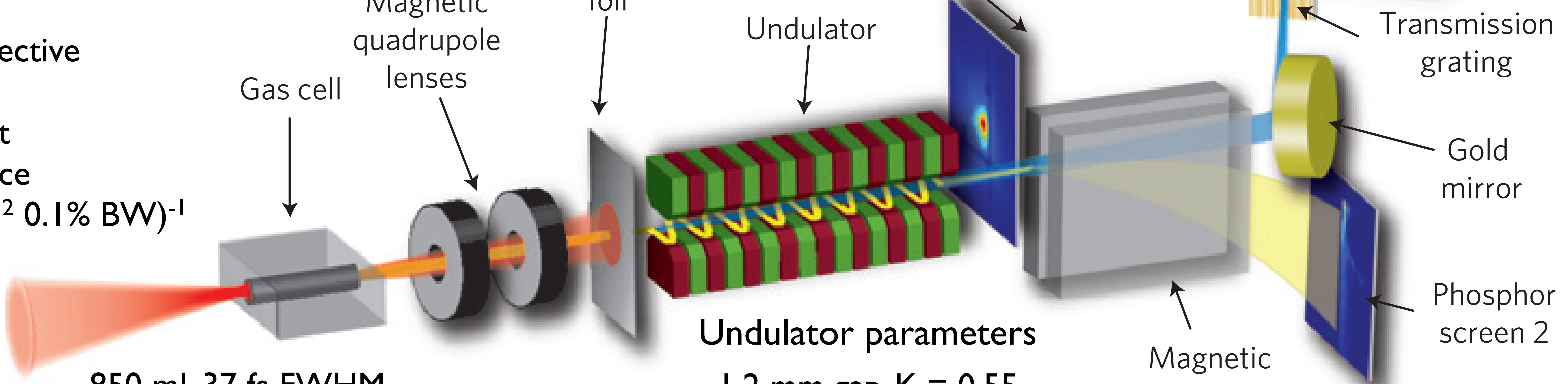

Laser pulse parameters

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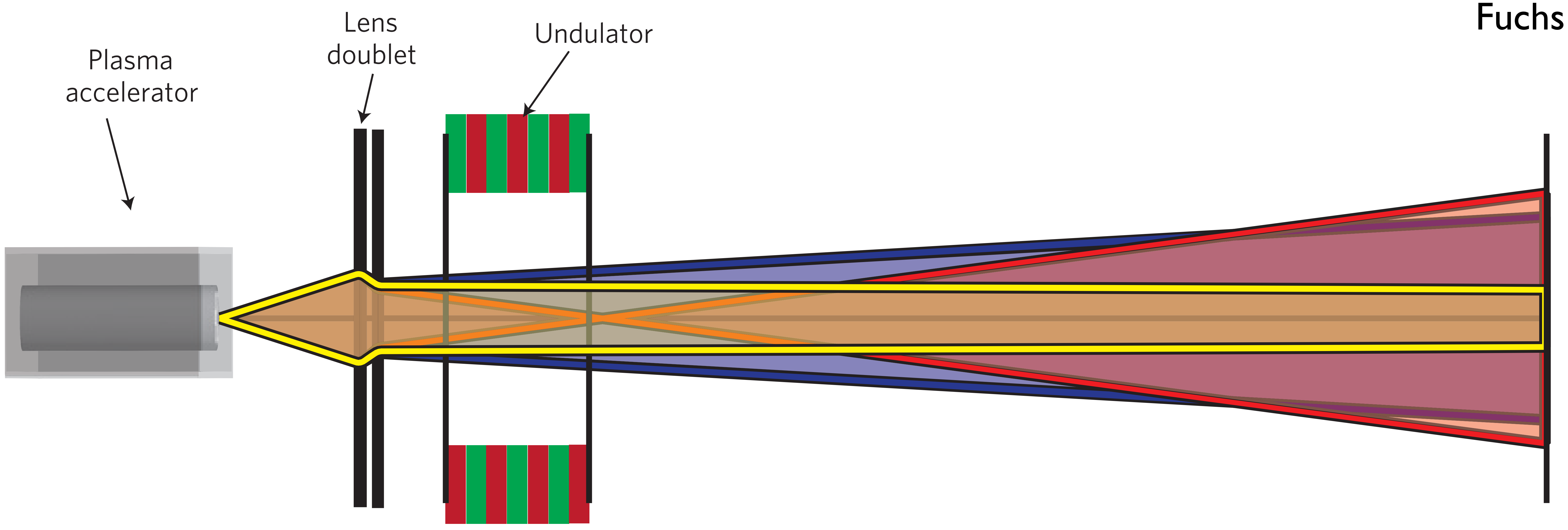
Quadrupole magnets act as electron energy filter

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



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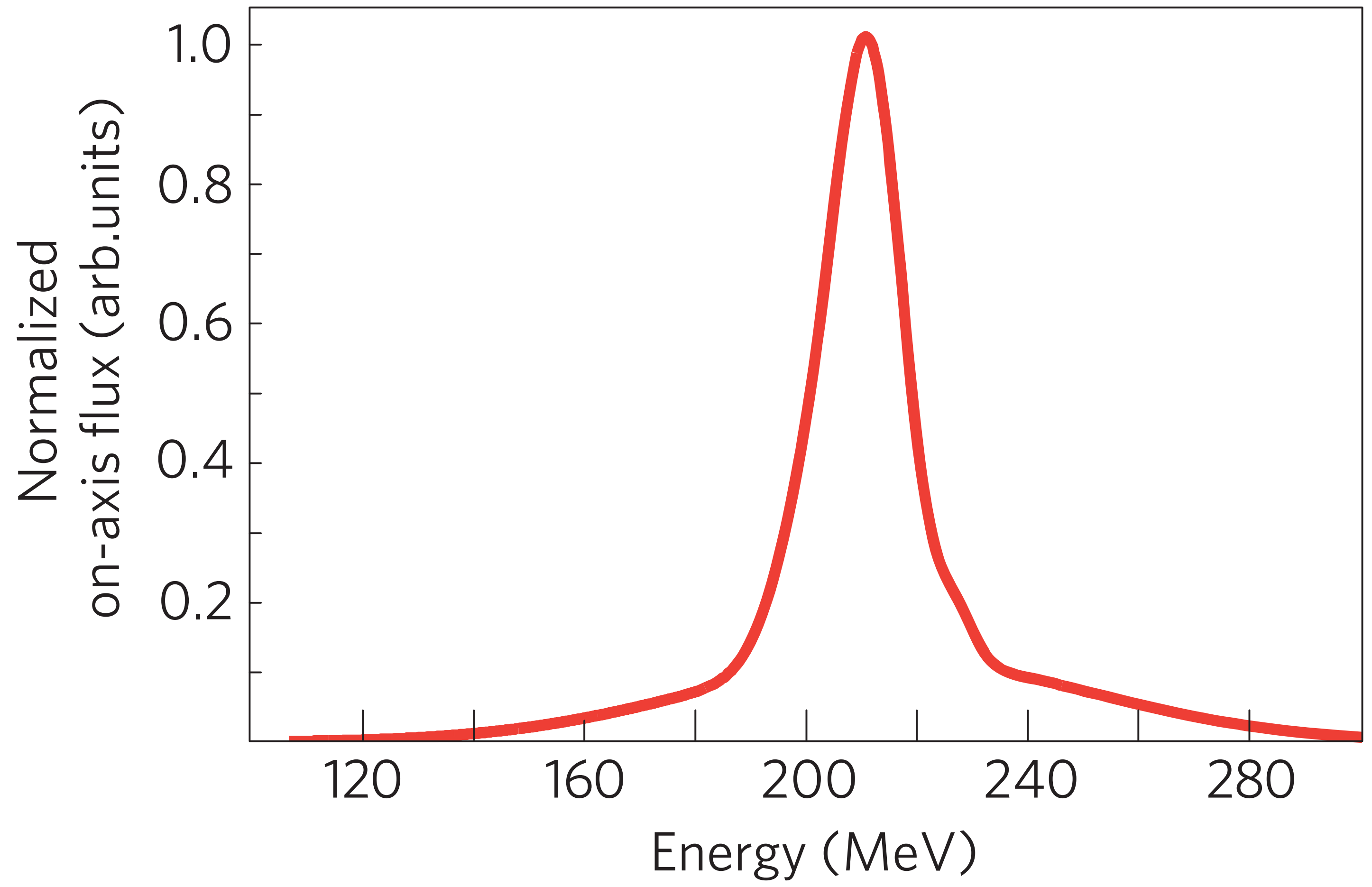

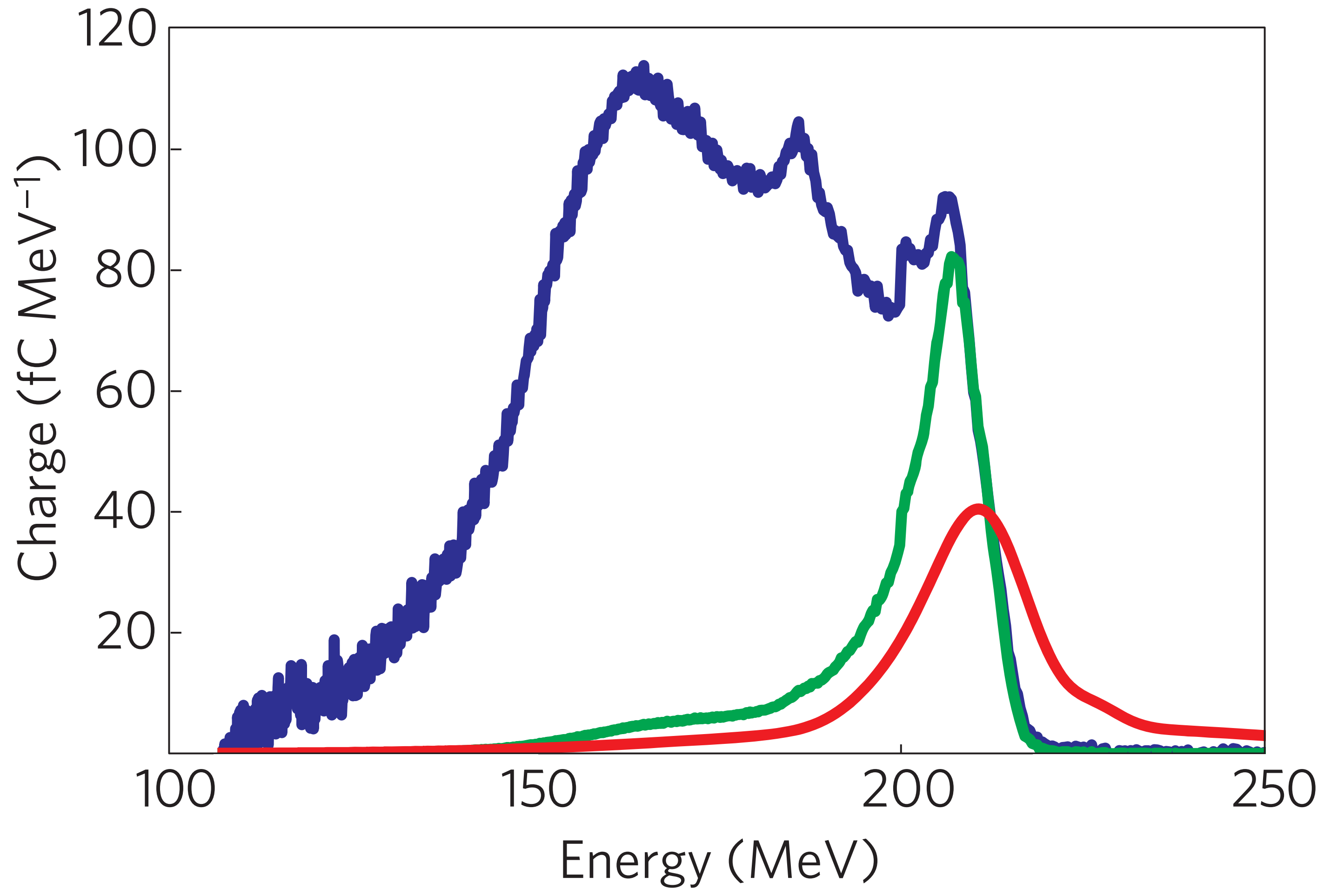

First small step towards
a table-top FEL
[cf. Grüner *et al.*,
Appl. Phys. B 86, 431 (2007)]

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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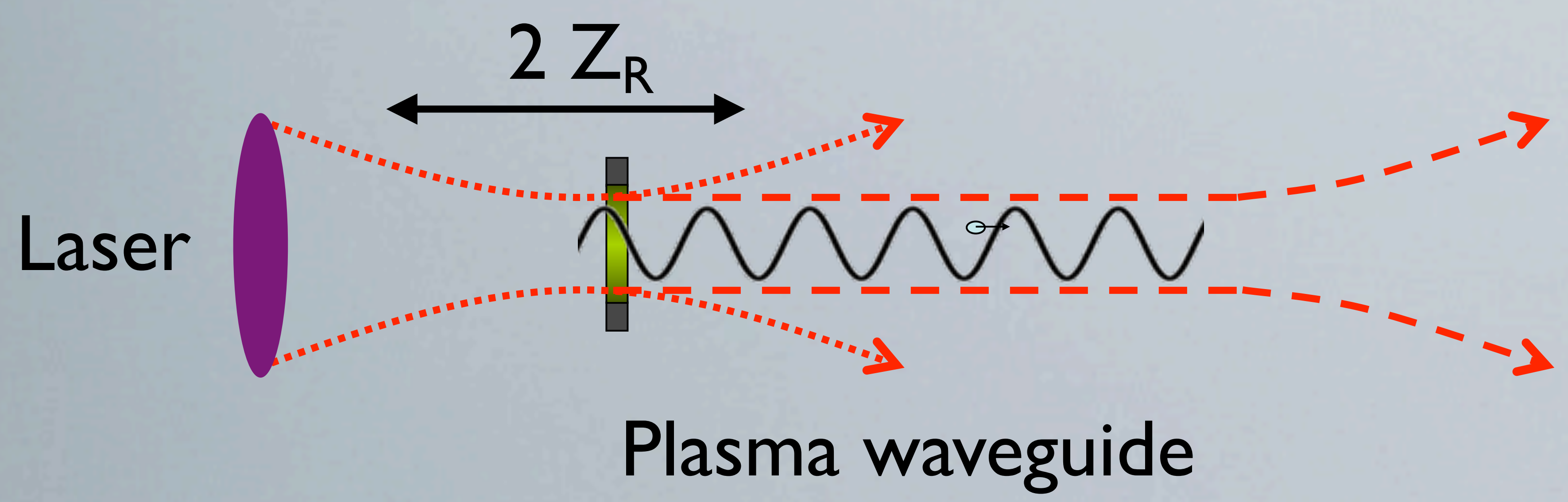
DESY know how would help to analyze LPA beams more thoroughly:

(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)

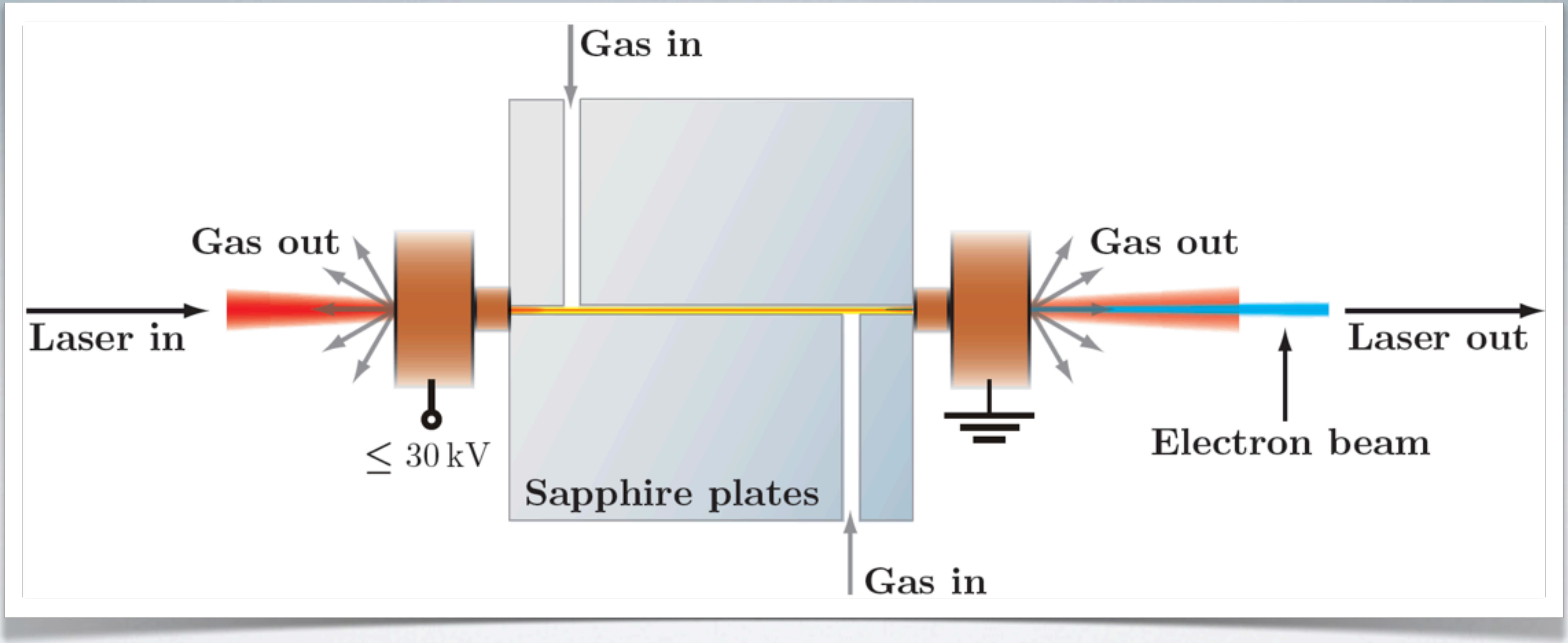
Energy gain scalings and single-stage limitations

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



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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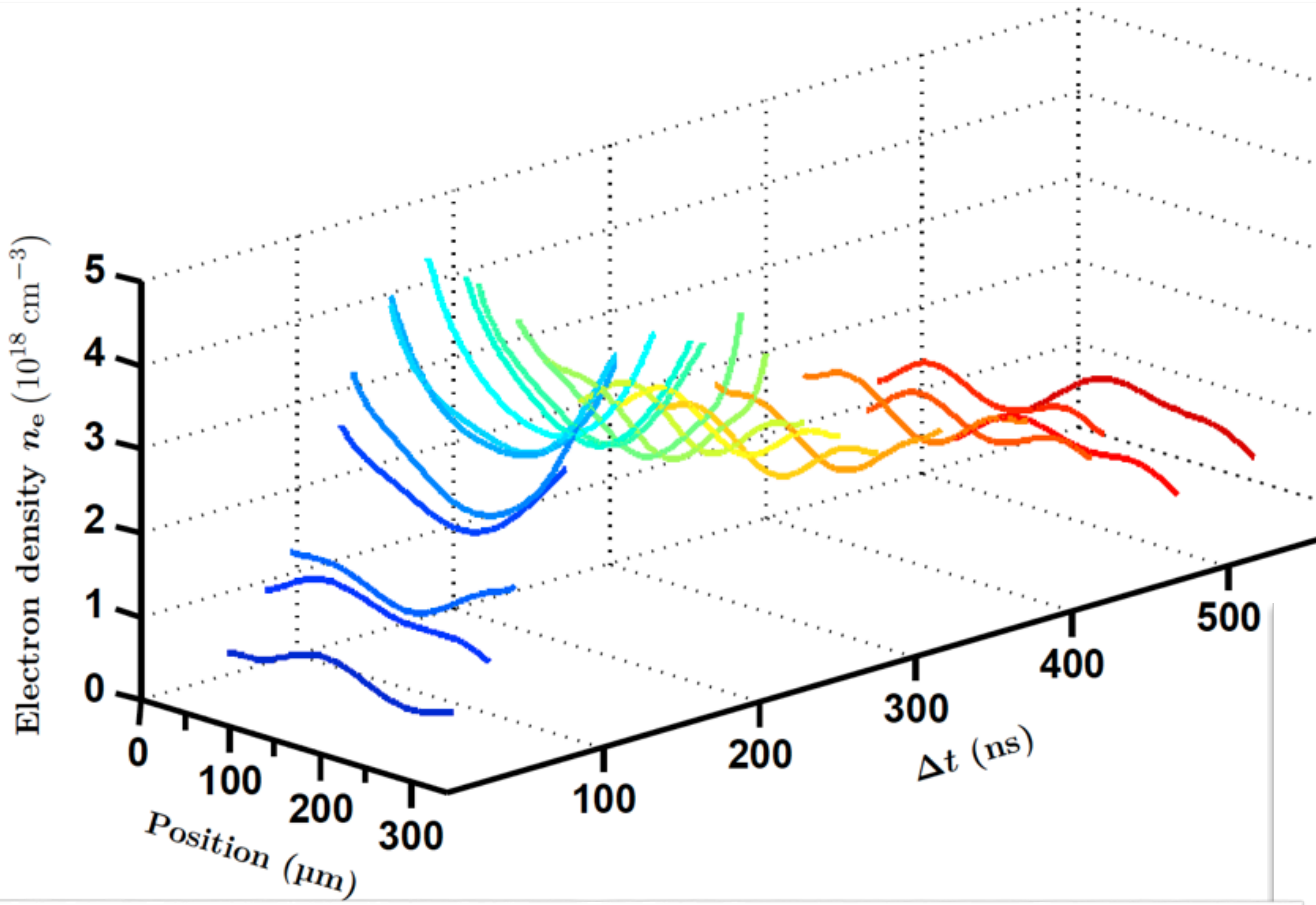

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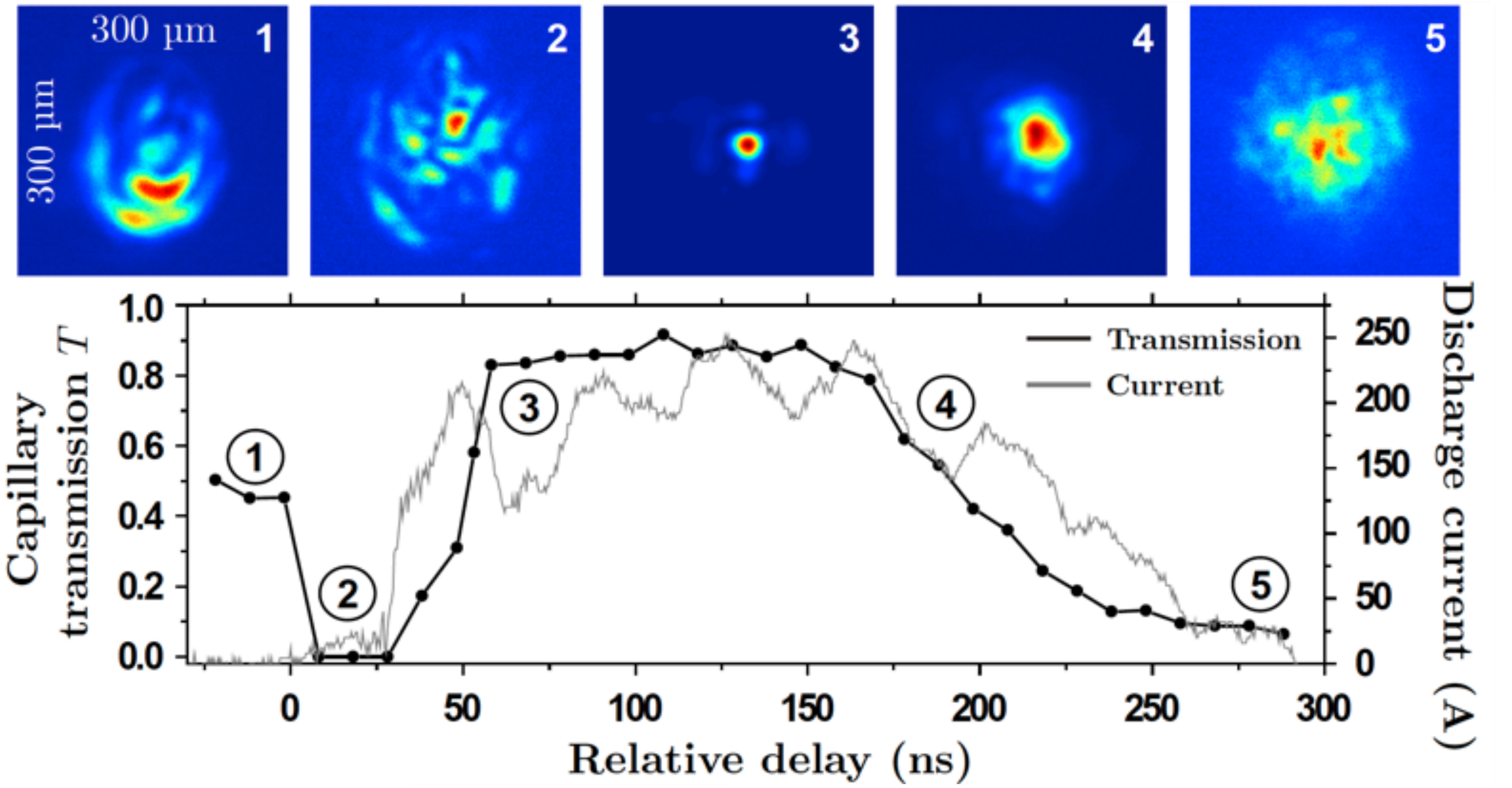


In this example:
Z_R = 2 mm, guiding over 16 mm, guiding efficiency > 90 %

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 $v_{wave} \approx v_g < c$
Electrons travel with $v_{wave} < v_e \lesssim c$

⇒ they outrun the accelerating field structure

Rising density plasma

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

⇒ electrons can be phase locked
[Rittershofer, Grüner *et al.*, submitted]

Energy gain scalings and single-stage limitations

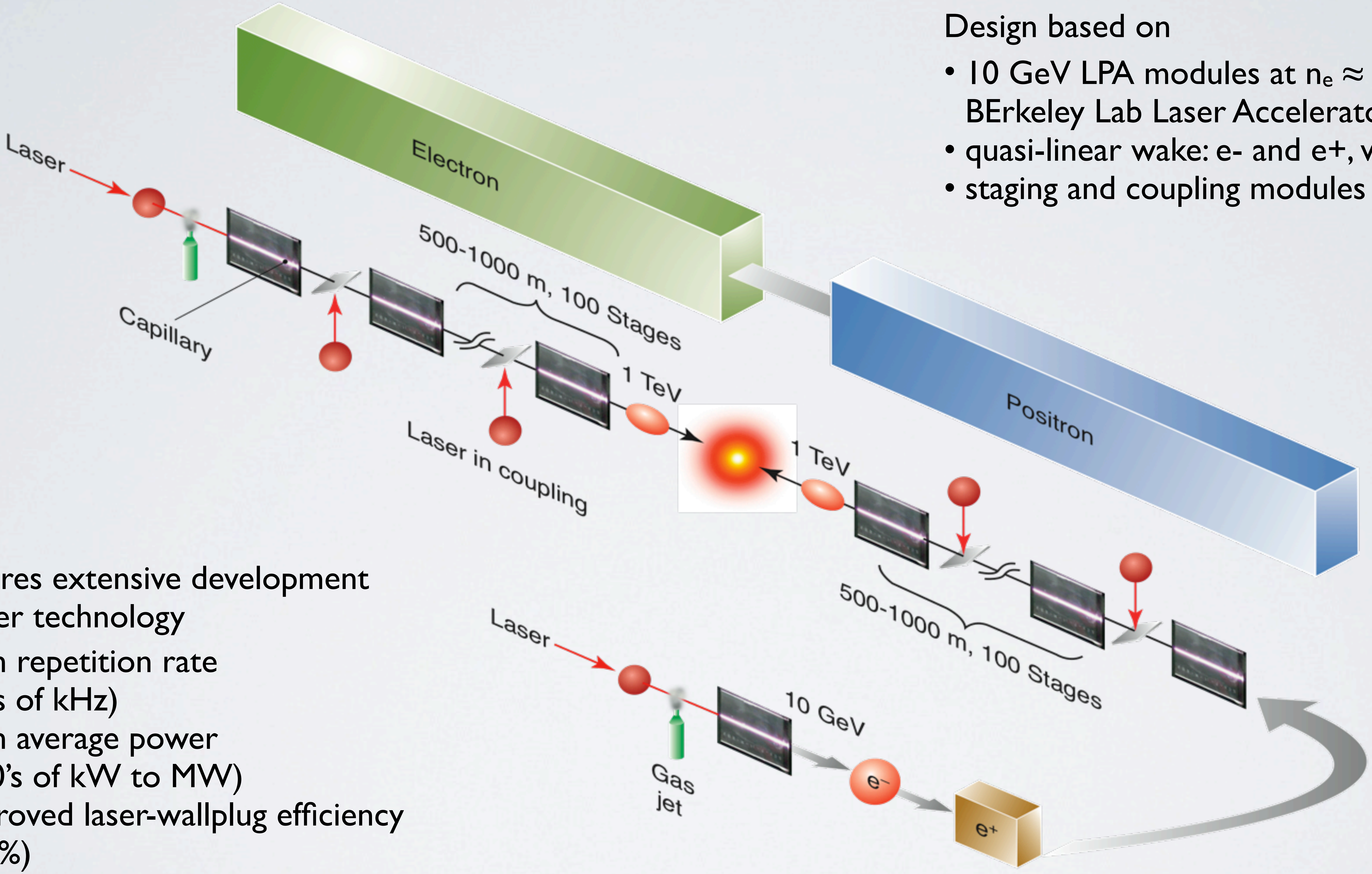
3. Laser depletion: energy loss into plasma wave excitation

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

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



Requires extensive development of laser technology

- High repetition rate (10's of kHz)
- High average power (100's of kW to MW)
- Improved laser-wallplug efficiency (10 %)

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

Accelerator length is determined by staging technology

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

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

Tape model

Crucial points:
- Renewable mirror surface required
- High demands on temporal laser contrast

Efficiency requirements demand laser development

Efficiency requirements demand laser development

Currently beyond state-of-the-art laser technology!

Wallplug efficiency of modern 100 TW-scale Ti:sapphire lasers < 1%

However:

Fiber technology and *diode pumping* might significantly improve laser efficiencies in the future

Optical parametric amplification could allow for high average output power (cf. ELI kHz rep. rate, PW frontend)

Efficiency requirements demand laser development

Careful theoretical and experimental efficiency studies needed

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Optical parametric amplification could allow for high average output power (cf. ELI kHz rep. rate, PW frontend)

User facilities require beam parameter stability

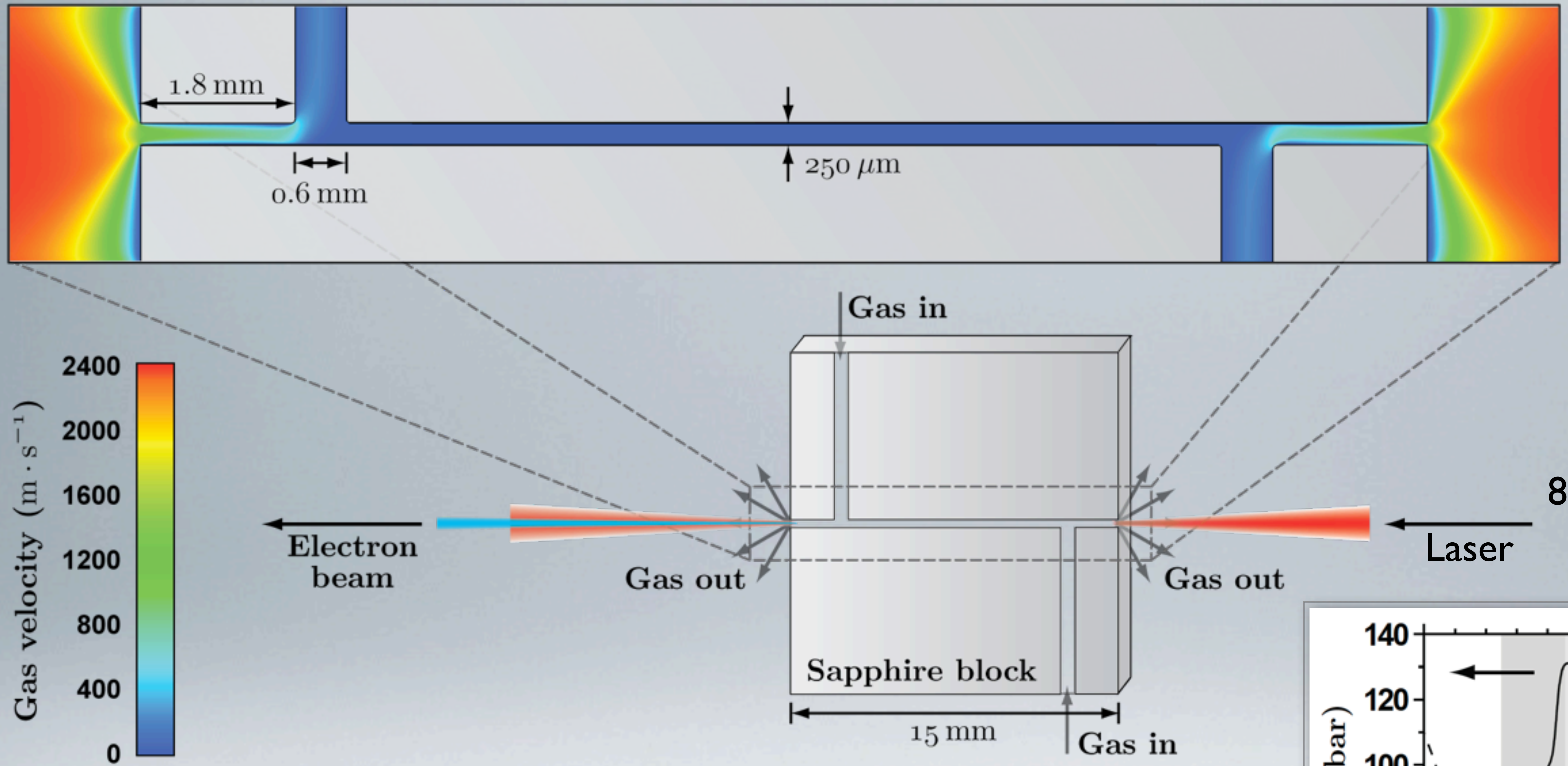
Laser-plasma accelerators have suffered from low shot-to-shot reproducibility

Ways to improve electron beam stability

- 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 *et al.*, accepted for publication in Phys. Rev. Lett.),
  laser pointing (Gonsalves *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

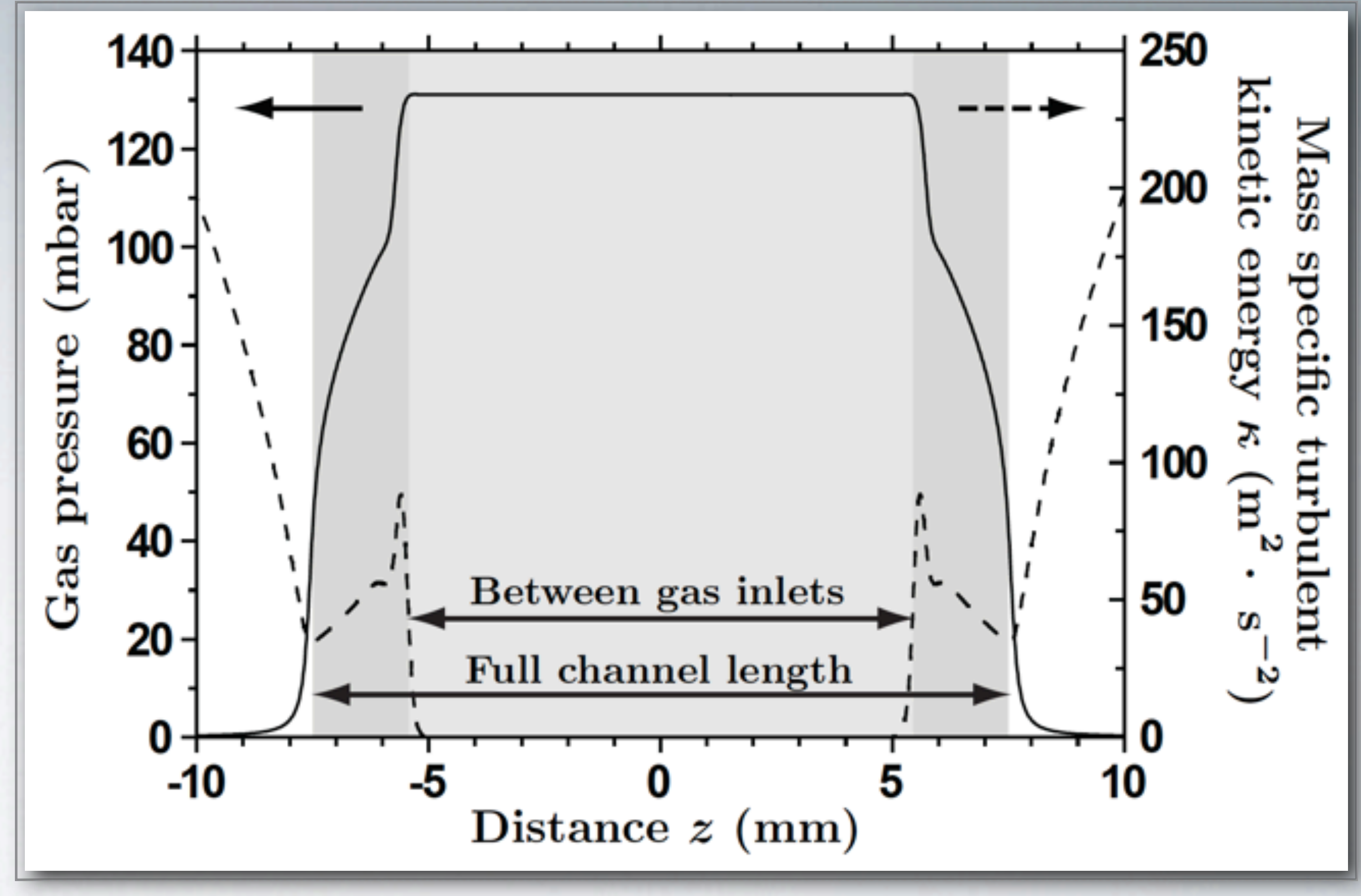
Osterhoff *et al.*,
Phys. Rev. Lett. 101, 085002 (2008)



FLUENT simulation

Pulse parameters

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



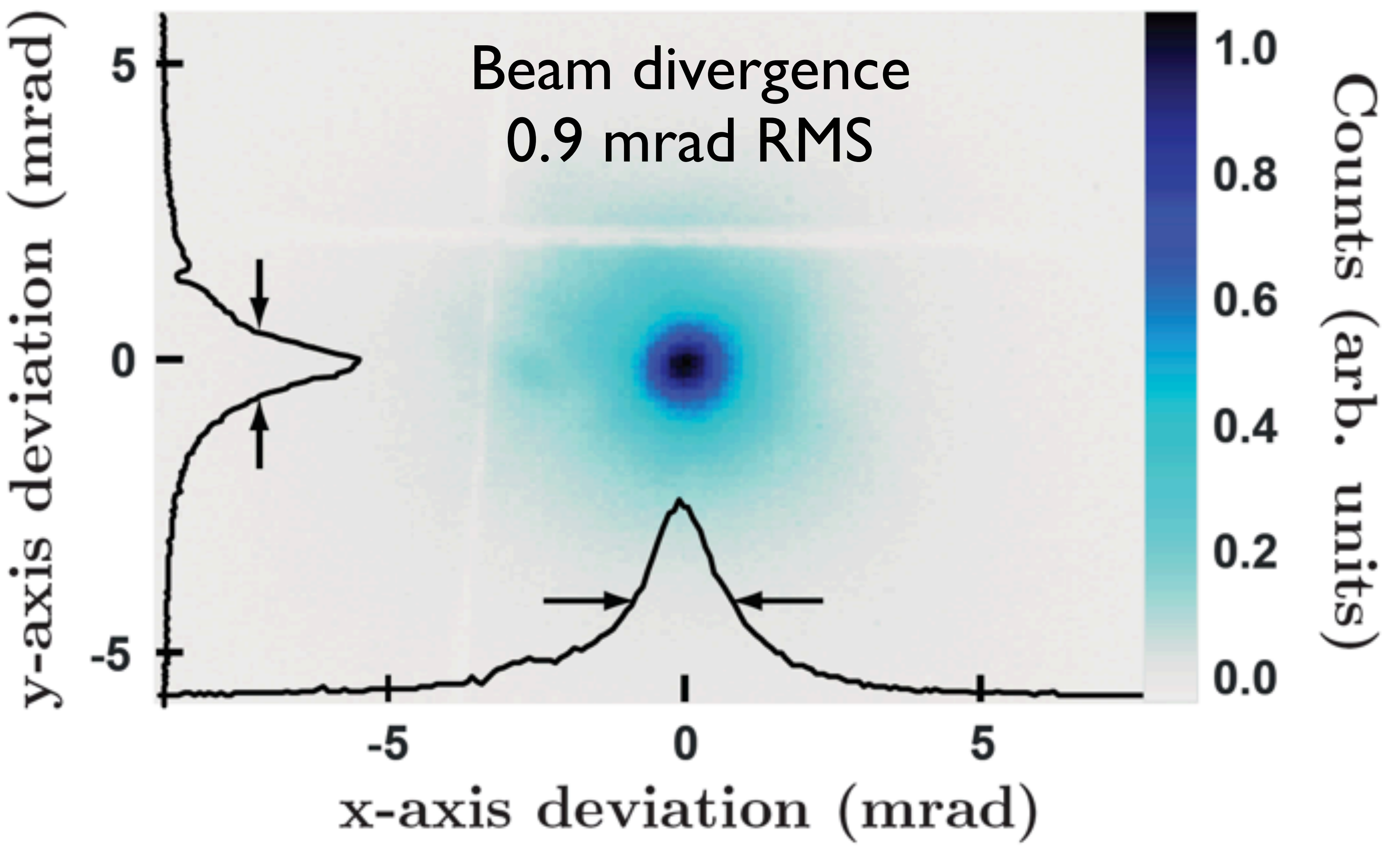
Steady-state-flow gas cell advantages over gas jets

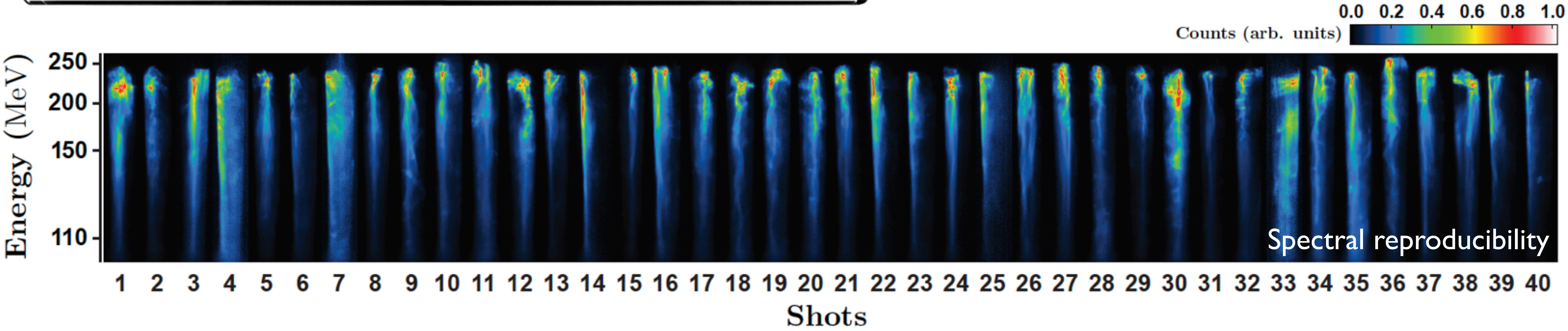
- Allows for high repetition rates (10's of kHz)
- Lasts > 10^5 shots
- Virtually no gas flow in the interaction region
- No turbulence or shocks (compared to jets)

A steady-state-flow gas cell stabilizes plasma conditions

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

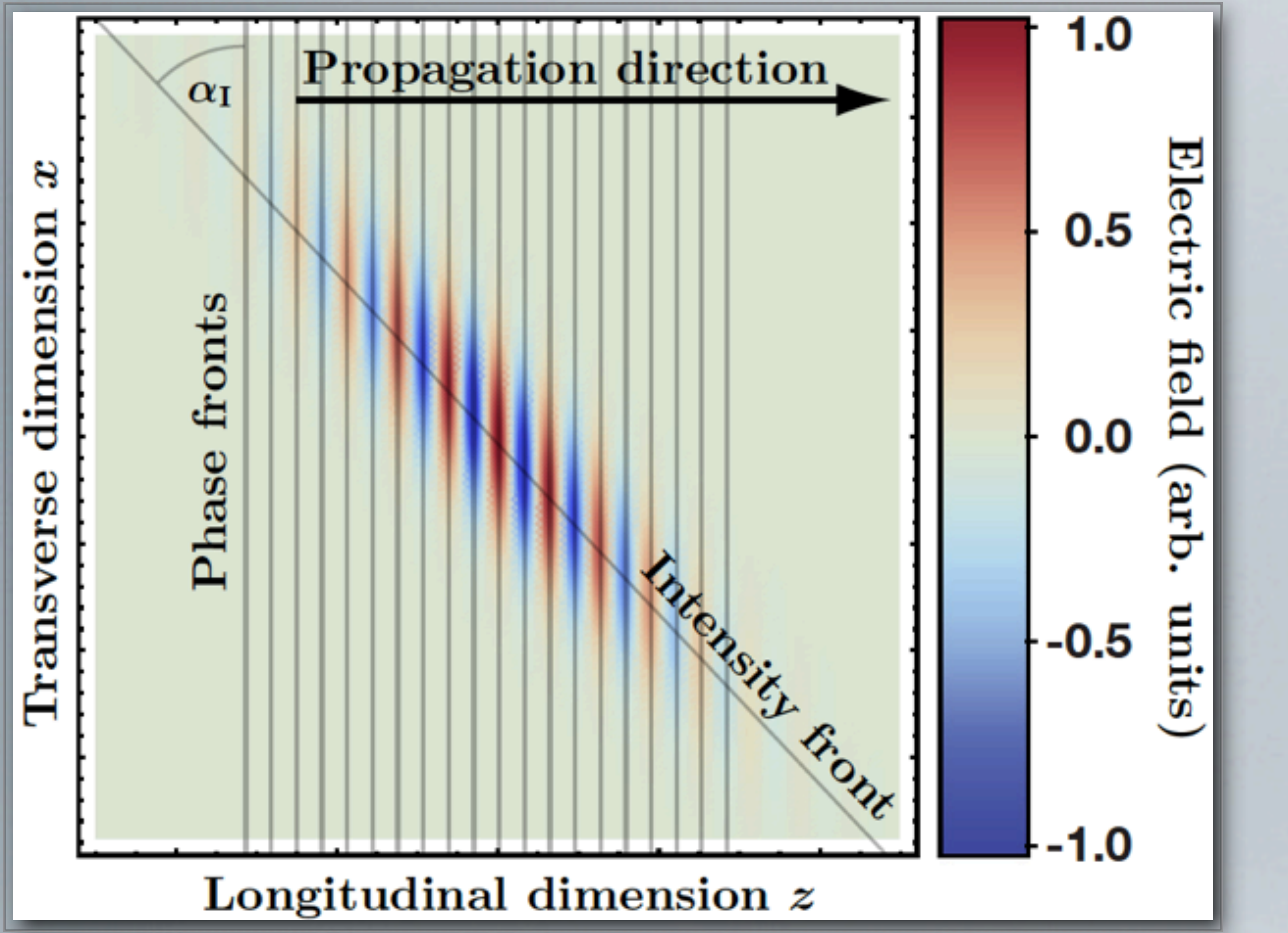
Acceleration results	Gas cell
Peak energies	220 MeV
Energy fluctuations	± 2.5 %
Energy spread	> 2 % RMS
Peak charge	~ 10 pC
Charge fluctuations	±16 %
Divergence	0.9 mrad RMS
Pointing stability	1.4 mrad RMS
Injection	~ 100 %





Spectral reproducibility

Eliminating laser intensity-front tilt increases stability



Popp *et al.*, accepted for publication in Phys. Rev. Lett.

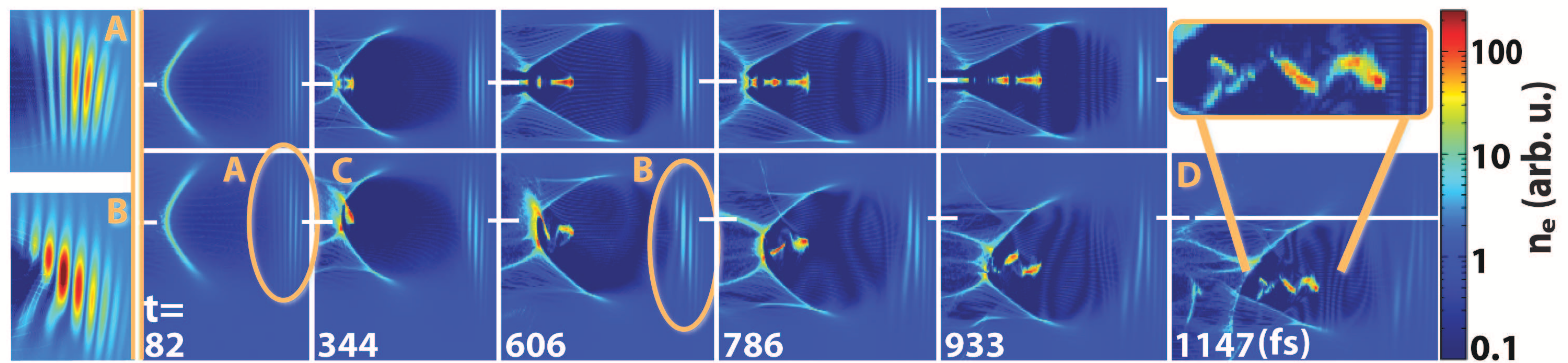
Intensity or pulse-front tilt usually originates from laser angular chirp (AC) caused by an imperfect stretcher/compressor alignment

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

Collective electron-stem oscillations

→ way to tailor betatron radiation photon source?

→ useful for beam cooling?



Summary

Laser-plasma accelerator technology has advanced quickly in recent years

<u>Milestone experiments</u>: 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 user facility

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

Major fields of work:

Staging, efficiency increase, improved stability, beam characterization and optimization

Plasma accelerators may have the potential to revolutionize accelerator technology and could make user facilities much more <u>compact</u>, <u>affordable</u>, and therefore <u>accessible</u>

Thanks for your attention!