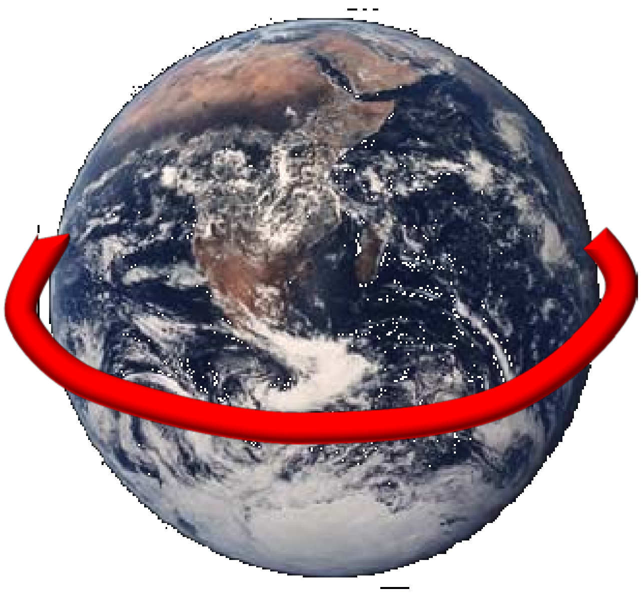
Compact acceleration



A. Pukhov
Uni Dusseldorf, Germany

F^{3}iA, Scharbeutz 2016

Petawatt Lasers

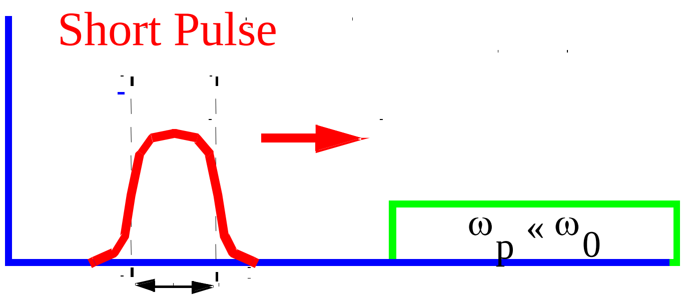
The laser electric field at $I = 10^{21}$ W/cm^2 is

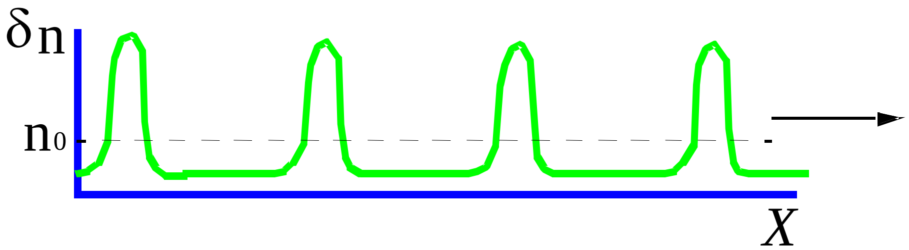
$$E = 100 \text{ TV/m} = 10^{14} \text{ V/m}$$

The field is transverse and requires rectification?

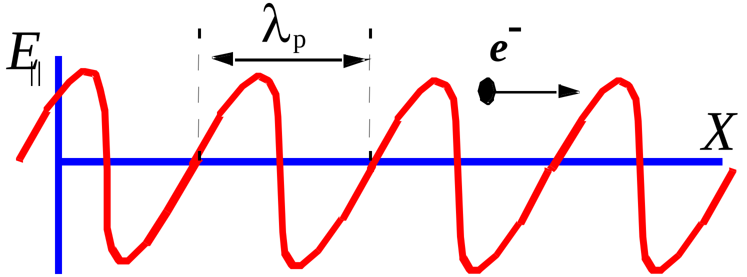
Laser Wake Field Acceleration

The idea was proposed by T. Tajima and J. W. Dawson, Phys.Rev.Lett. 43 , p.267, (1979)



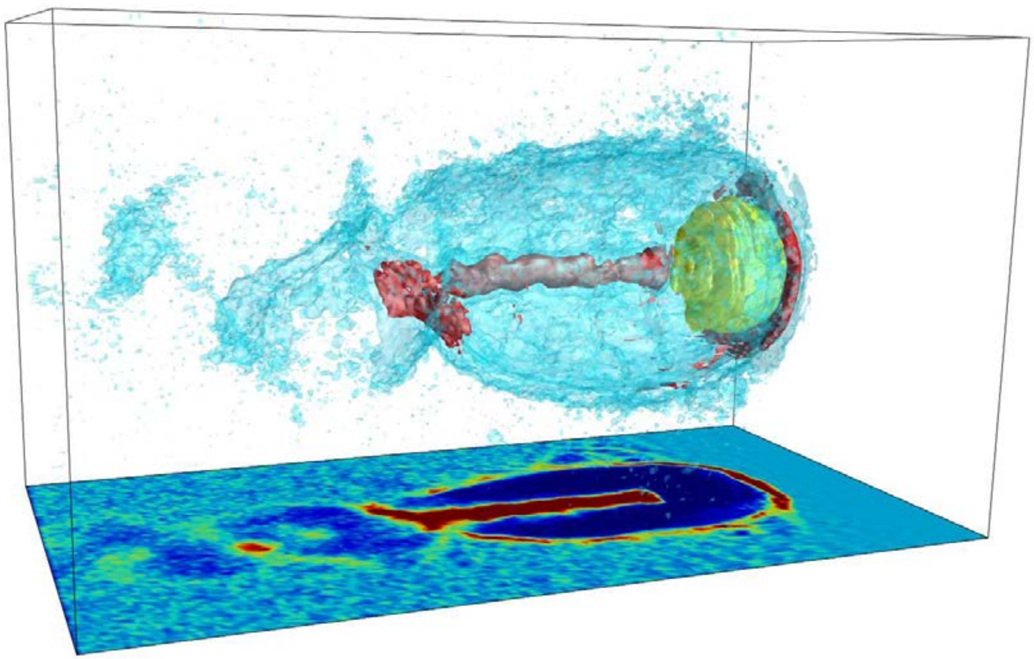


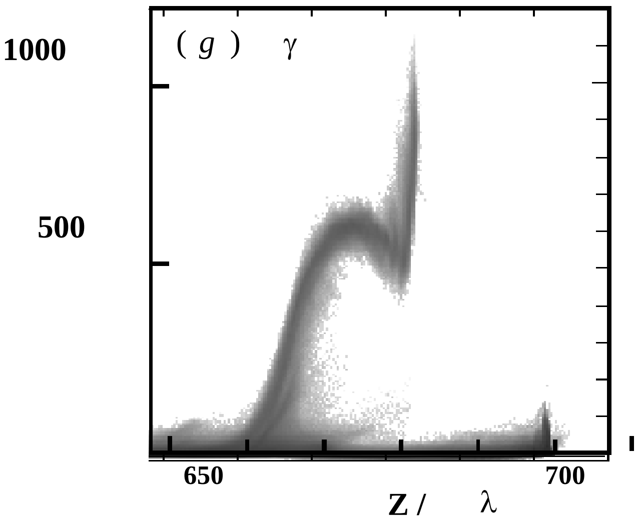
$$E_{\|} \cong \sqrt{\frac{n_e}{10^{14}\,\mathrm{cm}^{-3}}} \cdot \frac{\delta n_e}{n_e} \cdot 1\ \mathrm{GV/m}$$



Laser bubble acceleration: quasi-monoenergetic bunches

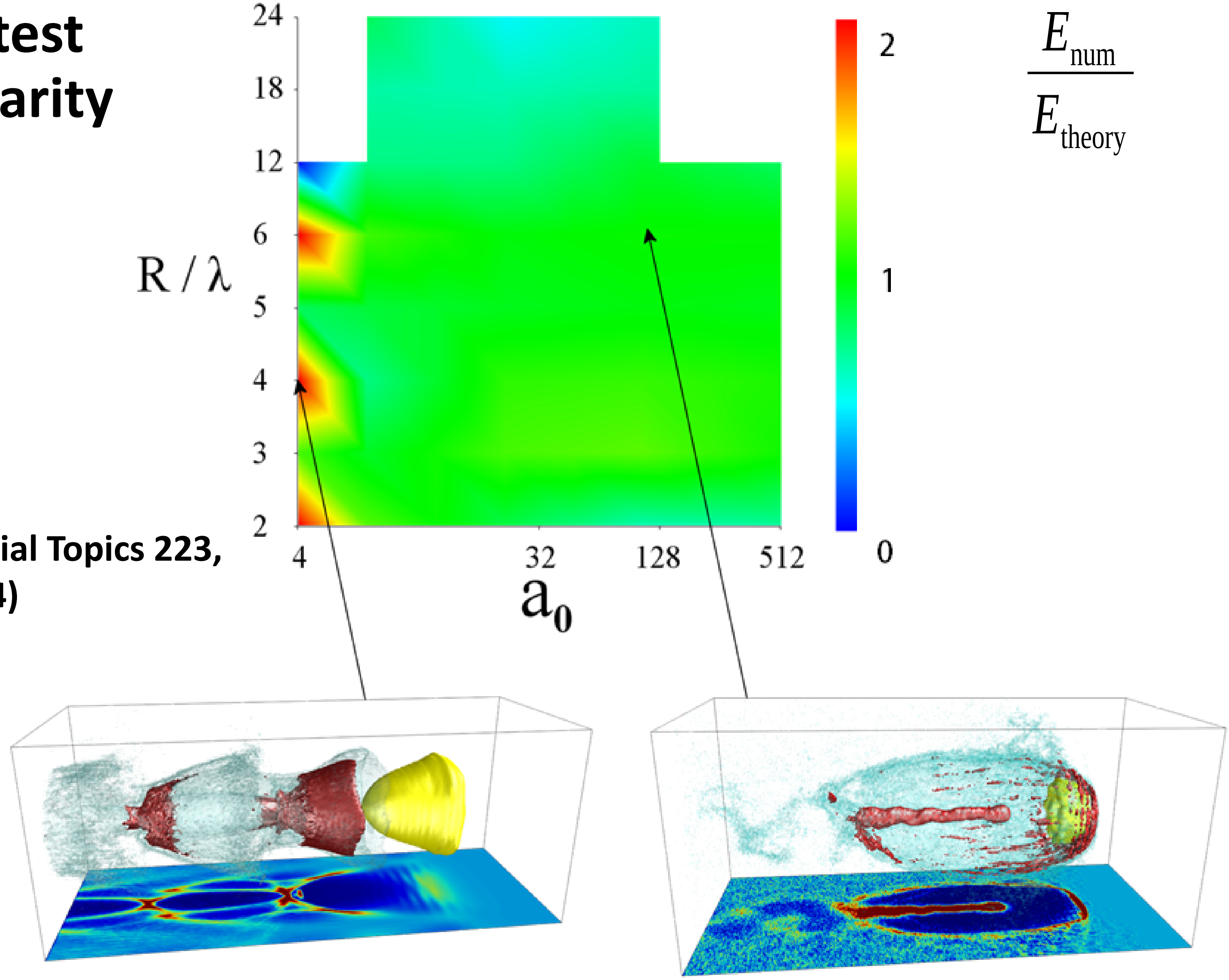
Pukhov & Meyer-ter-Vehn Appl. Phys. B **74**, pp. 355-361 (2002)





γ-factor of electrons

Numerical test of the similarity scalings



O. Jansen et al.
Eur. Phys. J. Special Topics 223, 1017–1030 (2014)

Laser bubble acceleration: limitations in uniform plasmas

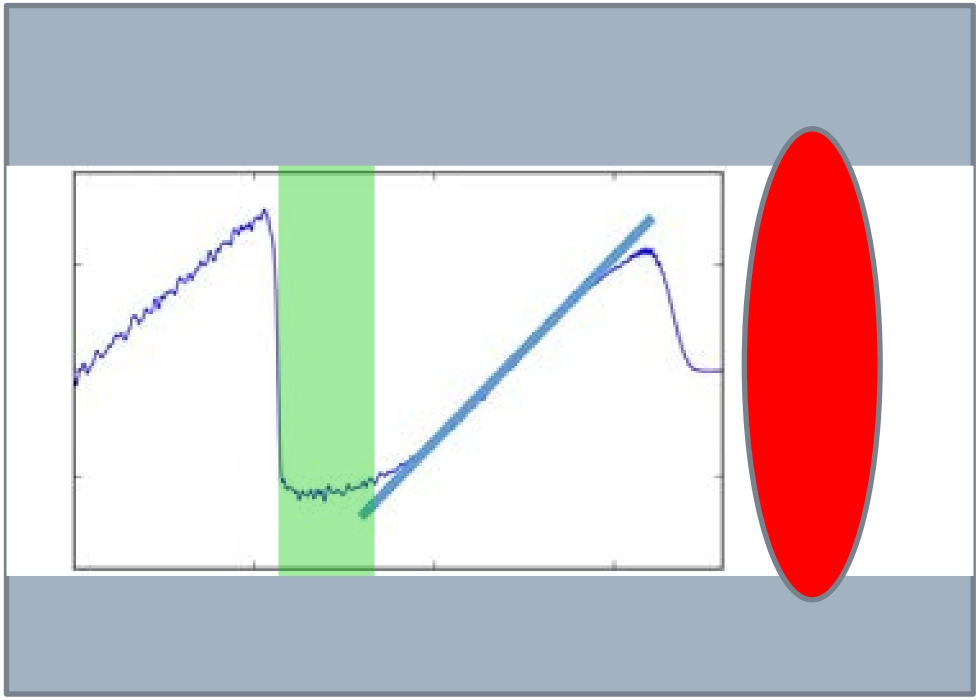
We might want an EMPTY plasma channel

1. Maximum energy gain per stage is limited by laser depletion

2. Radiation damping will limit acceleration around 100 GeV

3. Limits on bunch emittance and energy spread due to the direct laser interaction at the betatron resonance

Electron acceleration in a channel: towards high quality acceleration

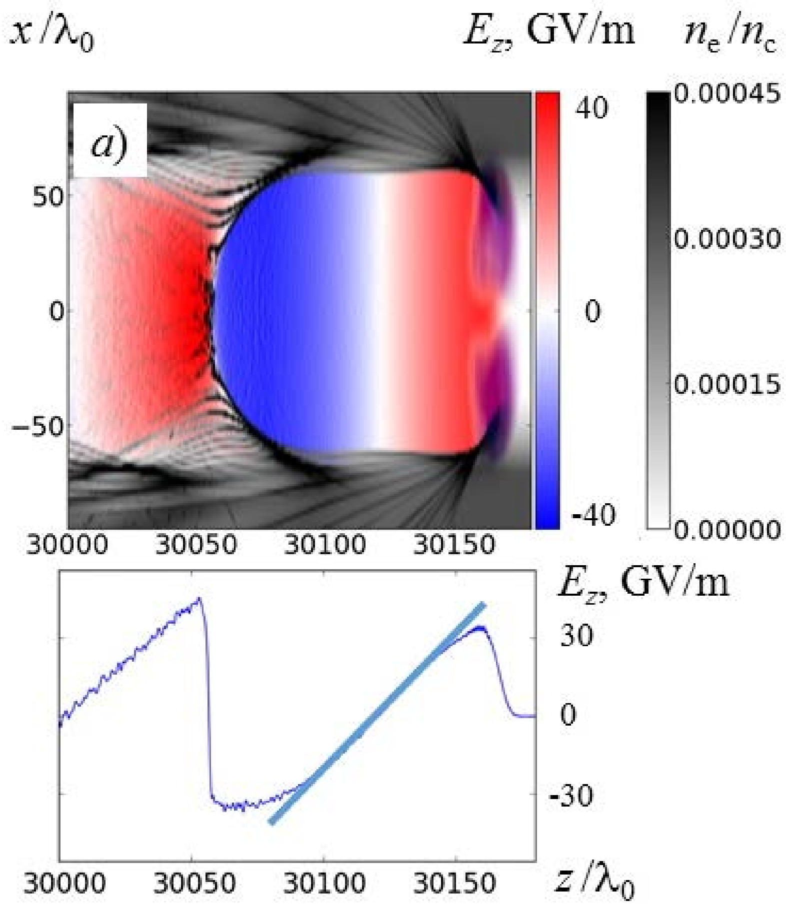


A channel helps to moderate the accelerating field and adjust the laser depletion length

A region of constant accelerating field appears where monoenergetic acceleration is possible

PRL 113, 245003 (2014)

Electron acceleration in a channel: towards high quality acceleration



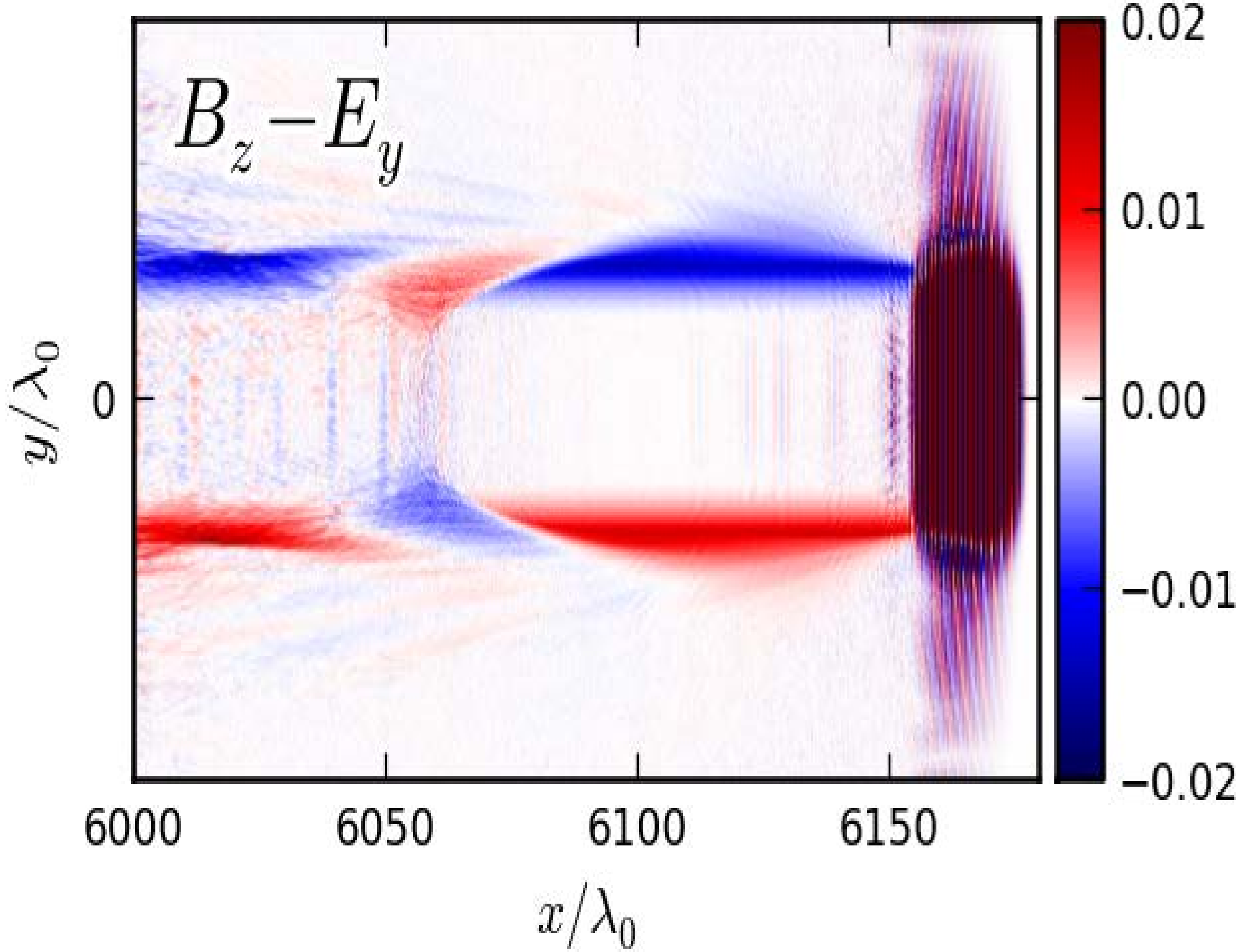
3D PIC simulation
in a Lorentz-boosted frame

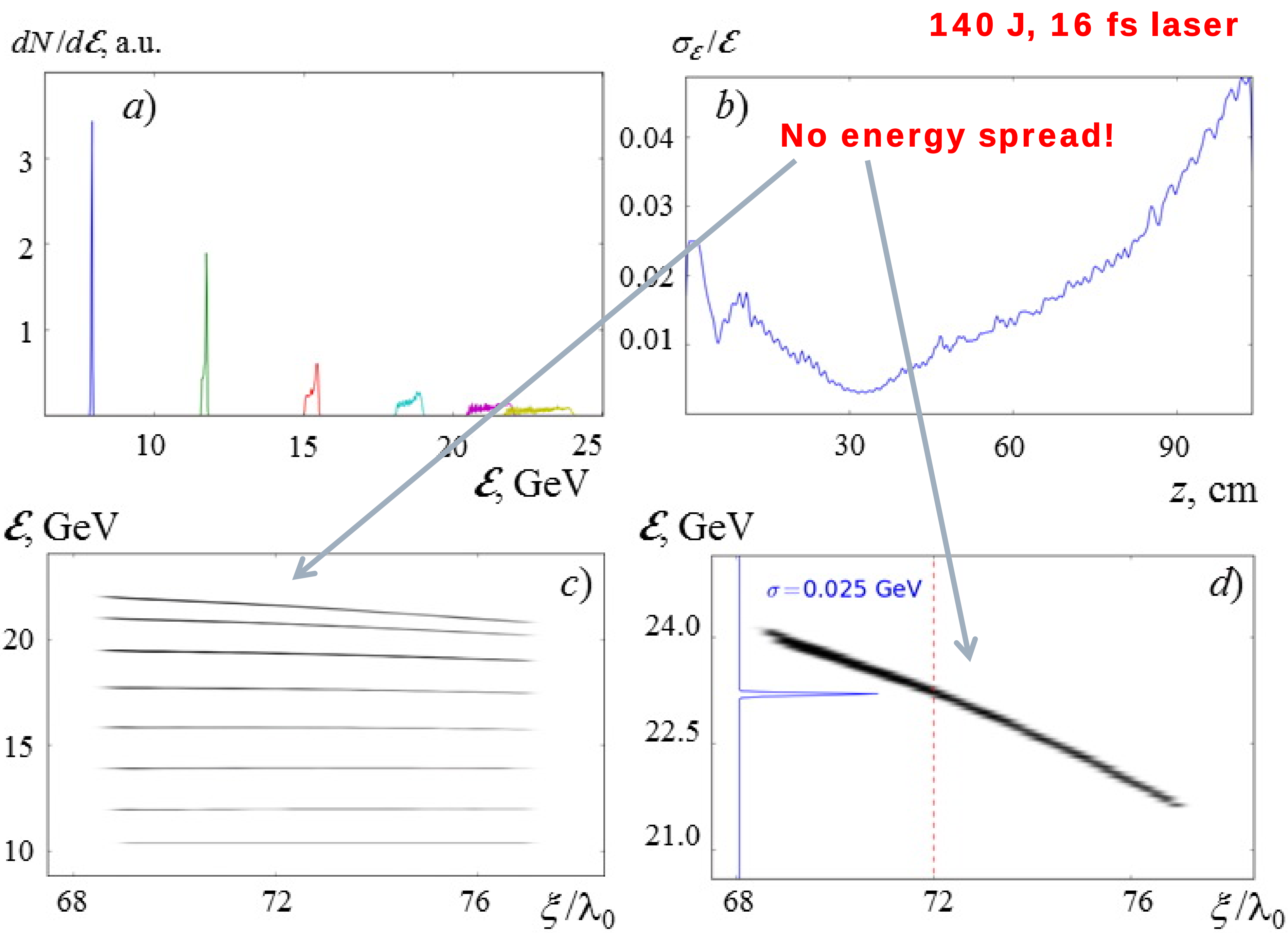
Energy gain: 24 GeV

Laser pulse: 140 J, 16 fs
Plasma: 3x10^{17} 1/cm^3.

Acceleration distance: 100 cm

Focusing force in the channel walls
No net transverse force in the void region





140 J, 16 fs laser
No energy spread!
$dN/d\mathcal{E}$, a.u.
a)
$\mathcal{E}$, GeV
$\sigma_\mathcal{E}/\mathcal{E}$
b)
z, cm
$\mathcal{E}$, GeV
c)
ξ/λ_0
$\mathcal{E}$, GeV
d)
σ = 0.025 GeV
ξ/λ_0

1 GeV / m sustained gradient

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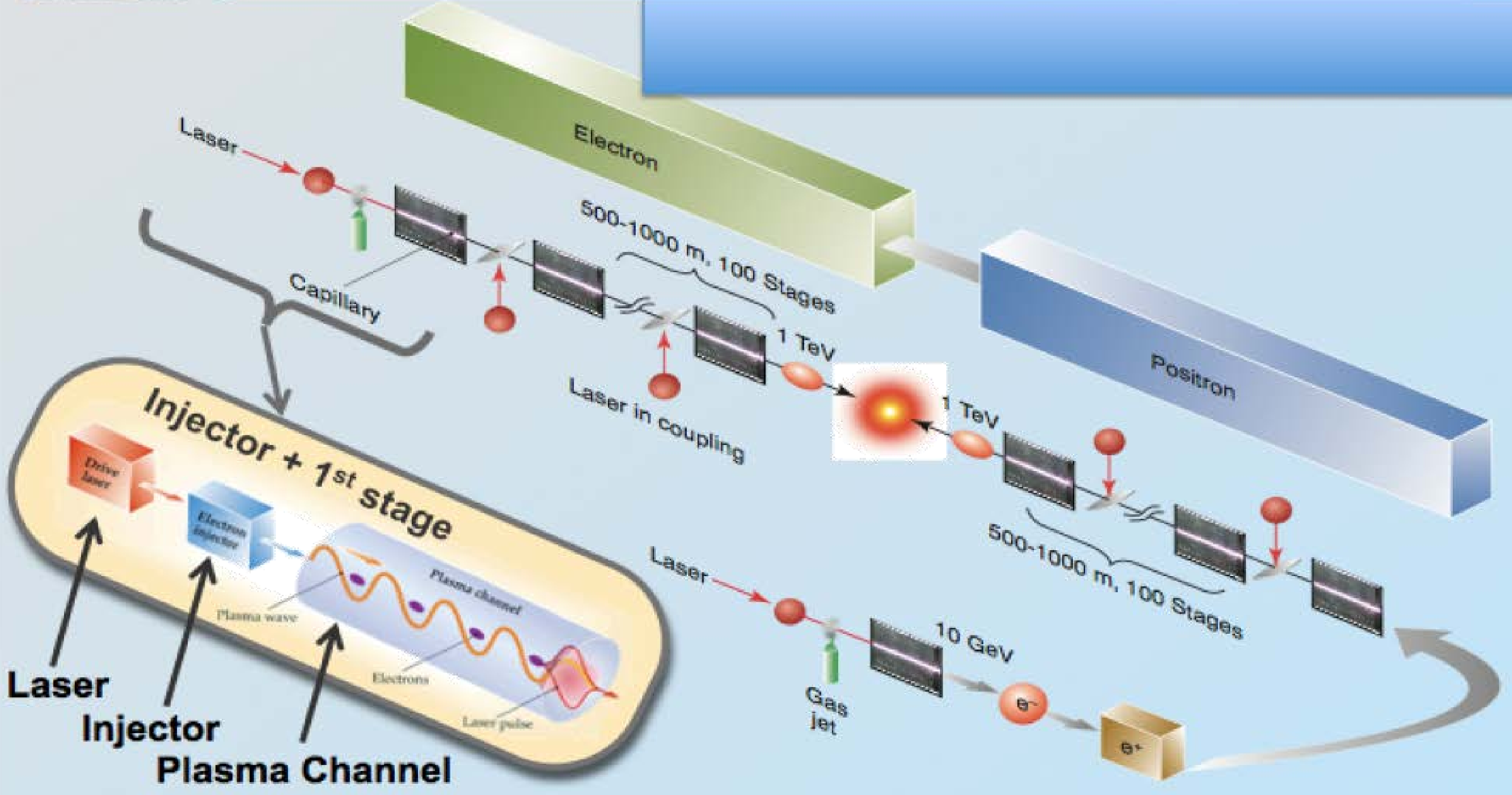
BERKELEY LAB

Strawman design of a TeV LPA Collider



Leemans & Esarey, Physics Today, March 2009

AWAKE: Proton beam self-modulation in plasmas

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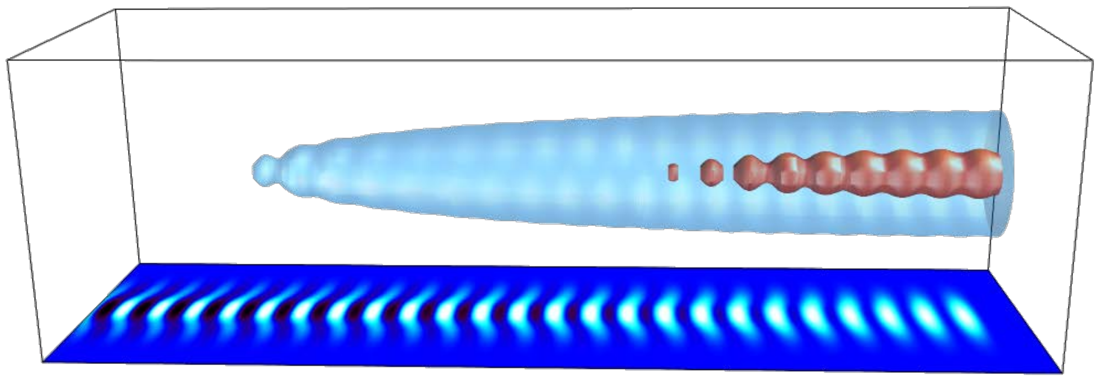
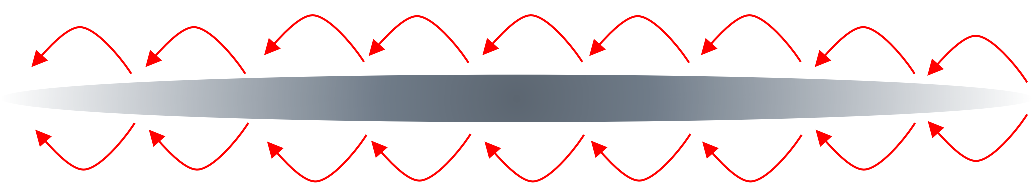
Kumar et al., PRL 104, 255003 (2010): Pukhov, et al. PRL 107, 145003 (2011)

Caldwell et al., Nucl. Instr. 2016
http://dx.doi.org/10.1016/j.nima.2015.12.050

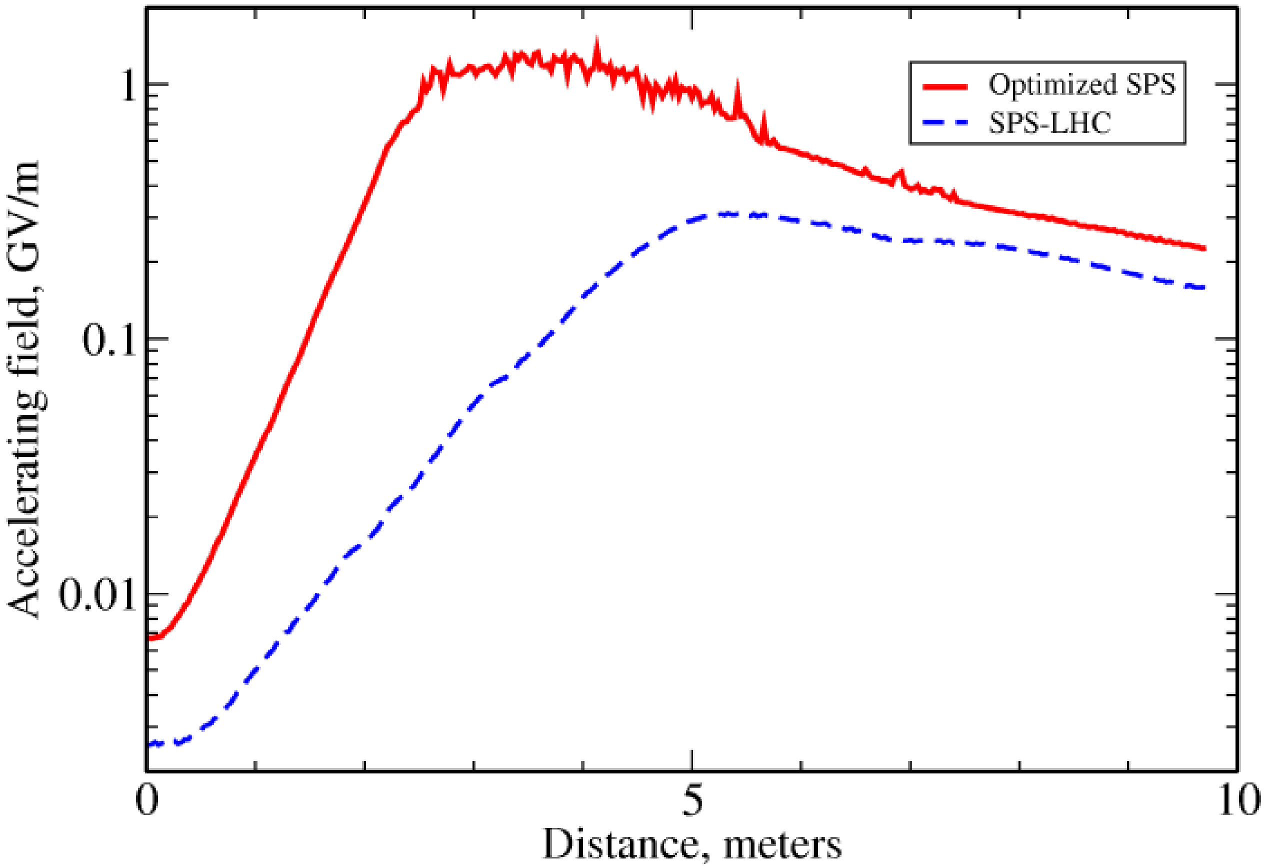


Beam self-modulates at plasma wavelength...



...and excites resonant wake field

AWAKE: Expected accelerating field



Limit on Wakefield Gradient?

Thesis: although ~GeV energy gains are possible with high gradients, the perspective multi-stage plasma wake field accelerators have sustained gradients ~1 GeV/m

Reason: plasma field is just a second order perturbation of the laser.

Wake field is small!

January 30, 2016

Breakthroughs in high power fiber lasers enables four times faster drilling through hard rock

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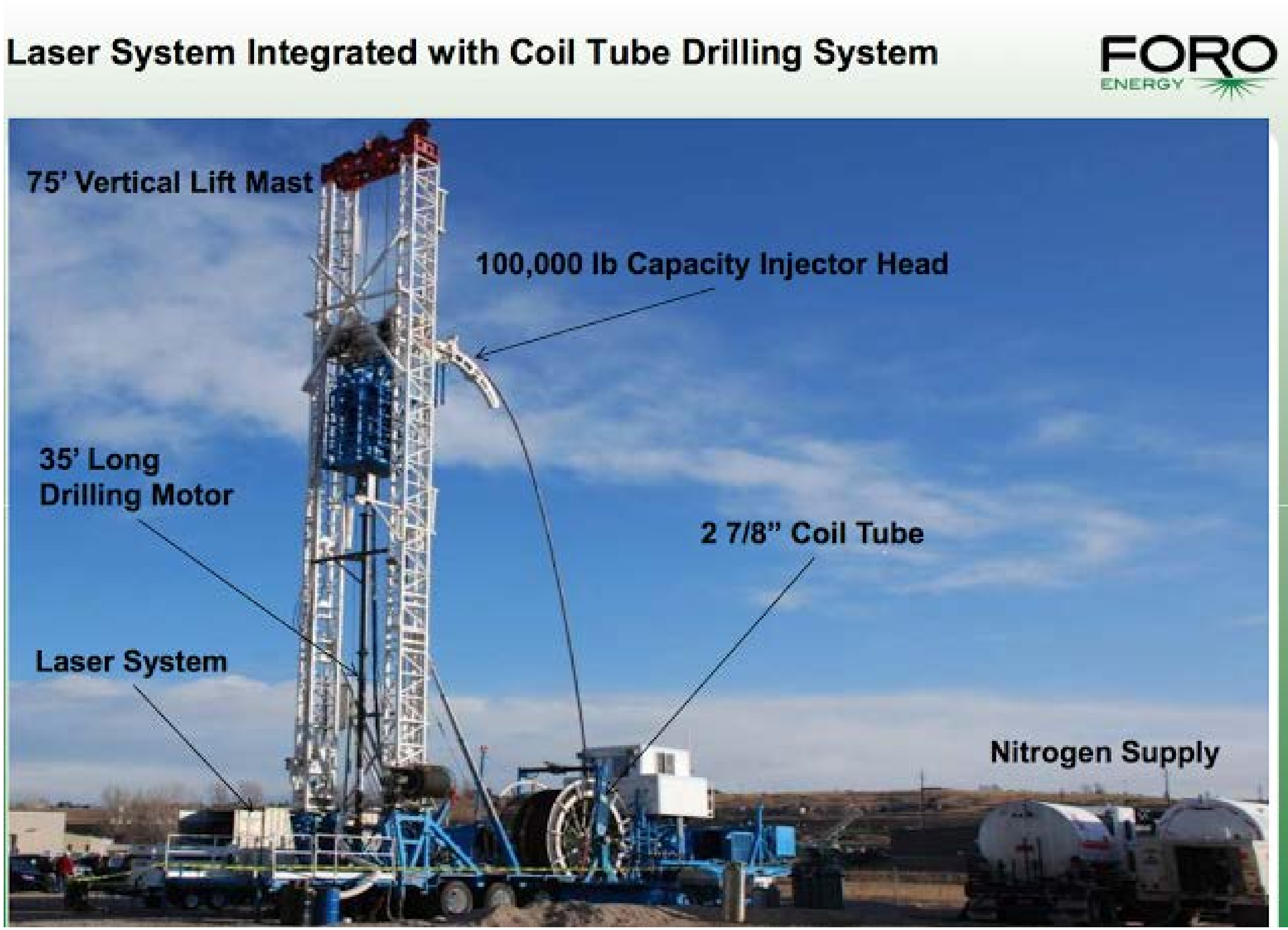


A portable oil-drilling setup includes a 20 kW fiber laser and a low-loss fiber-optic cable. The process potentially cuts the required power for drilling by nearly 90%.

Lasers fields

$I = 10^{21}$ W/cm^2 $\leftarrow$ $E = 100$ TV/m = 10^{14} V/m

$I = 10^{19}$ W/cm^2 $\leftarrow$ $E = 10$ TV/m = 10^{13} V/m

$I = 10^{17}$ W/cm^2 $\leftarrow$ $E = 1$ TV/m = 10^{12} V/m

Do we want rectification?

Non-plasma accelerating schemes

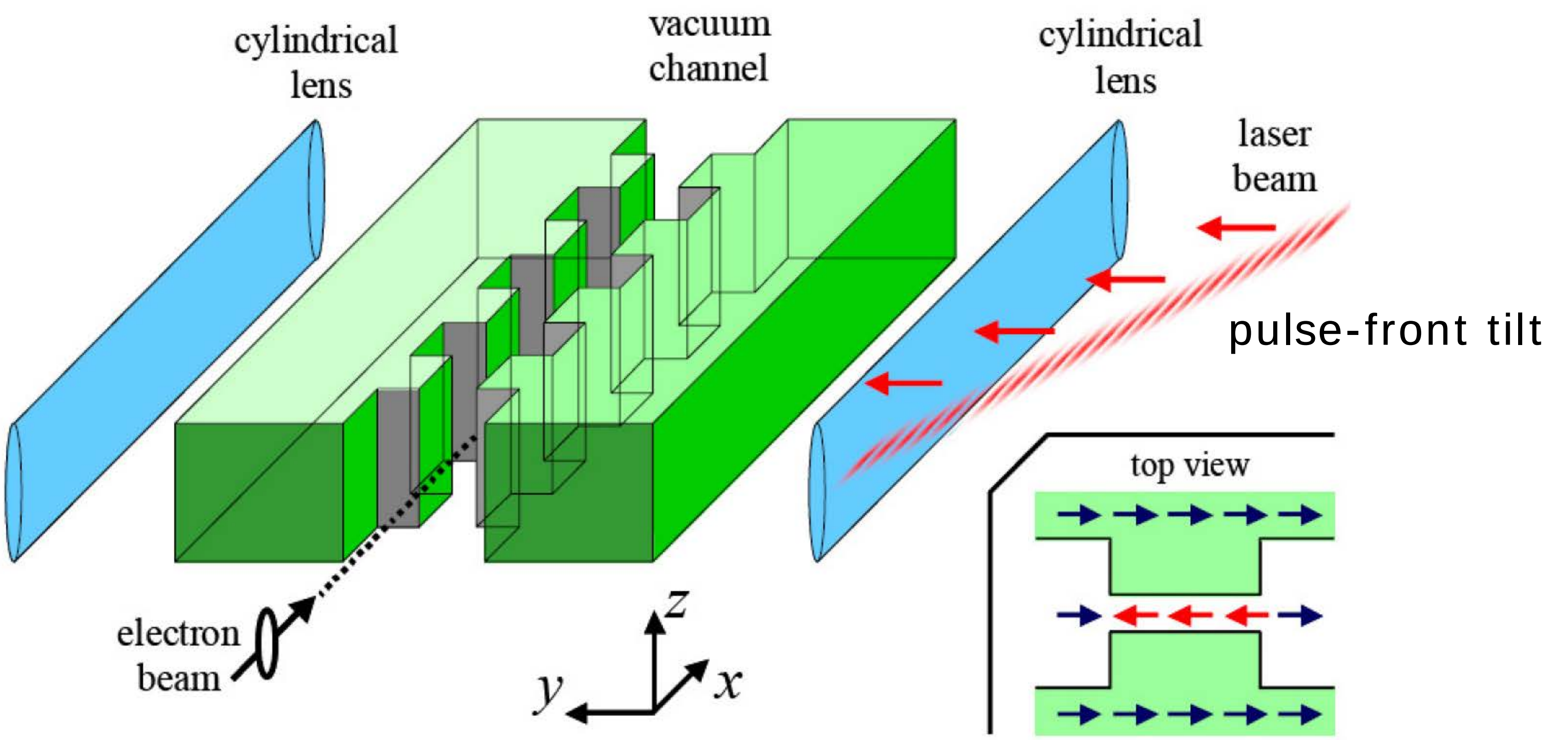
- Dielectric photonic crystals with axial laser coupling
- Dielectric phase masks with side laser coupling

Dielectrics combined with short pulse lasers
can provide sustained accelerating fields at GV/m level

Well competitive with weakly nonlinear wake fields.

Dielectric photonic mask with side laser coupling

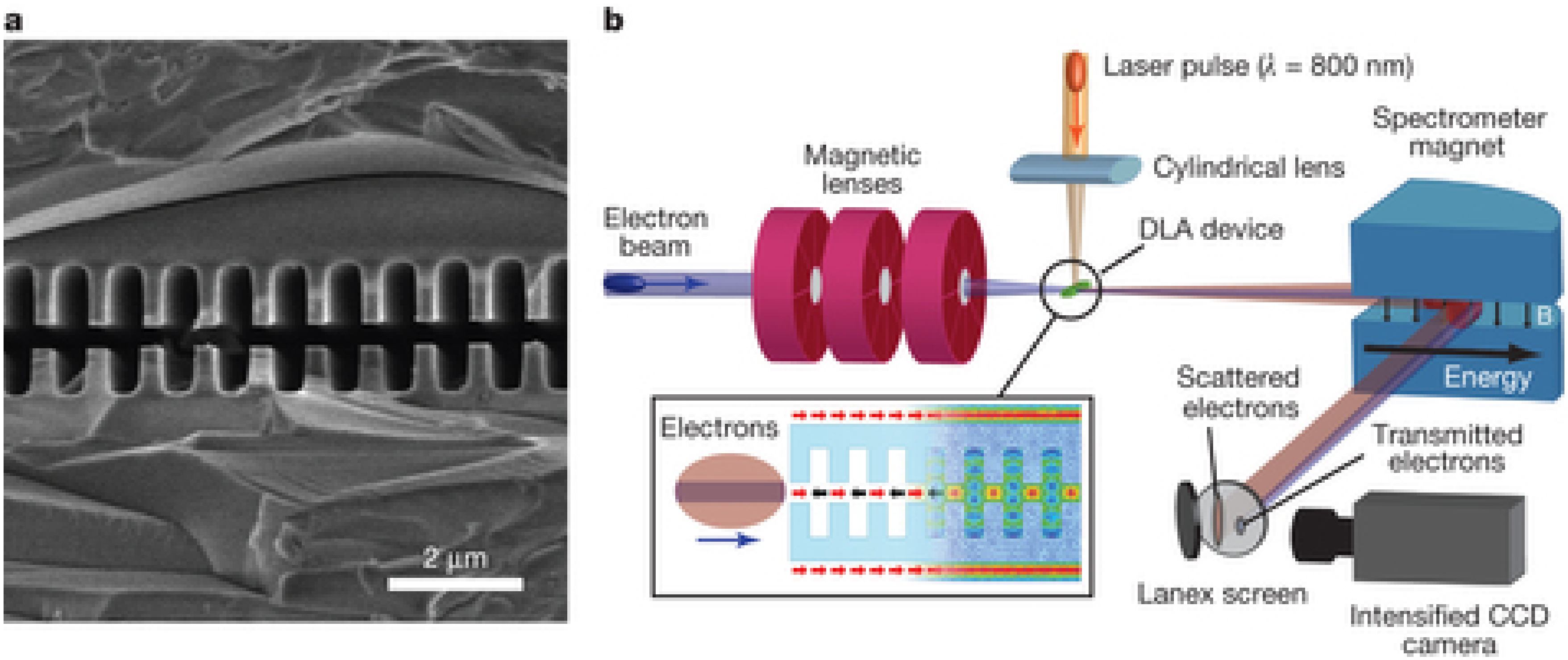
T. PLETTNER, P. LU, AND R. L. BYER Phys. Rev. ST Accel. Beams 9, 111301 (2006)



Demonstration of electron acceleration in a laser-driven dielectric microstructure

Peralta et al., Nature 503, 91, (2013)

Accelerating field >250 MV/m



Eur. Phys. J. ST **223**, 1197–1206 (2014)

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Let us go full plasma

- iCAN provides echelons of coherent laser pulses
- Intensities well above 10^{16} W/cm^2
- **Sustained** accelerating rates of 100 GV/m and above become possible
- Resonant and free streaming plasma structures can be discussed

The future is fiber accelerators

G. Mourou et al., Nature Photonics 2013

an echelon of mutually coherent laser pulses
→ revolution in laser technology

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Eur. Phys. J. ST **223**, 1197–1206 (2014)

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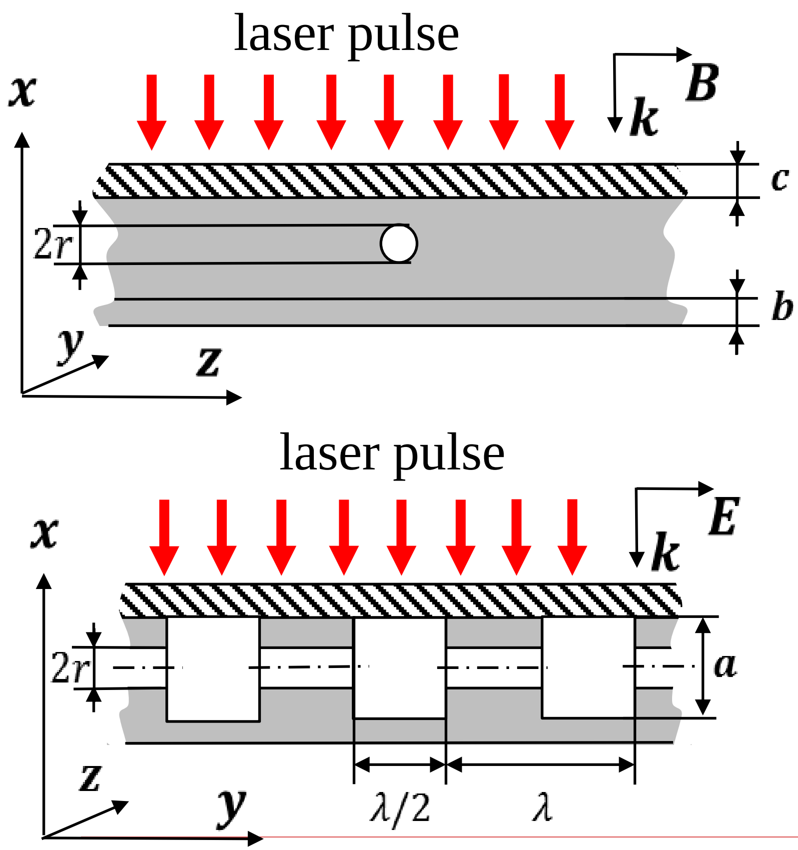
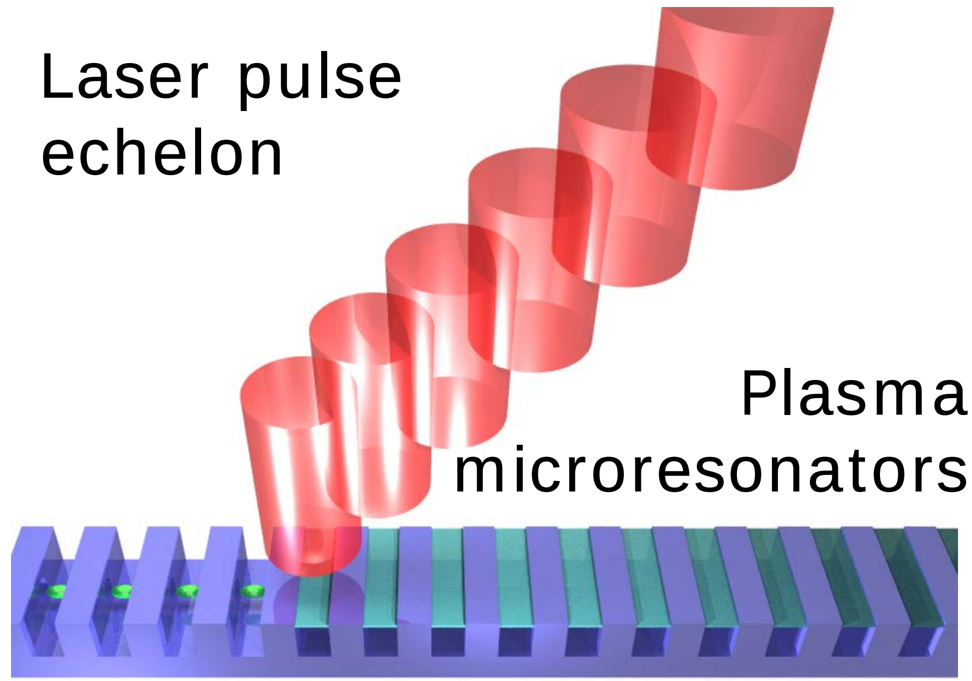
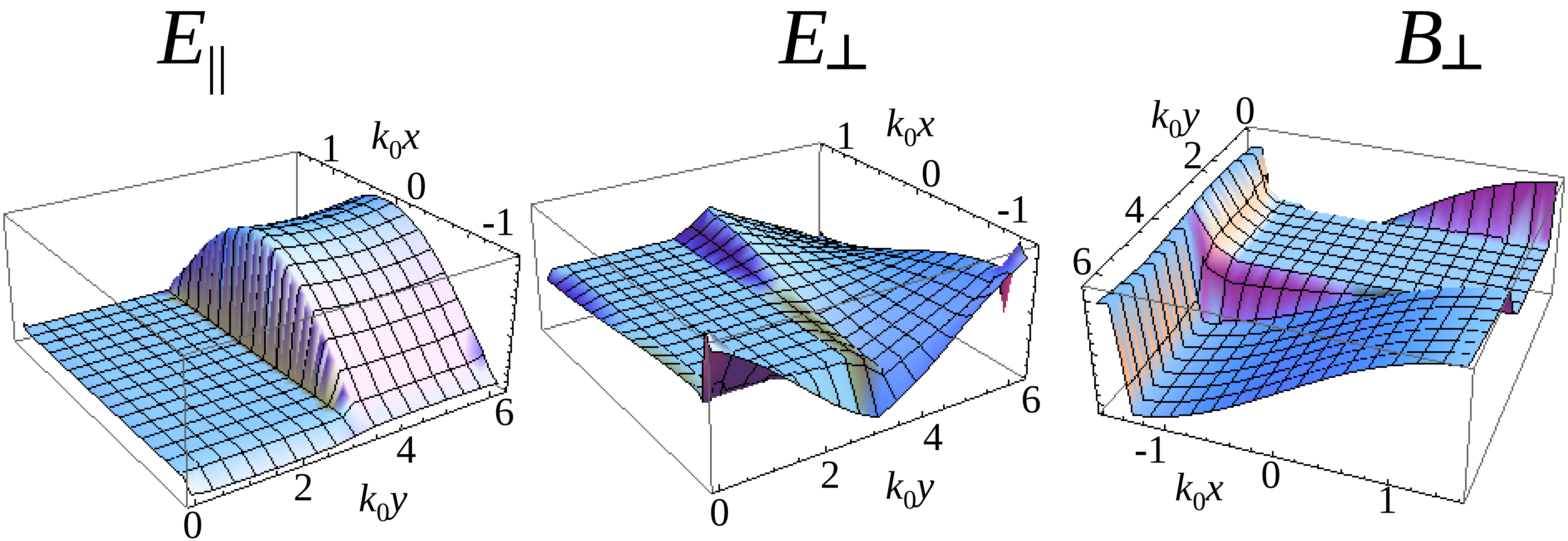
Resonant plasma structure





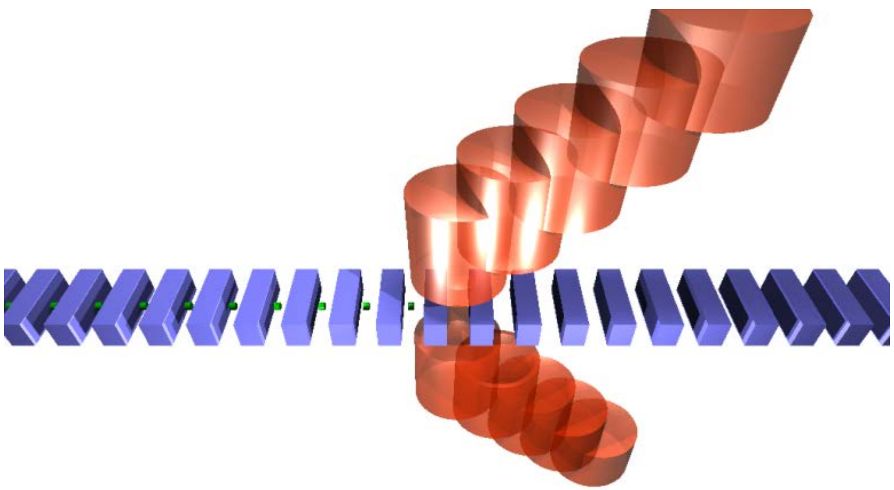
Eur. Phys. J. ST **223**, 1197–1206 (2014)

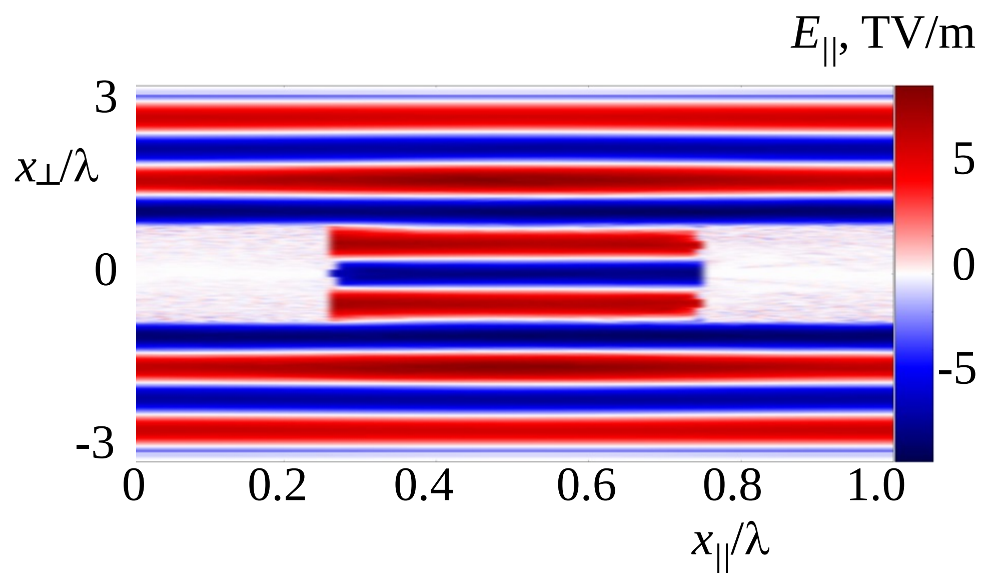
Fields in the resonant plasma cavity



Eur. Phys. J. ST **223**, 1197–1206 (2014)

Open plasma structures: multi TV/m fields are feasible





Two counter-propagating laser echelons and a periodic plasma structure

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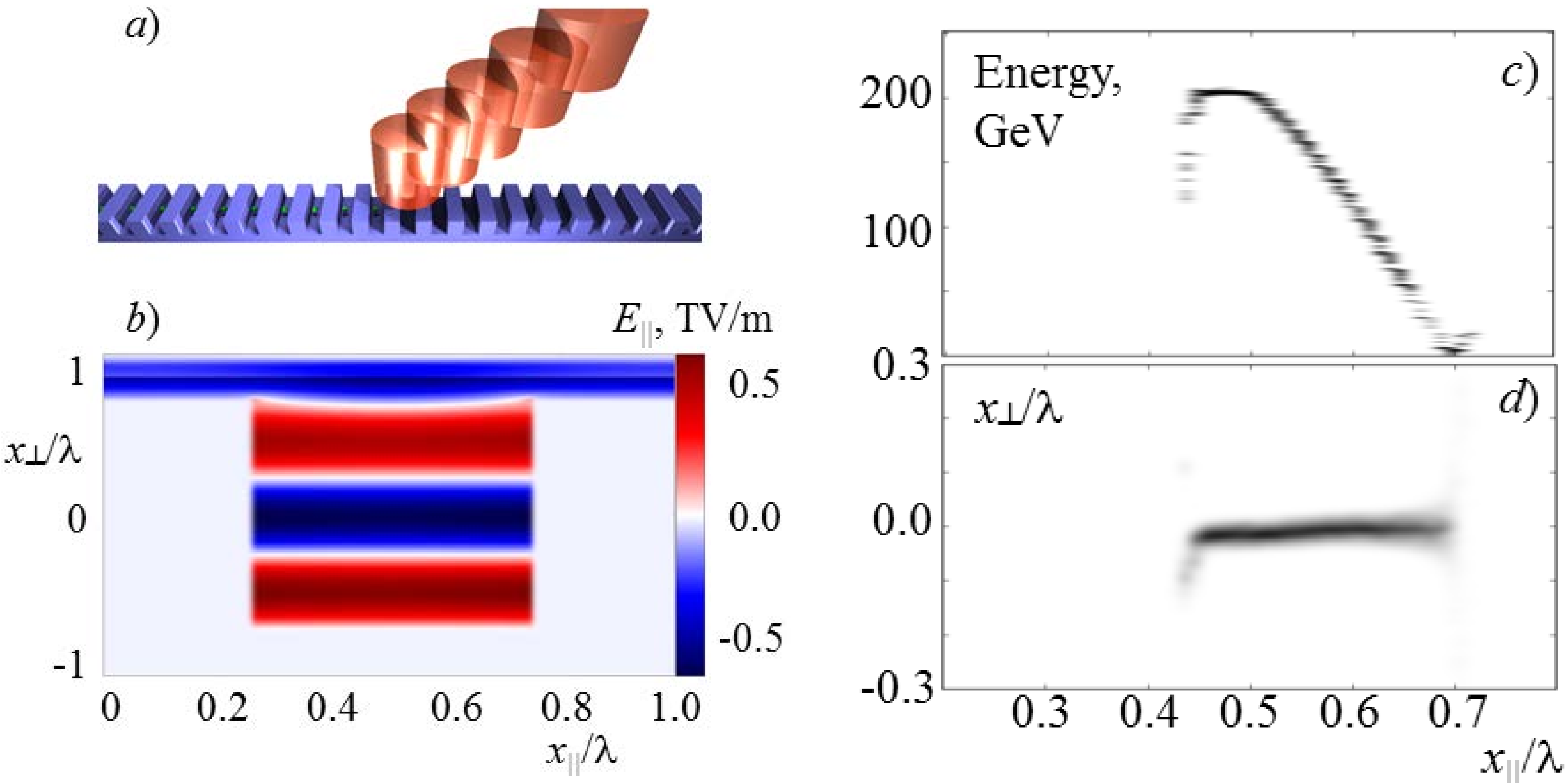
Plasma structure on a substrate



Eur. Phys. J. ST **223**, 1197–1206 (2014)

Plasma structure on a substrate

Eur. Phys. J. ST **223**, 1197–1206 (2014)

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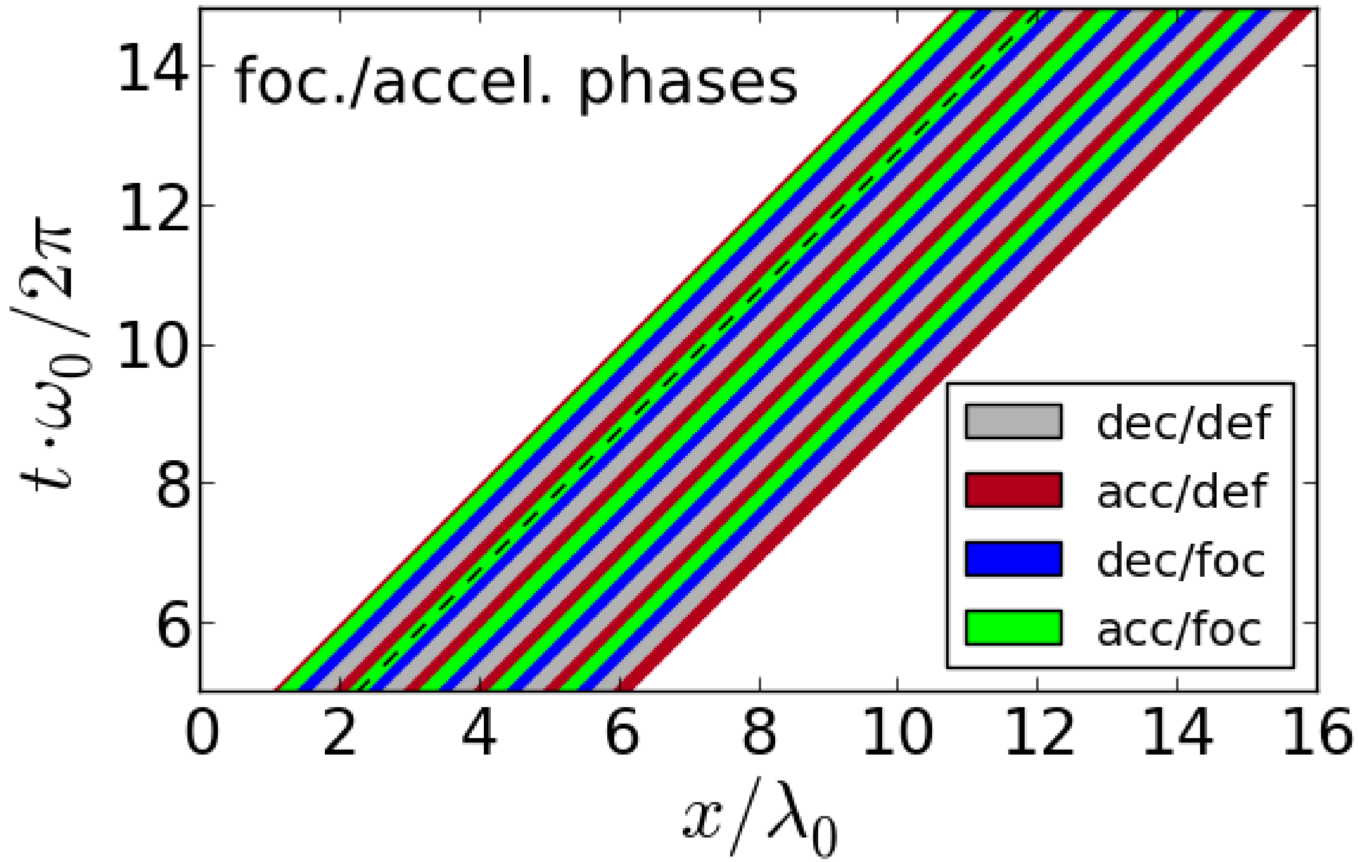
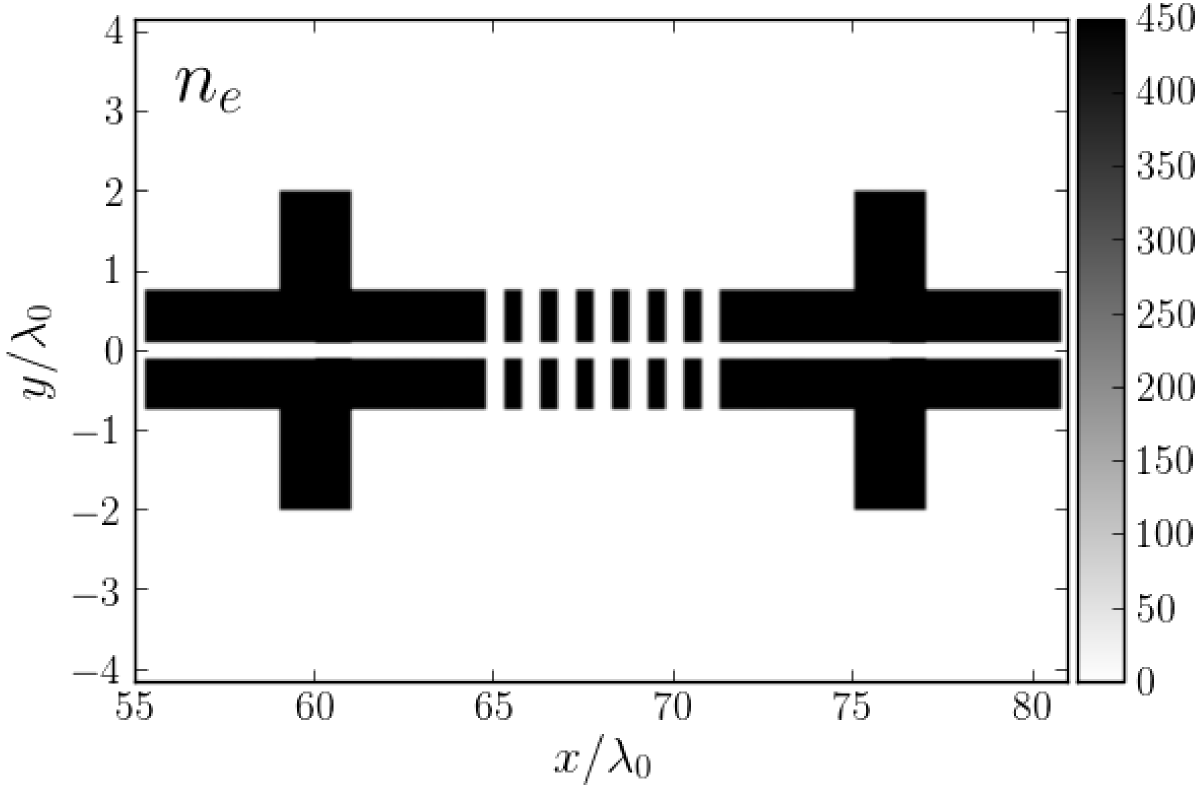
Accelerating and focusing phases



Eur. Phys. J. ST **223**, 1197–1206 (2014)

Plasma structure for multiple pulses

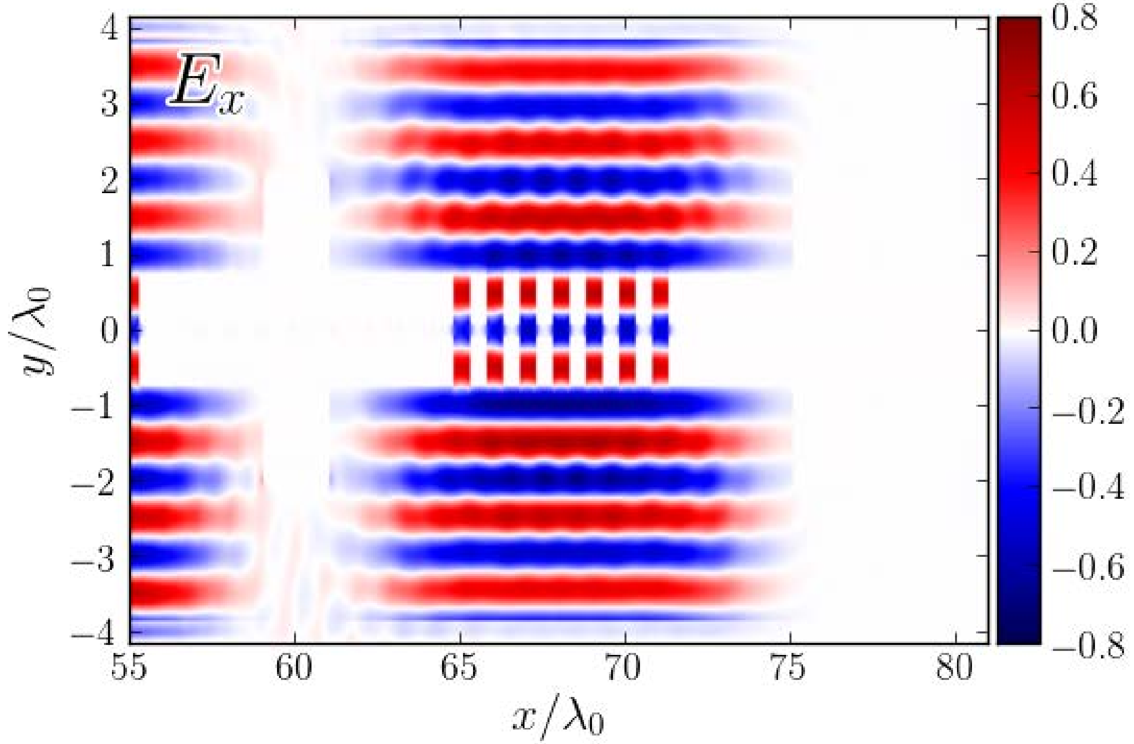


pukhov@tp1.uni-duesseldorf.de

Eur. Phys. J. ST **223**, 1197–1206 (2014)

Plasma structure for multiple pulses

Accelerating field



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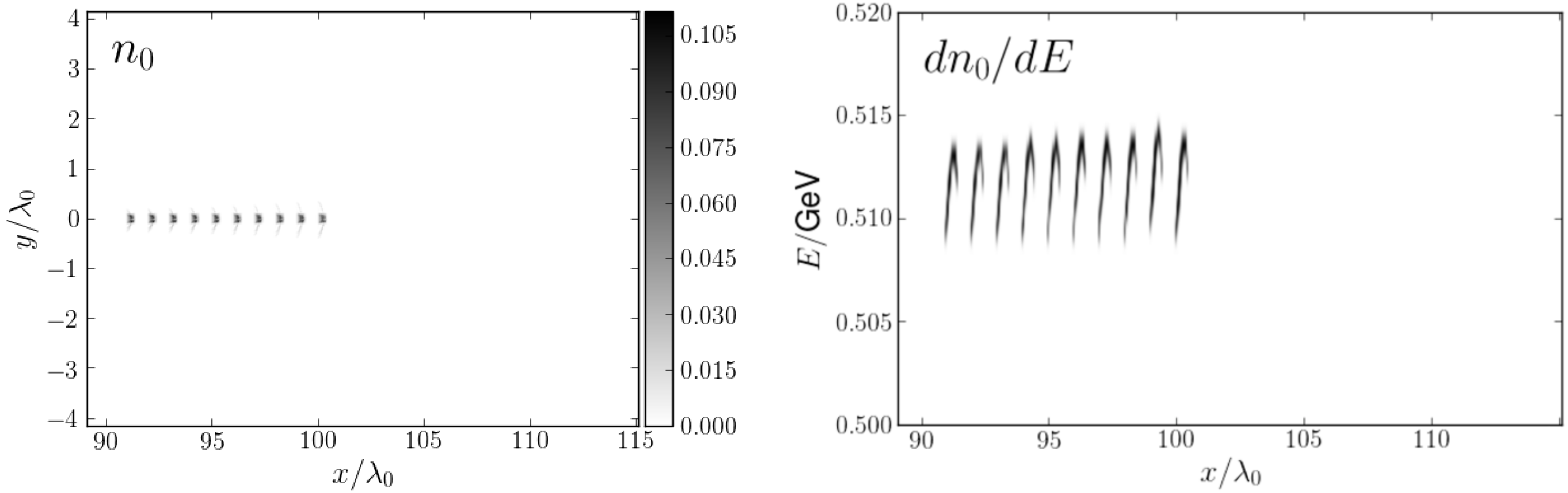
Plasma structure for multiple pulses

Particle beam



pukhov@tp1.uni-duesseldorf.de

Summary

- **Wake field plasma accelerators have sustained acceleration gradients ~GV/m**
- **Hollow plasma channels are better for acceleration: no collisional scattering**
- **Coherent electron acceleration in plasma structures may lead to sustained TV/m gradients**