

High quality electron acceleration in deep plasma channels

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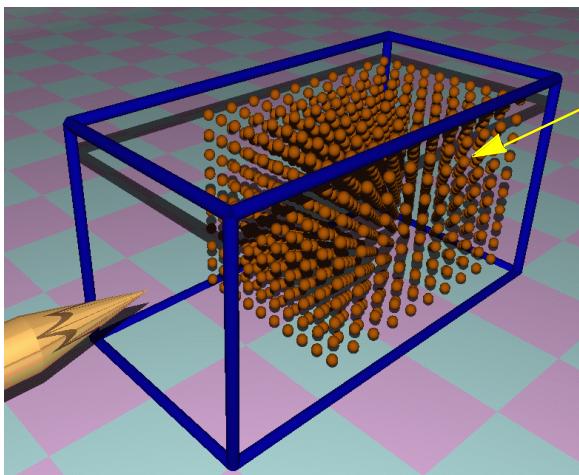
LA3NET, Mallorca, 2015

Outline

- **Laser-Plasma Wake Field Acceleration:
the Bubble regime**
- **Problems of the Bubble regime in uniform plasma:
broad energy spectra, limited energy gain**
- **Bubble in a deep plasma channel:
reversed fields and high quality acceleration**
- **New scaling laws for deep plasma channels:
much higher energy gains per Joule laser energy**

Virtual Laser Plasma Lab

A. Pukhov, J. Plasma Phys. **61**, 425 (1999)



Plasma or neutral gas

Gas of an arbitrary element can be used.

The code VLPL is written in C++, object oriented,
parallelized using MPI for **Massively Parallel** performance
 10^9 particles and 10^8 cells can be treated

Advanced physics & numerics

Fields

$$\nabla \times \mathbf{B} = \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c} \mathbf{j}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

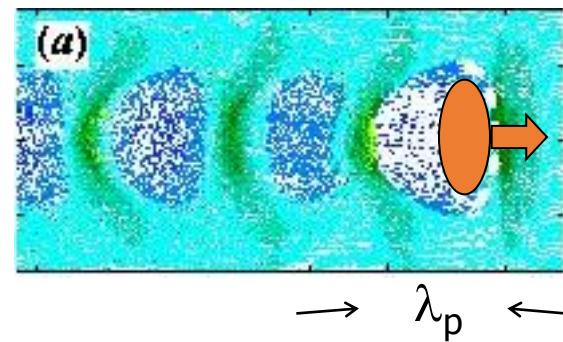
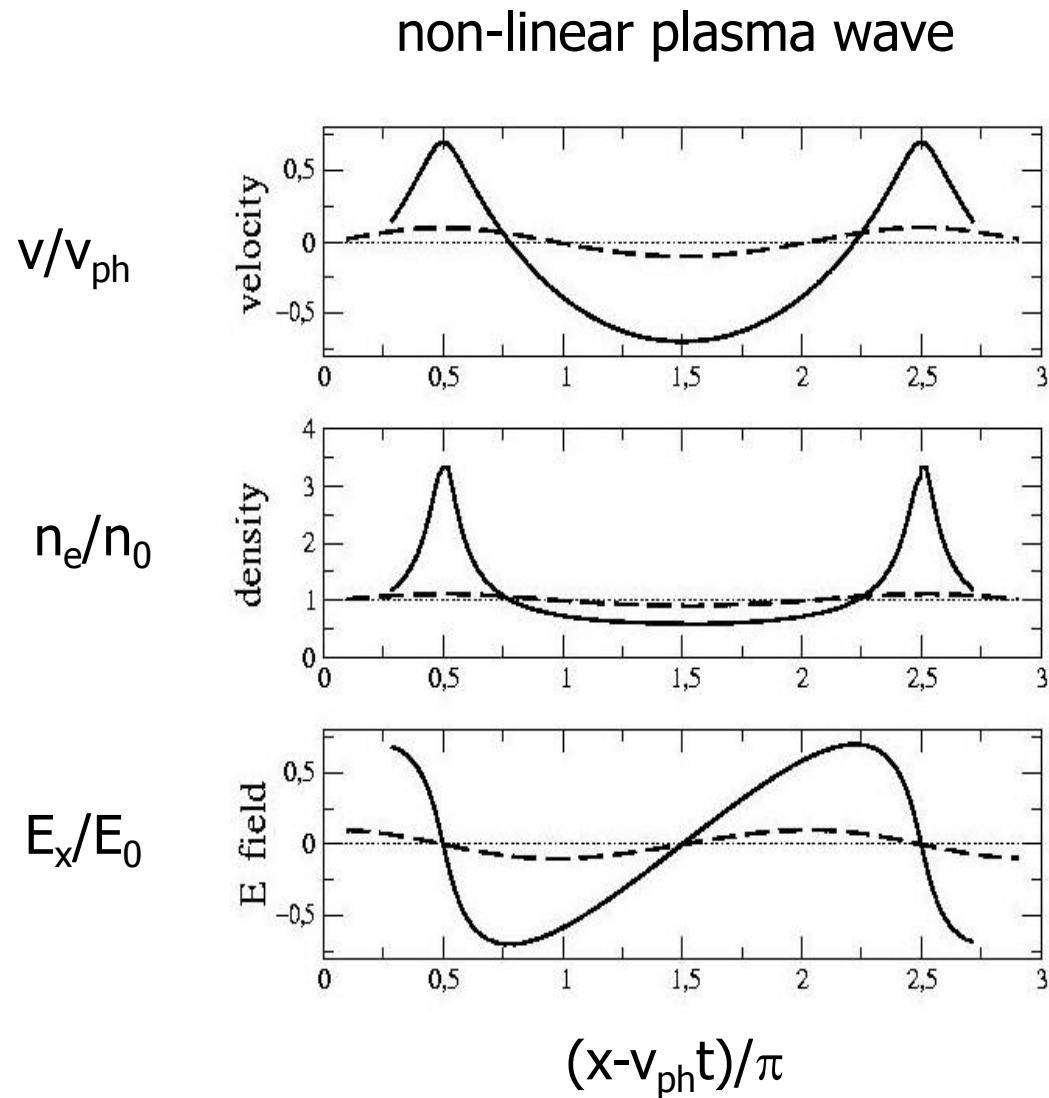
Particles

$$\frac{d\mathbf{p}}{dt} = q\mathbf{E} + \frac{q}{c\gamma} \mathbf{p} \times \mathbf{B}$$

$$\gamma = \sqrt{1 + \frac{p^2}{(mc)^2}}$$

- Inelastic processes
- QED, radiation damping
- hybrid hydro model
- quasi-static approximation
- Lorentz boost

Wakefield excitation



Laser pulse

$$v_g^{\text{Las}} = v_{ph}^{\text{plas}}$$

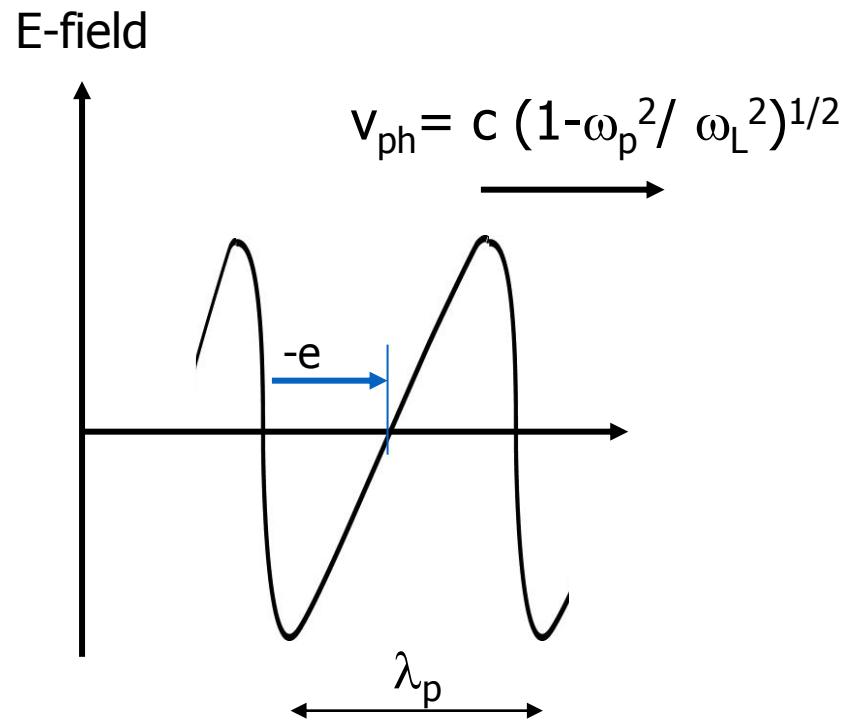
$$eE_{\parallel} \cong \frac{\delta n}{n} mc \omega_p = \frac{\delta n}{n} \cdot \sqrt{\frac{n_e}{10^{14} \text{ cm}^{-3}}} \text{ GV/m}$$

$$\omega_p^2 = \frac{4\pi e^2 n_e}{m_e}$$

$$\lambda_p = 1 \text{ mm} \cdot \sqrt{\frac{1 \cdot 10^{-15} \text{ cm}^{-3}}{n_e}}$$

Wakefield acceleration

Tajima, Dawson, PRL43, 267 (1979)



Plasma wave γ -factor

$$\gamma_{ph} = (1 - v_{ph}^2/c^2)^{-1/2} = \omega_p / \omega_L$$

Limiting factors

Maximum energy gain

$$\mathcal{E}_{max} = eE_{max} \min(L_d, L_L)$$

Dephasing length

$$L_d \approx \gamma_{ph}^2 \lambda_p$$

Laser depletion length

$$L_L \approx W_L / (R_L E_{max})^2$$

Wave breaking



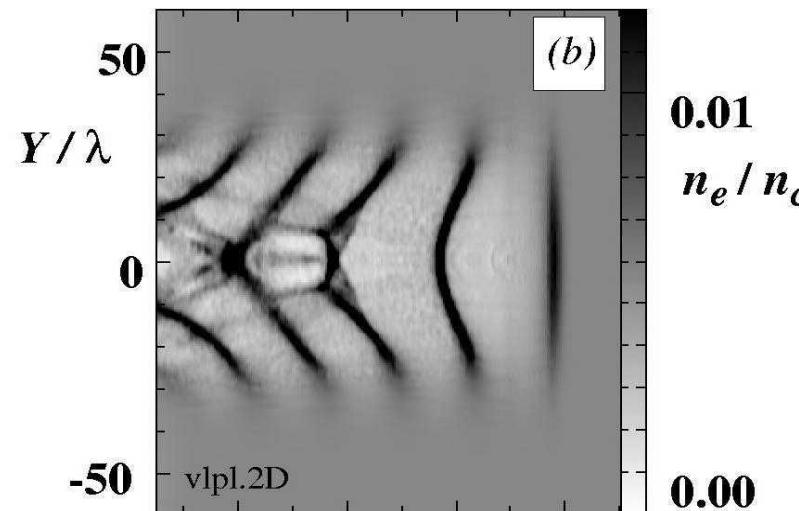
2D wave breaking

Bulanov Pegoraro Pukhov Sakharov
PRL 78 (1997)

Wave breaking E-field

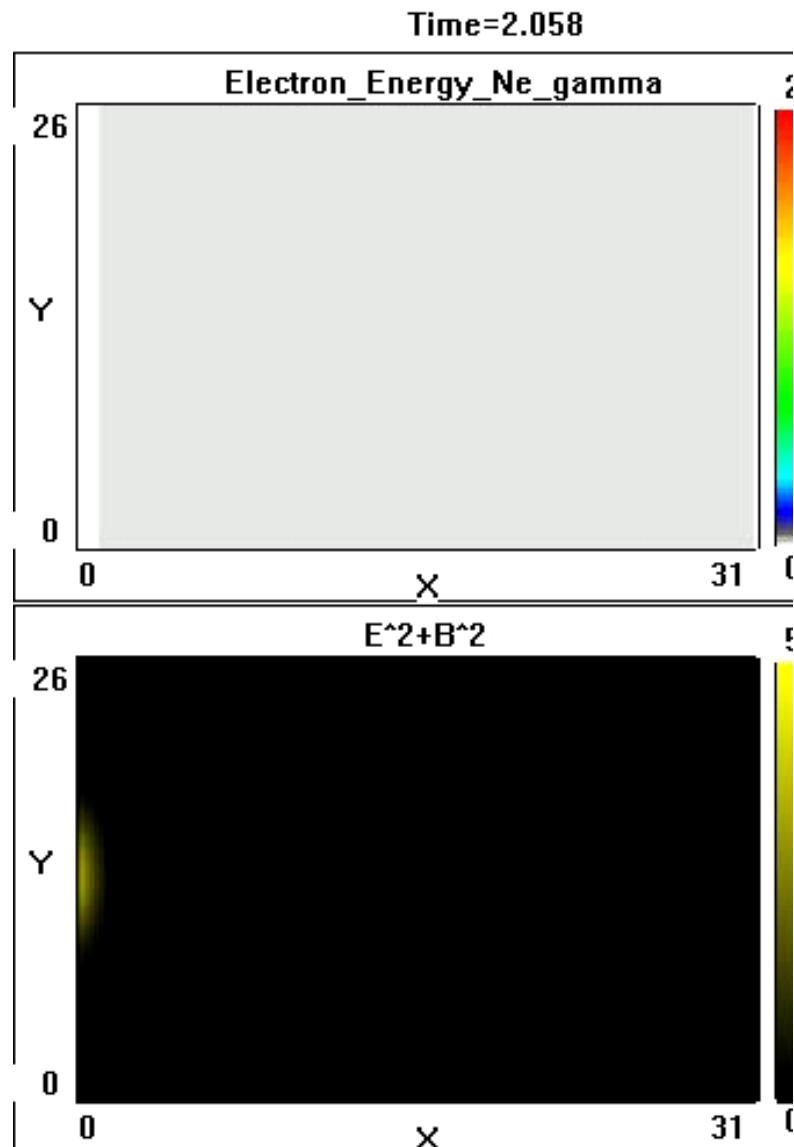
$$E_{wb} / E_0 = \sqrt{2(\gamma_{ph} - 1)} \propto \sqrt{\omega_L / \omega_p}$$

Akhieser, Polovin (1956)

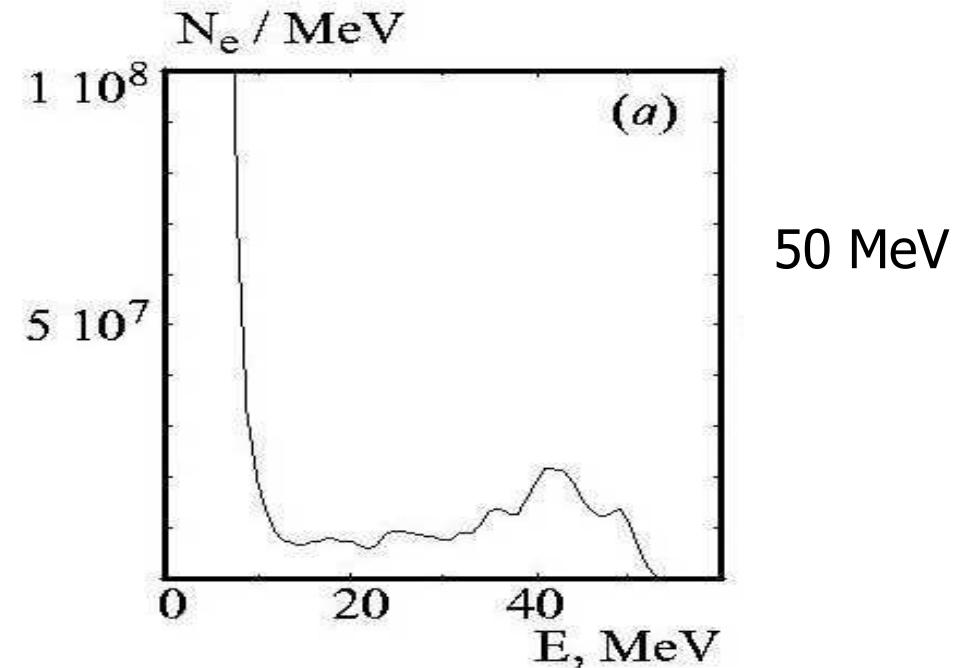


Wakefield acceleration

electron density



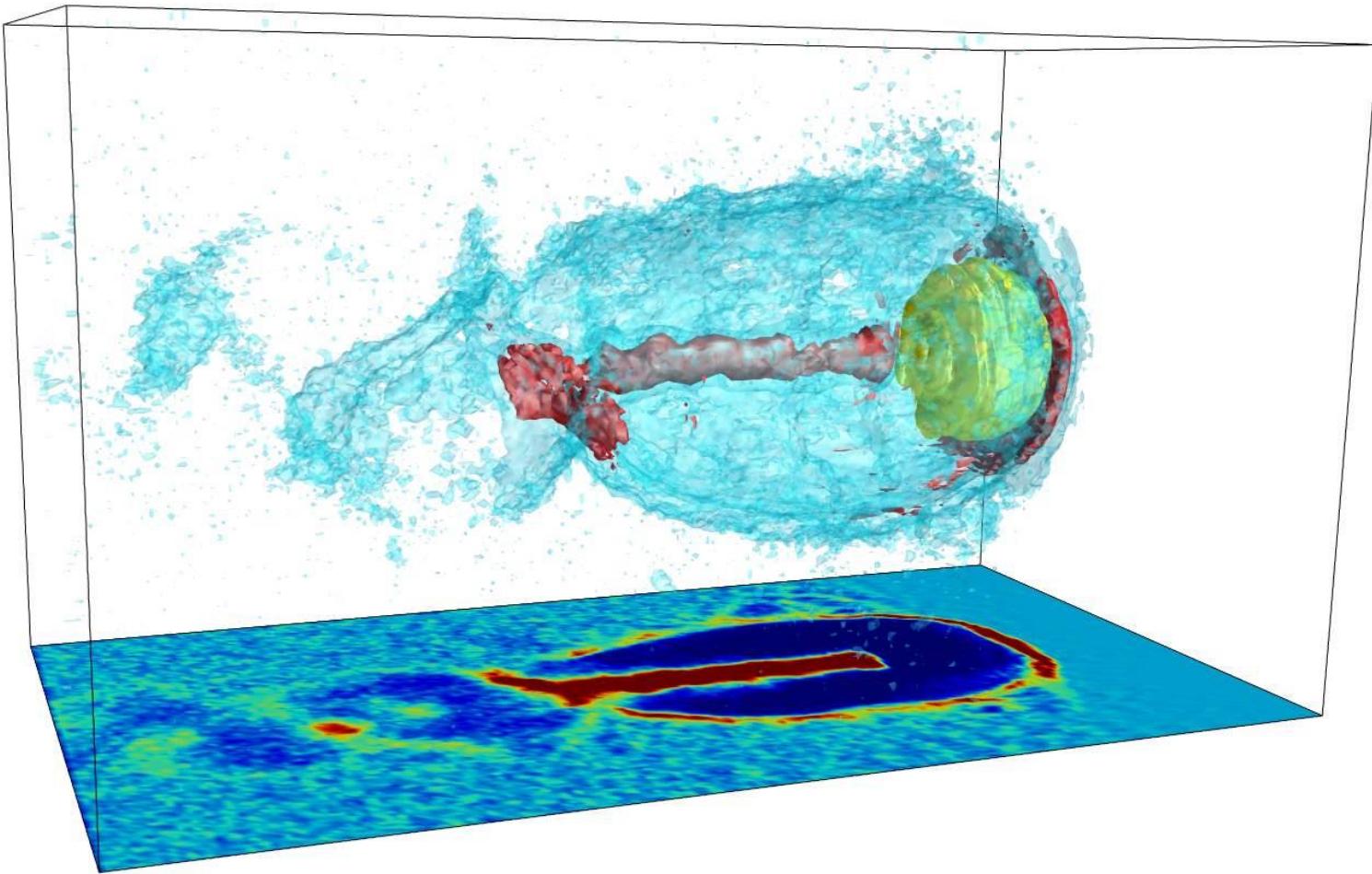
laser intensity



$10 < \gamma < 100$
 10^9 electrons
ang. spread : $\pm 1^\circ$
 $\gamma \epsilon_\perp < \pi \text{ mm mrad}$
conv. eff. : 15 %

Laser bubble acceleration

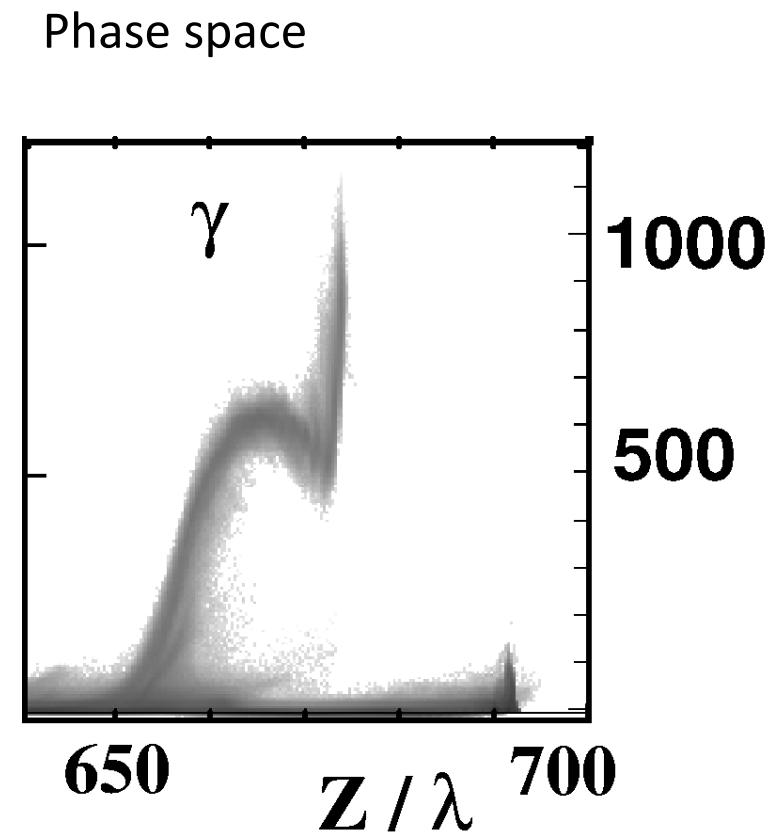
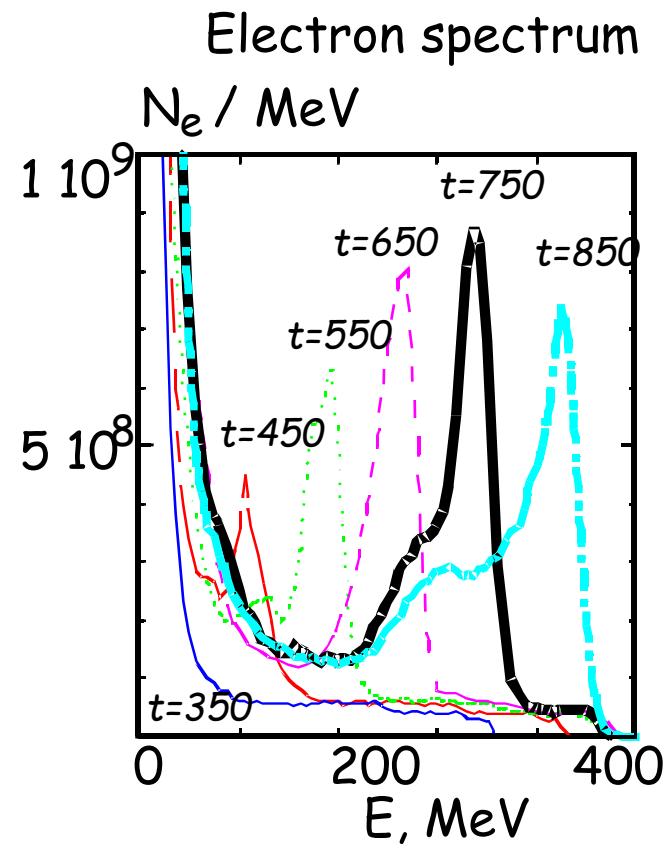
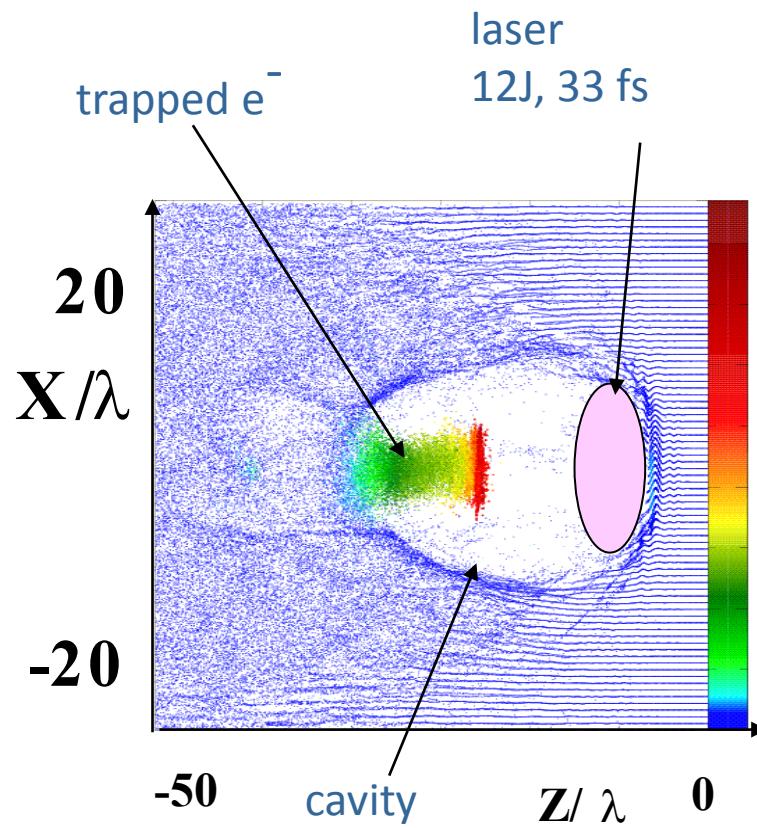
Pukhov & Meyer-ter-Vehn Appl. Phys. B **74**, pp. 355-361 (2002)



Bubble regime:

Ultra-relativistic laser, $I=10^{20} \text{ W/cm}^2$:

A.Pukhov & J.Meyer-ter-Vehn, *Appl. Phys. B*, **74**, p.355 (2002)

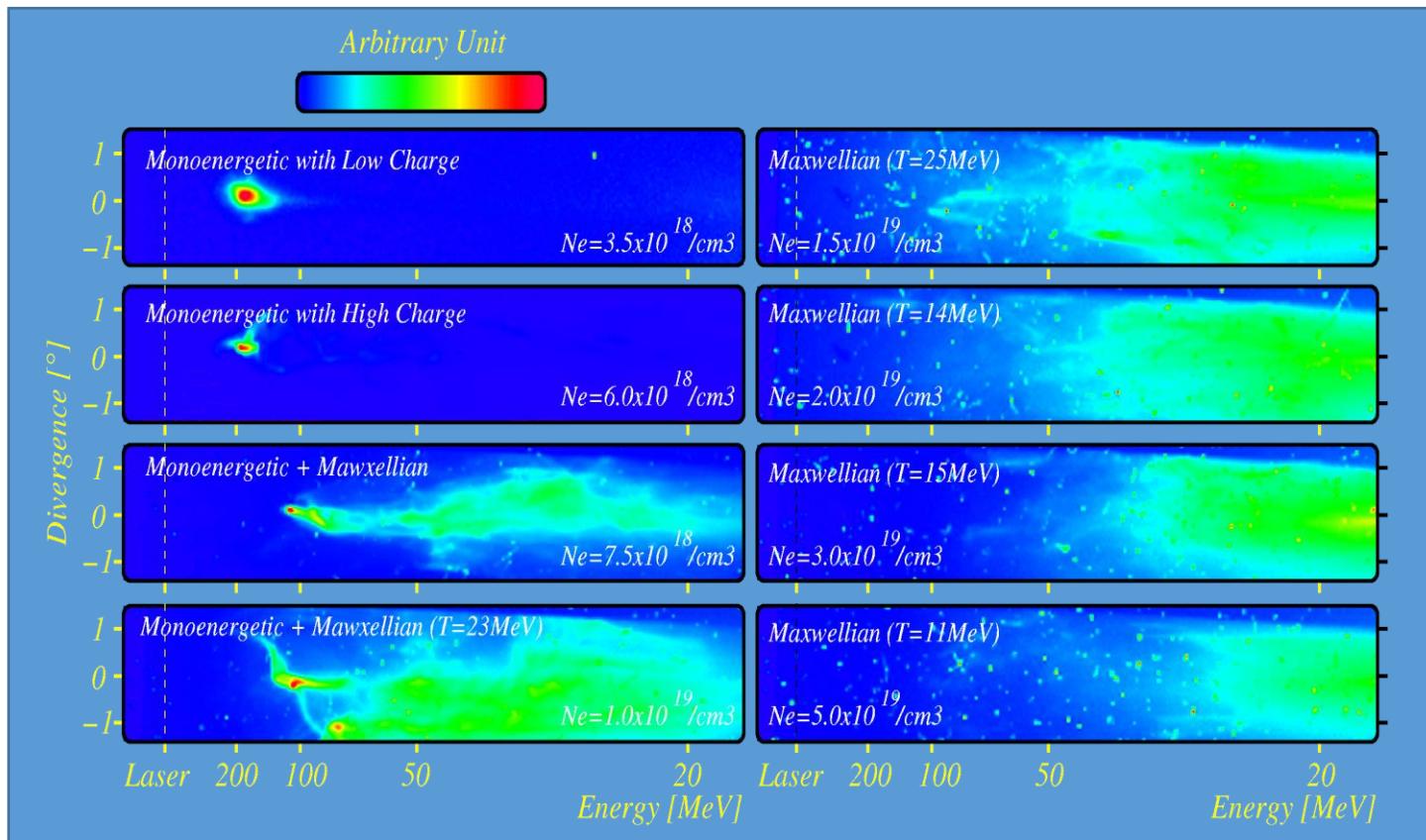


Accelerators go compact

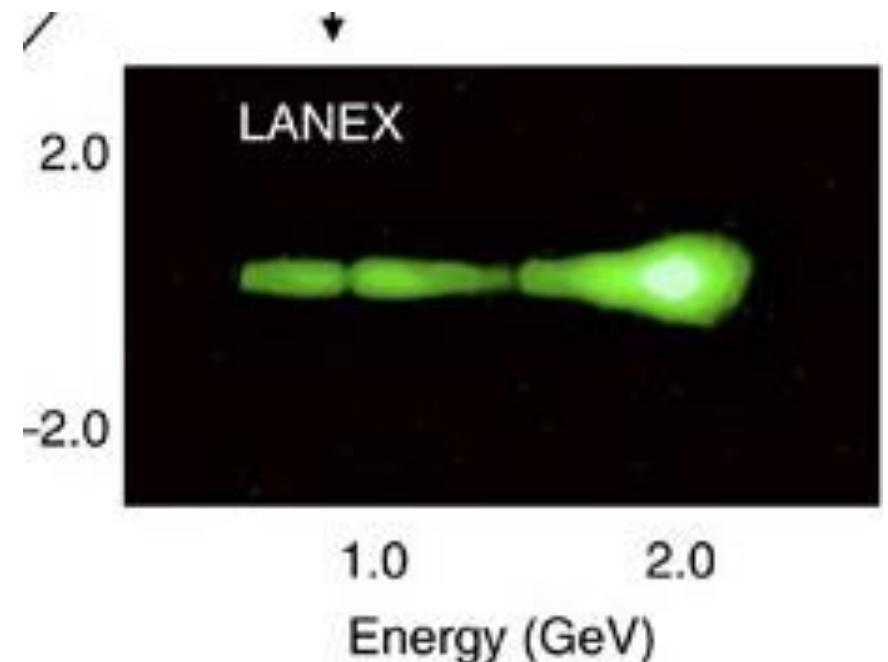
Mangles et al, Rutherford:
70 MeV beam

Geddes et al, LBNL:
85 MeV beam

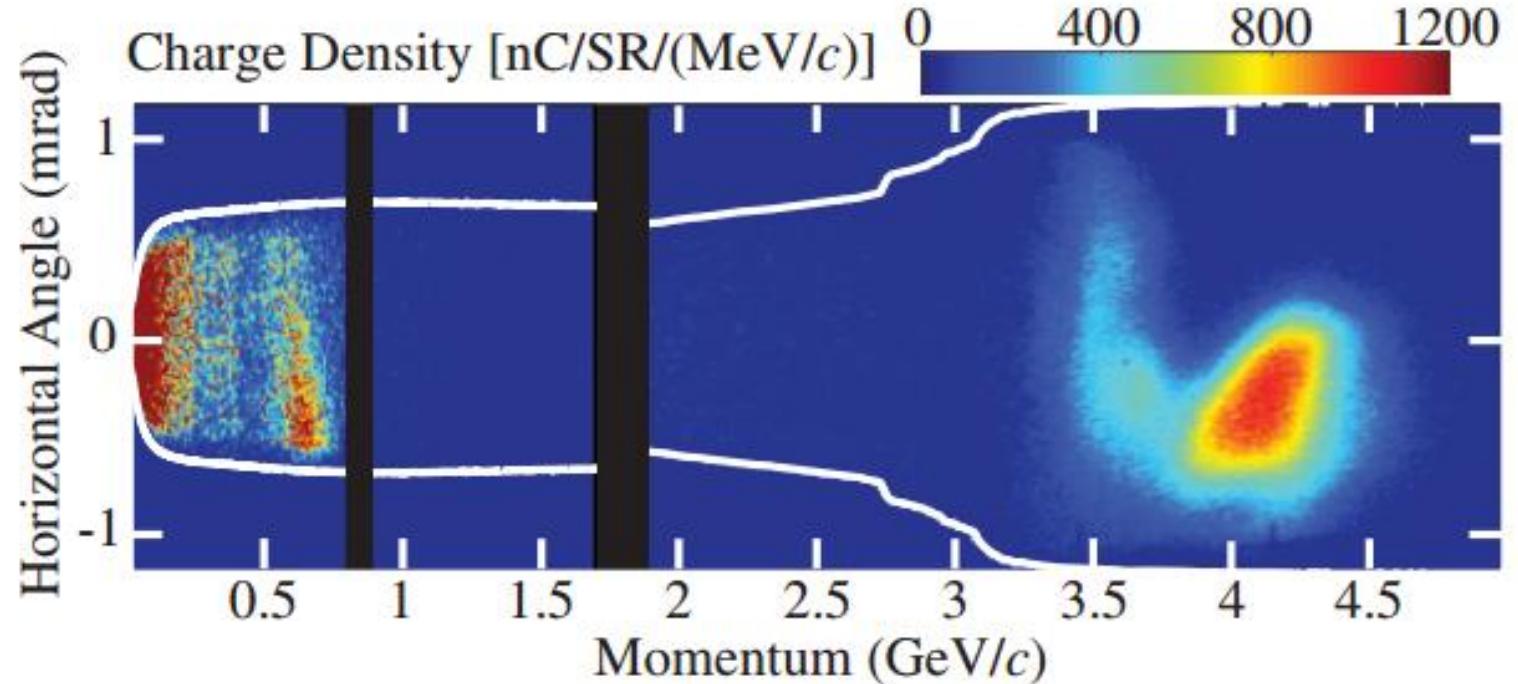
Faure et al, LOA:
170 MeV beam



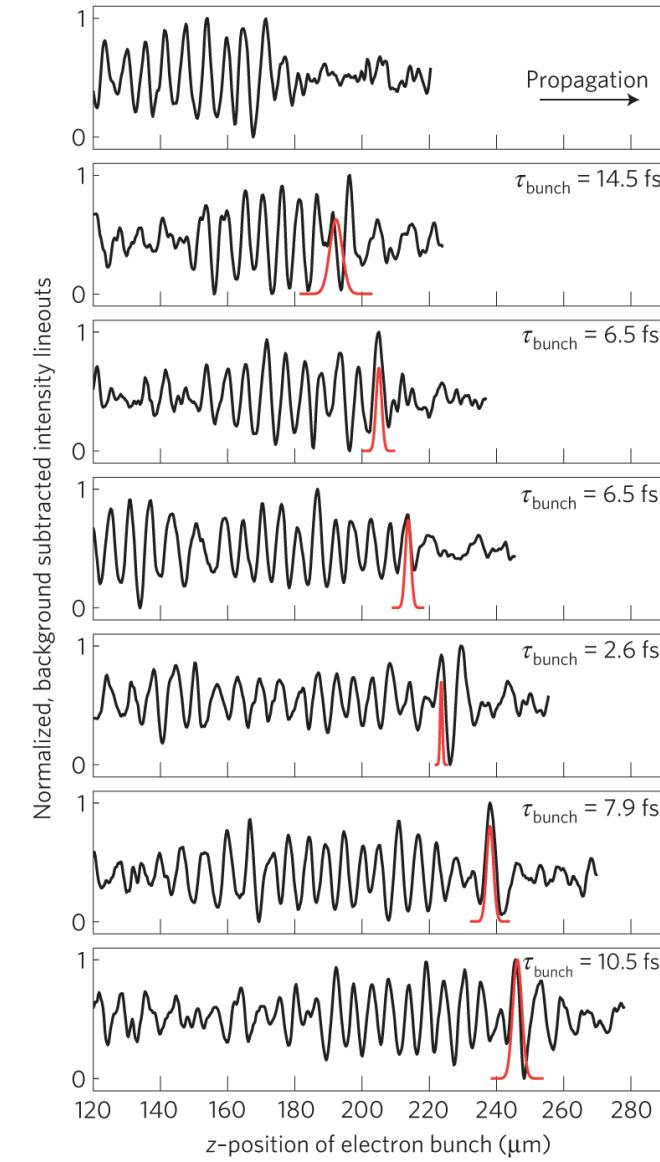
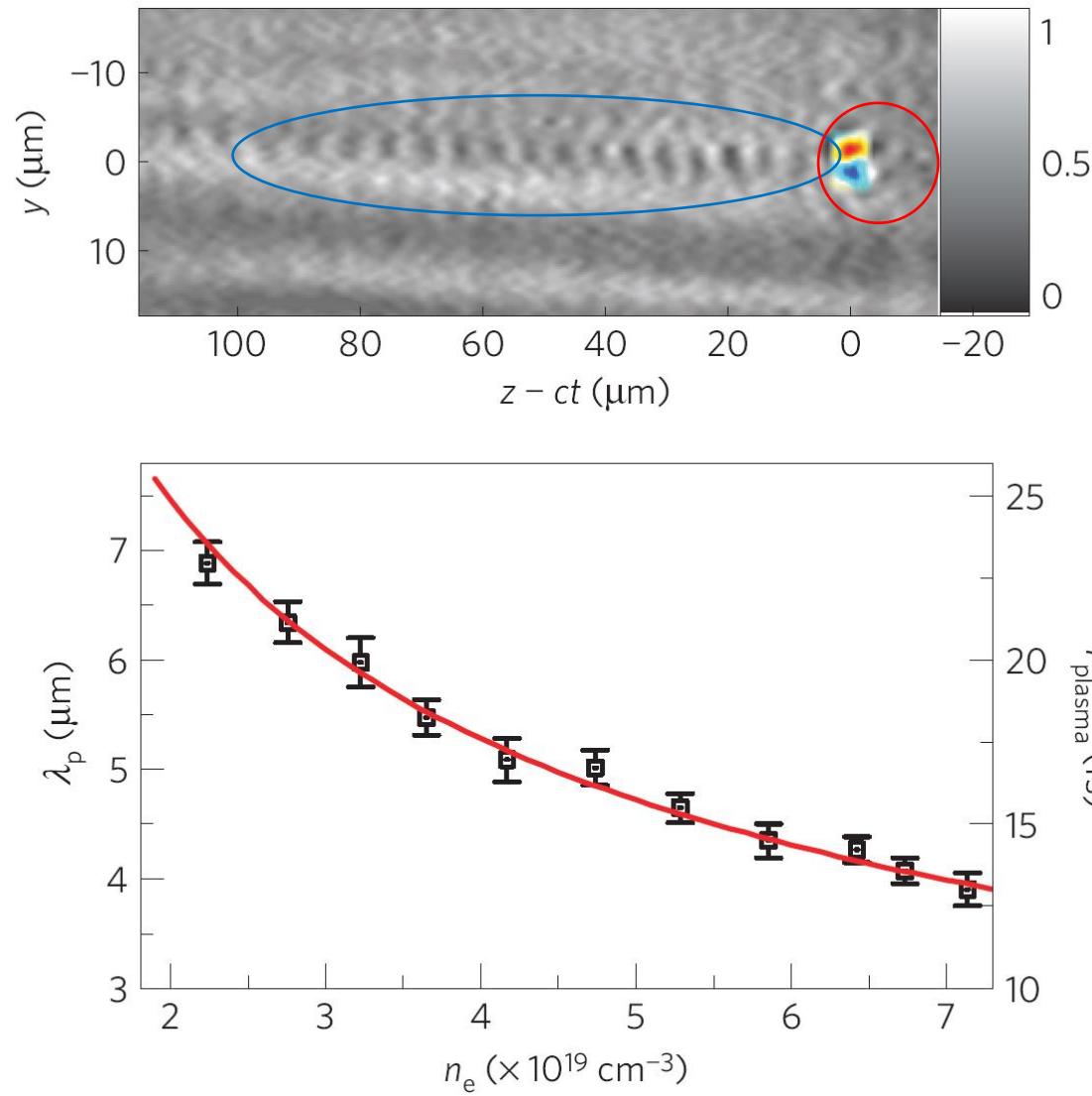
Texas PetaWatt: 2 GeV electrons
Nature Communications 4, 1988 (2013)



LBNL: 4.2 GeV
Phys. Rev. Lett. 113,
245002 (2014)



Snapshot of a bubble



S -Similarity for Relativistic Plasmas

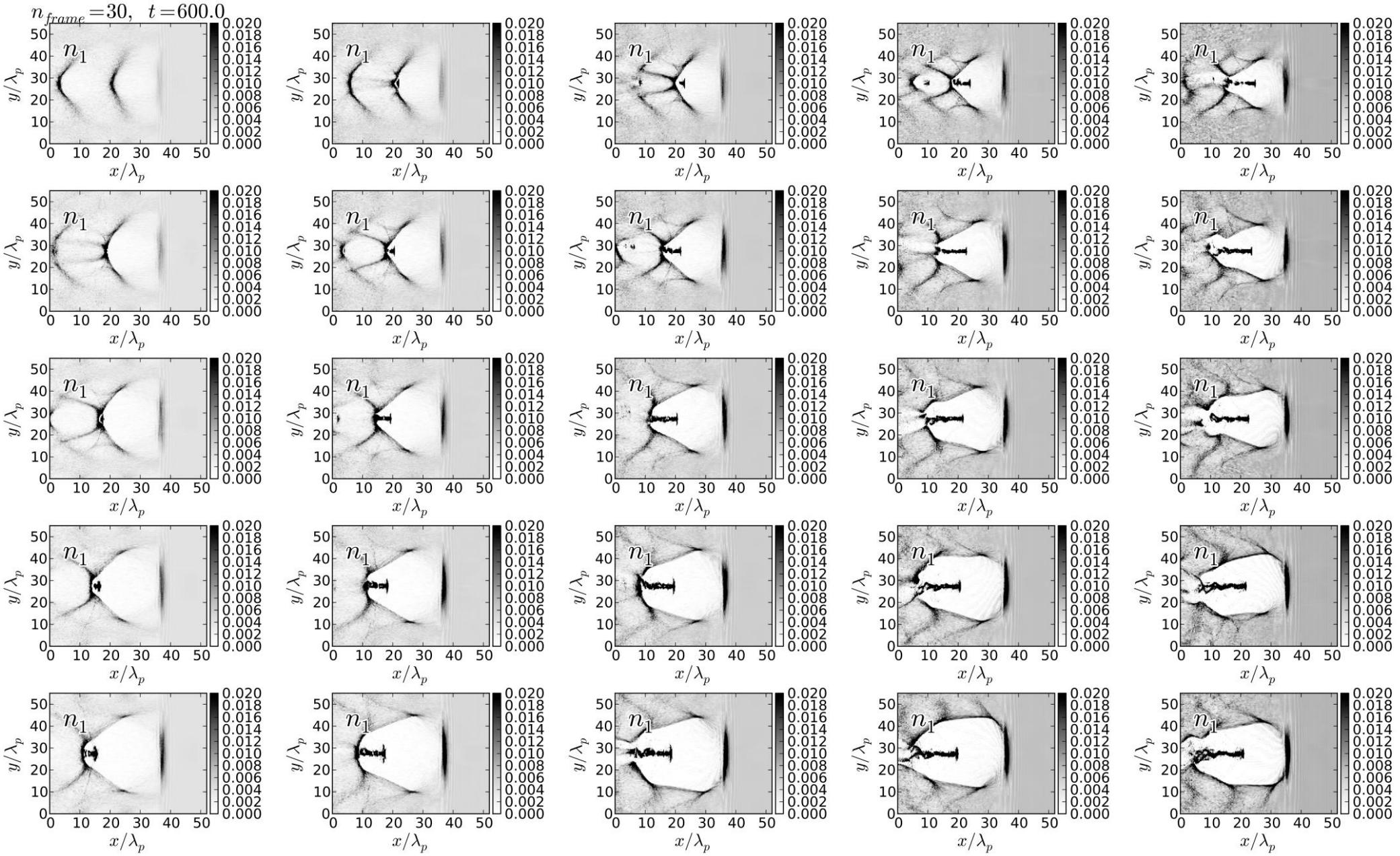
Gordienko, Pukhov, *Phys. Plasmas* **12**, 043109 (2005)

Ultra-relativistic laser plasmas, $a \gg 1$,
have the similarity parameter

$$S = \frac{n_e}{an_c}$$

Dynamics of plasmas with $S=const$ is similar.
The electron distribution function scales as

Families of bubbles



Scalable plasma cavity: the Bubble

Pukhov, Gordienko, Phil Trans. R. Soc. A, (2006) **364**, 623–633
A.Pukhov & J.Meyer-ter-Vehn, *Appl. Phys. B*, **74**, p.355 (2002)

Beam energy:

$$E_{\text{beam}} = 0.95mc^2 \sqrt{\frac{P}{P_{\text{rel}}}} \frac{c\tau}{\lambda}$$

Number
of accelerated electrons:

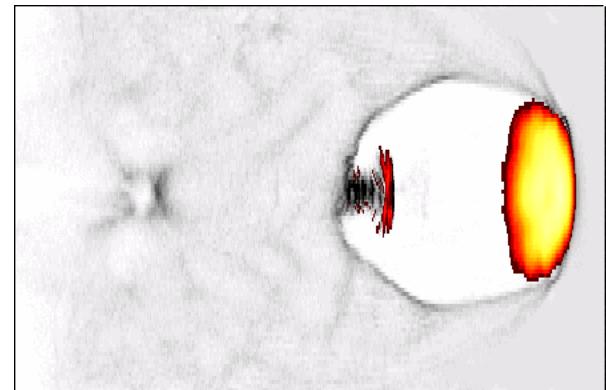
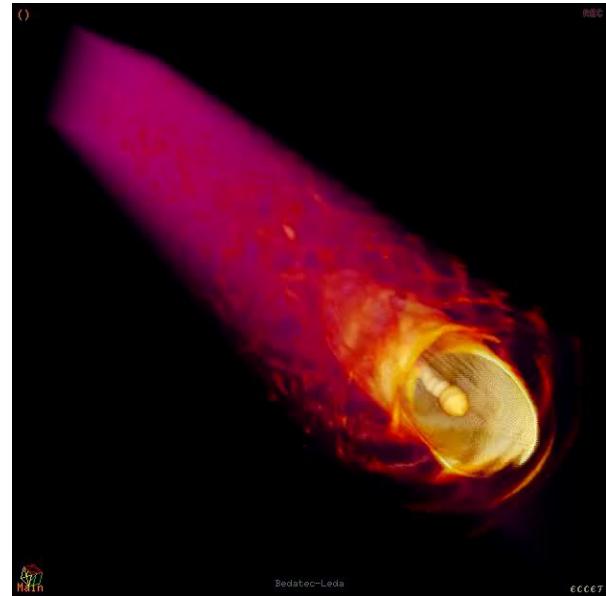
$$N_{\text{beam}} = \frac{1.8}{k_0 r_e} \sqrt{\frac{P}{P_{\text{rel}}}}$$

Acceleration
distance:

$$L_{\text{acc}} = 0.7 \frac{c\tau}{\lambda} Z_R = 0.5c\tau \frac{P}{a^2 P_{\text{rel}}}$$

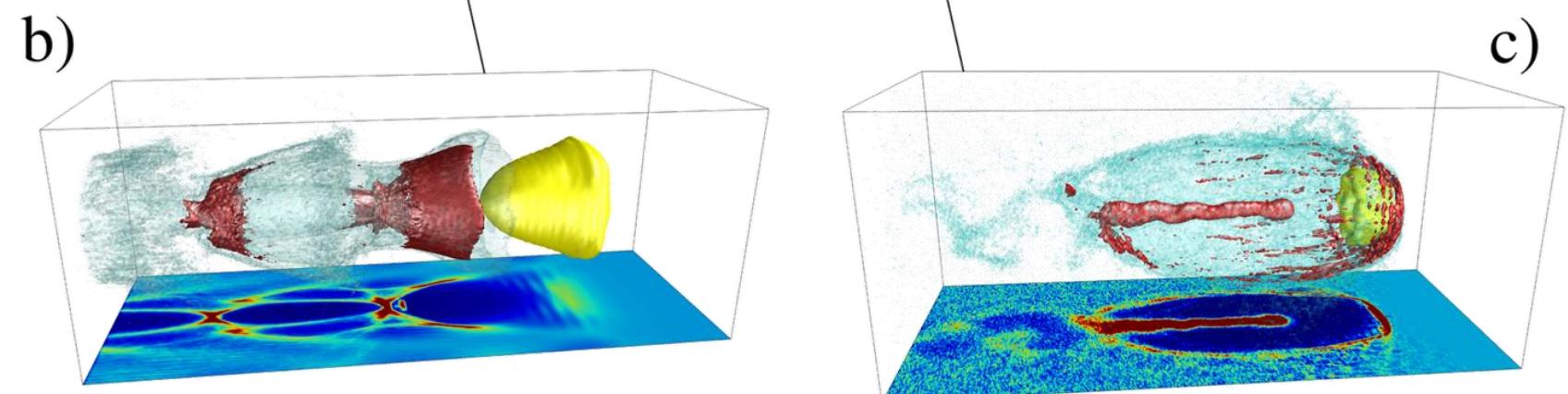
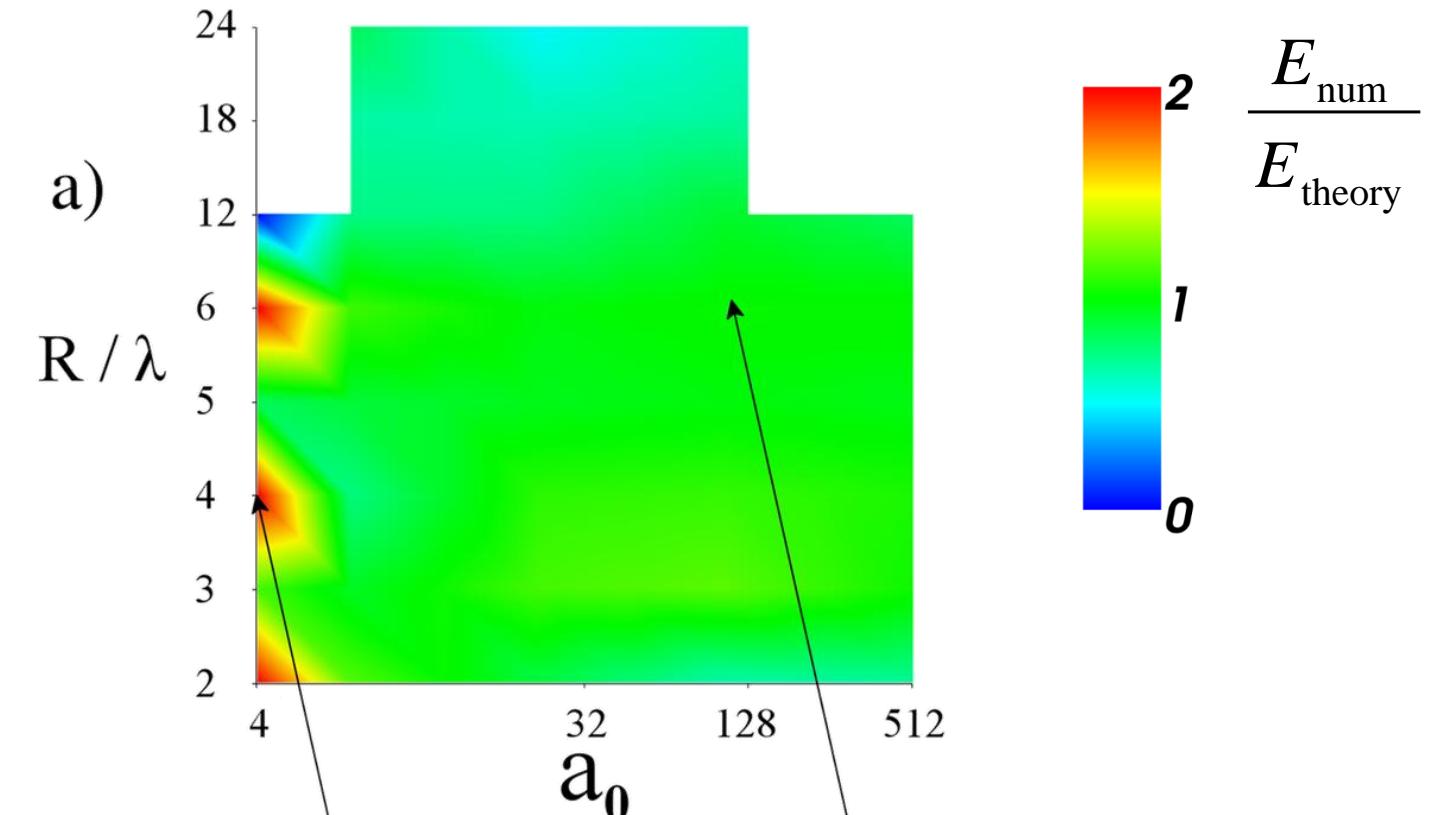
$$P_{\text{rel}} = \frac{m_e^2 c^5}{e^2} \approx 8.5 \text{ GW}$$

$$r_e = \frac{m_e c^2}{e^2} \approx 2.82 \cdot 10^{-13} \text{ cm}$$



Numerical test of the similarity scalings

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



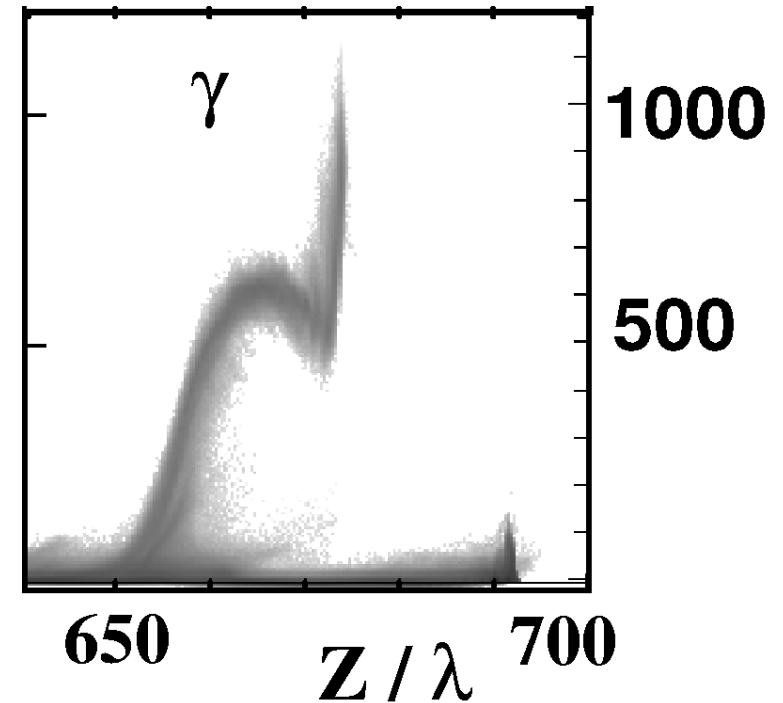
Bubble: reasonably high acceleration gradients have been demonstrated

The next step:
Quality of the accelerated electron bunches should be improved.

Betatron resonance: broadening of the spectrum

Betatron frequency: $\omega_\beta = \frac{\omega_p}{\sqrt{2\gamma}}$

Resonance condition: $\omega_0 \left(1 - \frac{v_{||}}{v_{ph}} \right) = \omega_\beta$



Bubble dilemma in uniform plasma

- Bubble fields are prescribed by the similarity theory
- The acceleration is limited by pulse energy depletion
- The longest pulses give the maximum energy gain

$$E_{\max} \propto \frac{2\pi}{\lambda_0} \sqrt{W_L e^2 \tau}$$

- When the laser fills the bubble, it interacts with the beam

Field-Reversed Bubble in Deep Plasma Channels for High-Quality Electron Acceleration

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²*Lobachevsky National Research University of Nizhni Novgorod, 603950 Nizhny Novgorod, Russia*

³*Institute of Applied Physics RAS, Nizhny Novgorod 603950, Russia*

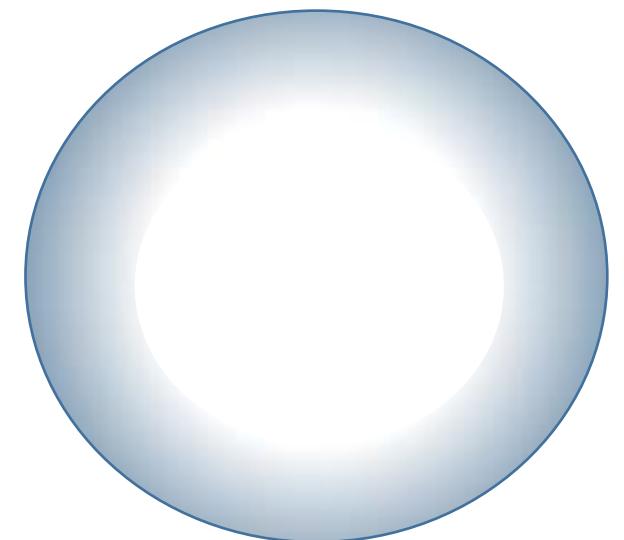
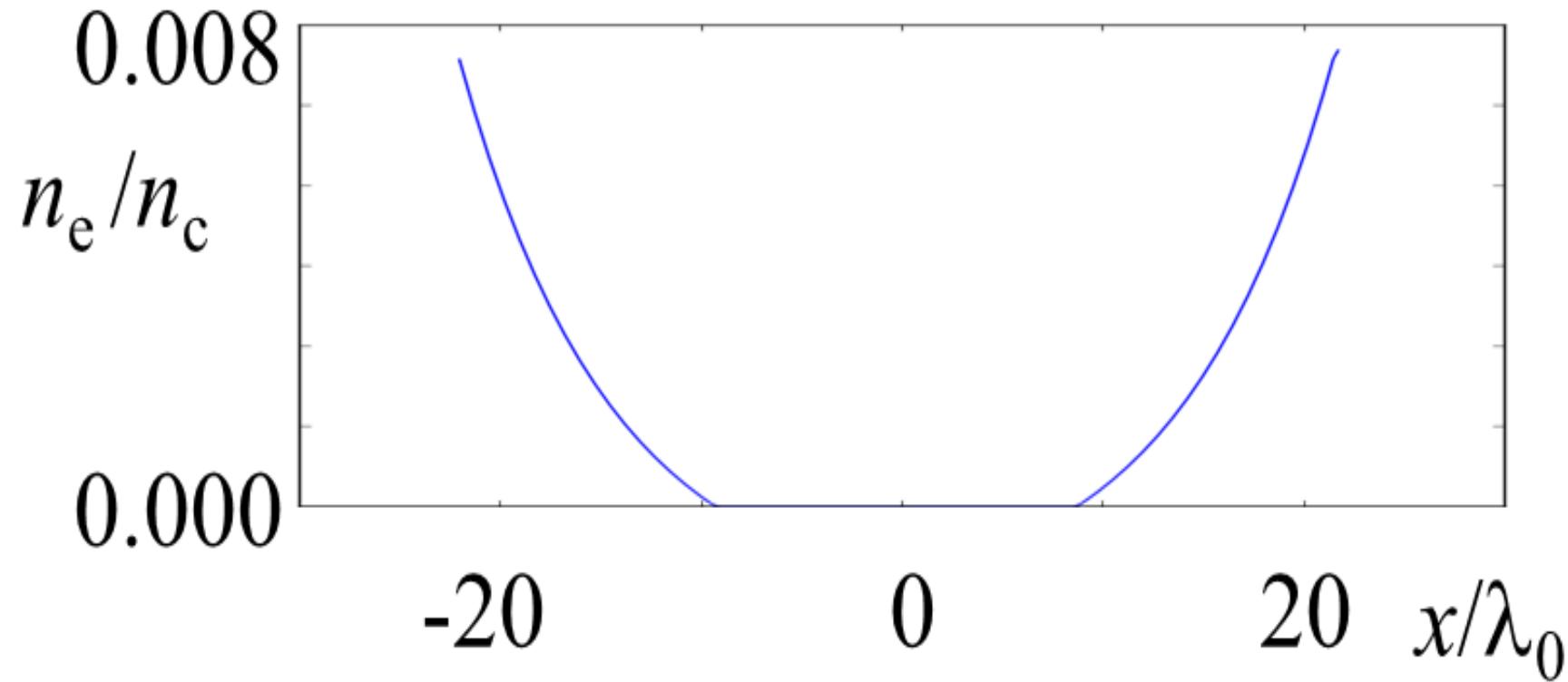
(Received 1 August 2014; published 11 December 2014)

We study hollow plasma channels with smooth boundaries for laser-driven electron acceleration in the bubble regime. Contrary to the uniform plasma case, the laser forms no optical shock and no etching at the front. This increases the effective bubble phase velocity and energy gain. The longitudinal field has a plateau that allows for monoenergetic acceleration. We observe as low as 10^{-3} rms relative witness beam energy uncertainty in each cross section and 0.3% total energy spread. By varying the plasma density profile inside a deep channel, the bubble fields can be adjusted to balance the laser depletion and dephasing lengths. Bubble scaling laws for the deep channel are derived. Ultrashort pancakelike laser pulses lead to the highest energies of accelerated electrons per Joule of laser pulse energy.

DOI: [10.1103/PhysRevLett.113.245003](https://doi.org/10.1103/PhysRevLett.113.245003)

PACS numbers: 52.38.Kd, 52.65.Rr

Breaking similarity chains:
deep plasma channels give us additional freedom



Fields in the channel can be adjusted
to balance depletion and dephasing

New scaling law for electron energy gain:

$$E_{\max} \propto \frac{2\pi}{\lambda} \sqrt{mc^2 W_L r_e R}$$

Wide, ultra-short
pancake-like pulses
optimize energy gain

$r_e = \frac{e^2}{mc^2}$ is the classical electron radius

R is the laser pulse radius

Ultra-short pancake-like laser pulses optimize electron energy gains

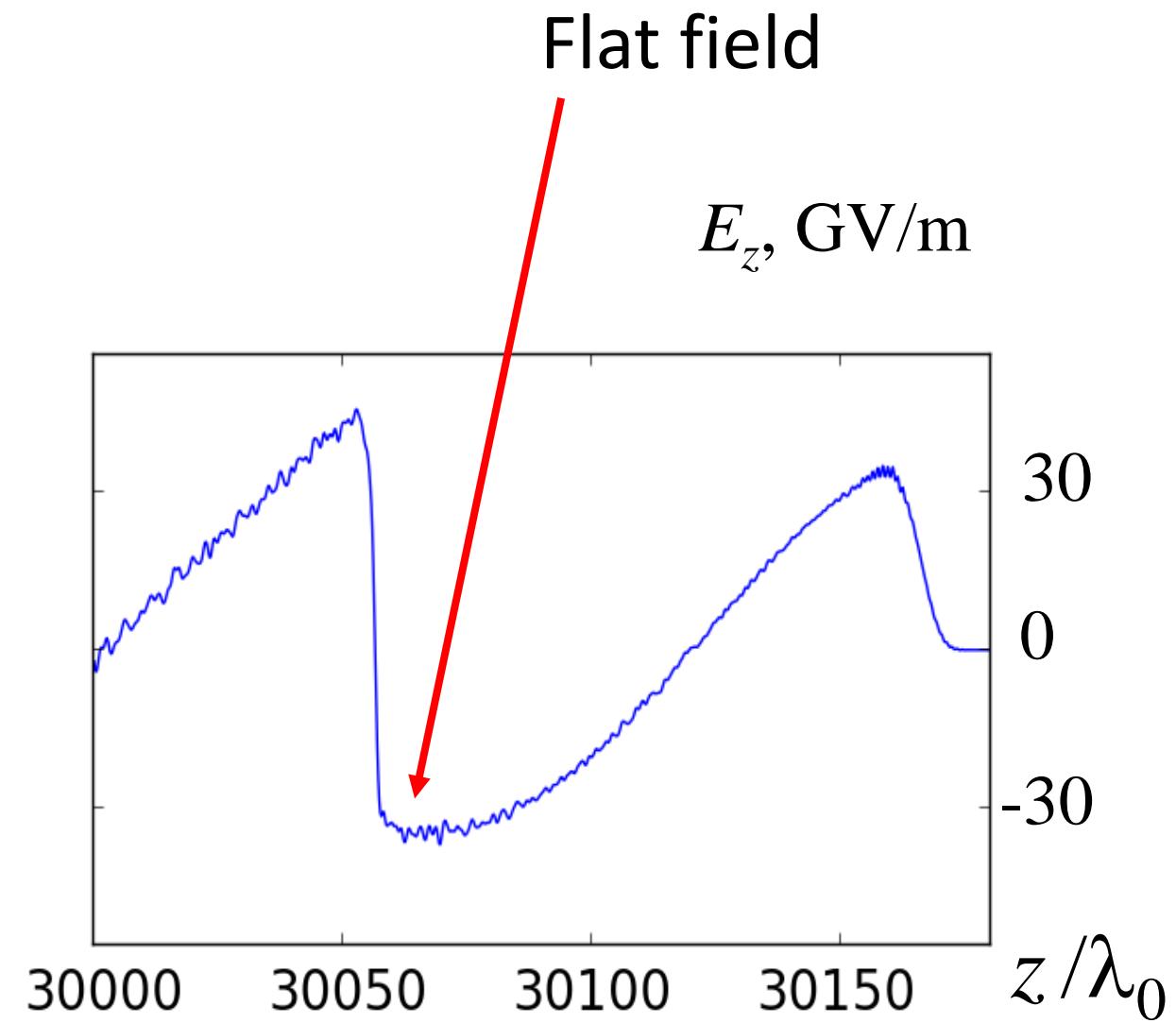
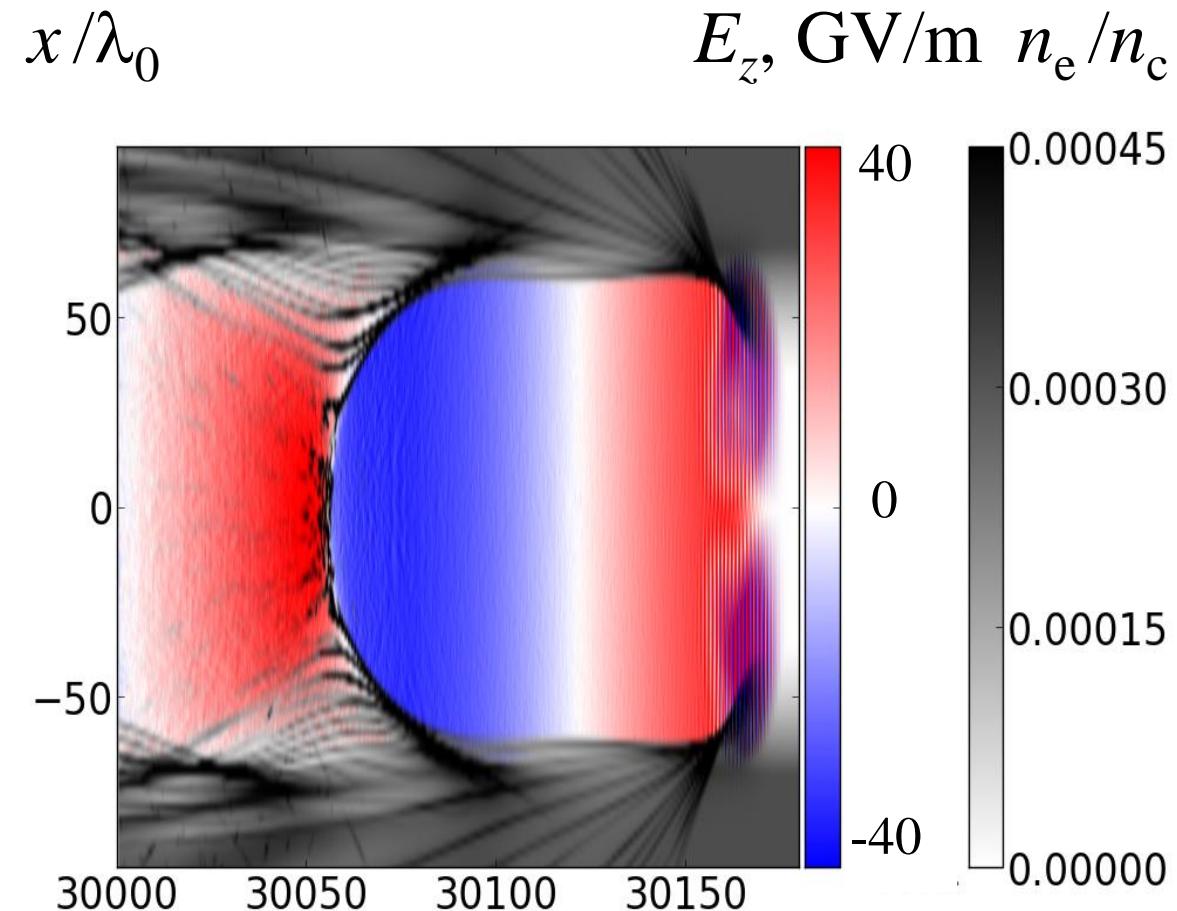
	2 PW	10 PW	
W_L , J	2.2	17.6	141
τ , fs	4	8	16
a_0	10	10	10
$R, \mu\text{m}$	8	16	32
n_0 , $1/\text{cm}^3$	$5 \cdot 10^{18}$	$1.25 \cdot 10^{18}$	$0.31 \cdot 10^{18}$
L_A , cm	1.6	12.8	100
$\mathcal{E}_{\max}^{\text{dc}}$, GeV	1.5	6	24

Aspect ratio
of the laser pulses

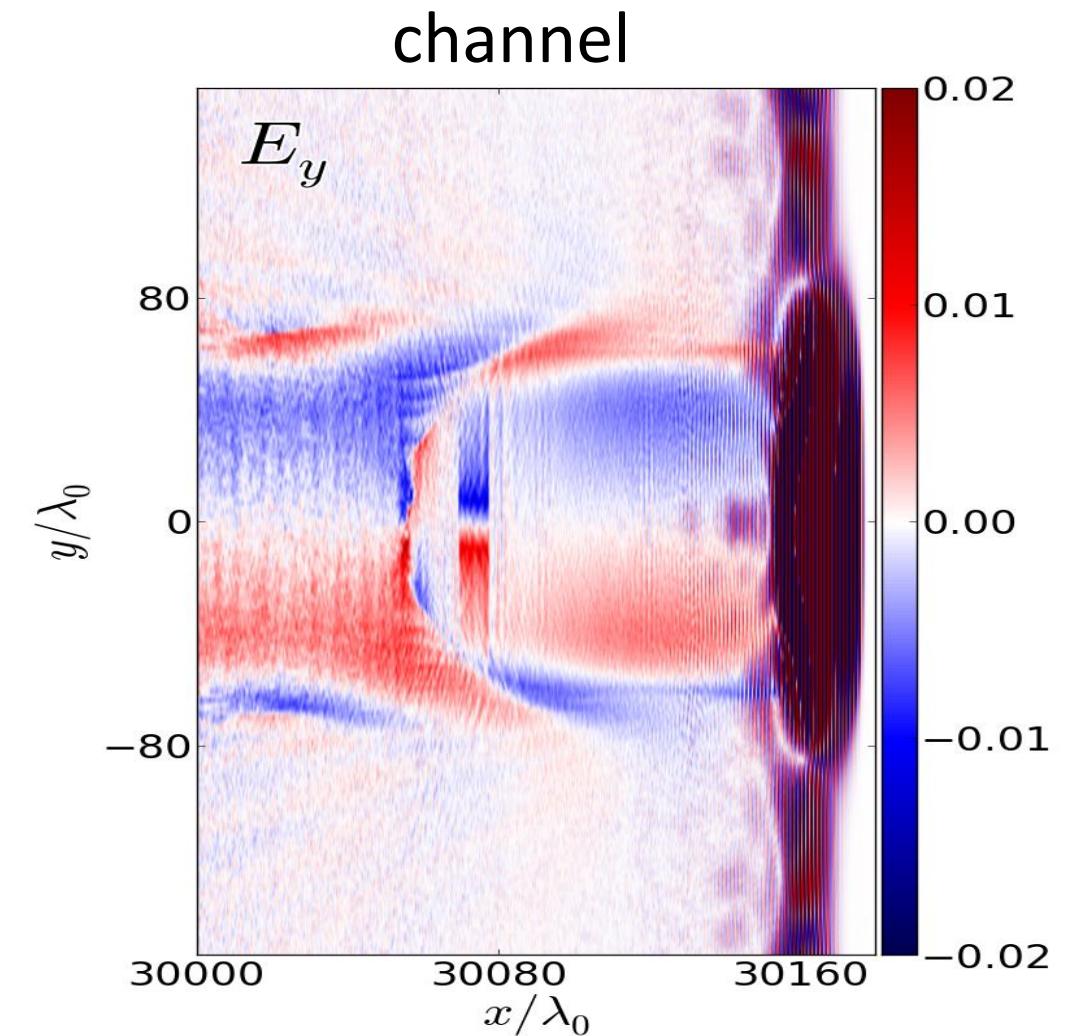
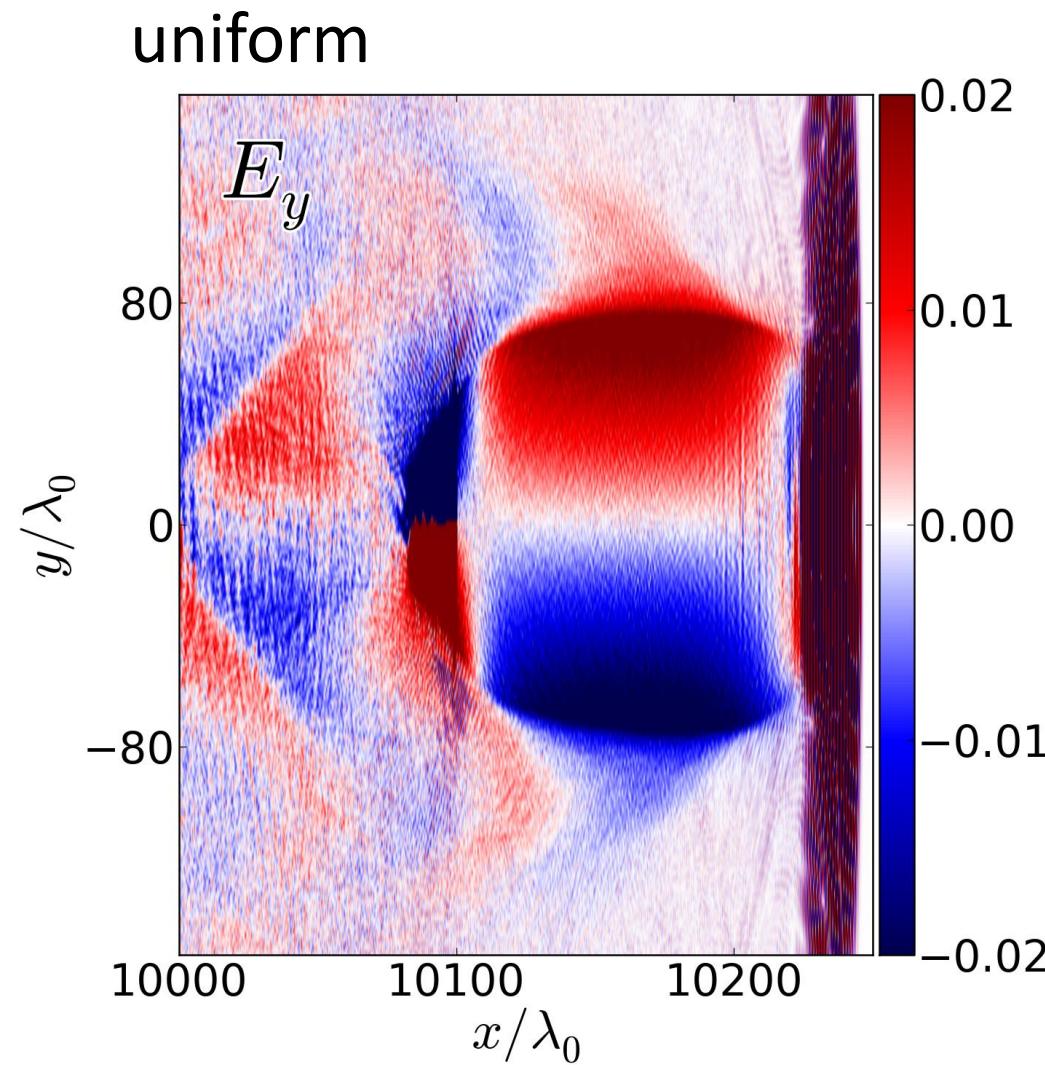
$$\Pi = \frac{R}{c \tau} = 6.7$$

Bubble in a deep channel

What is new?



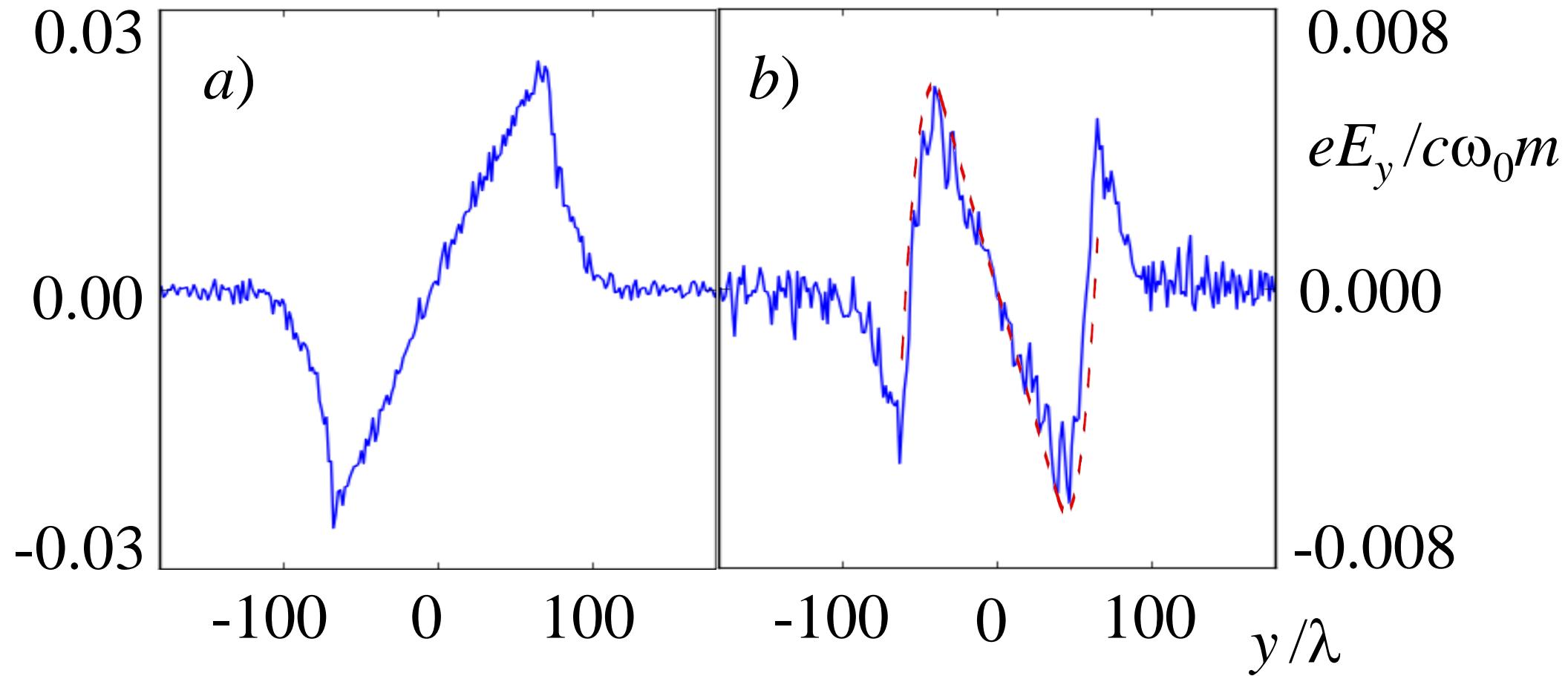
Reversed radial field in the bubble



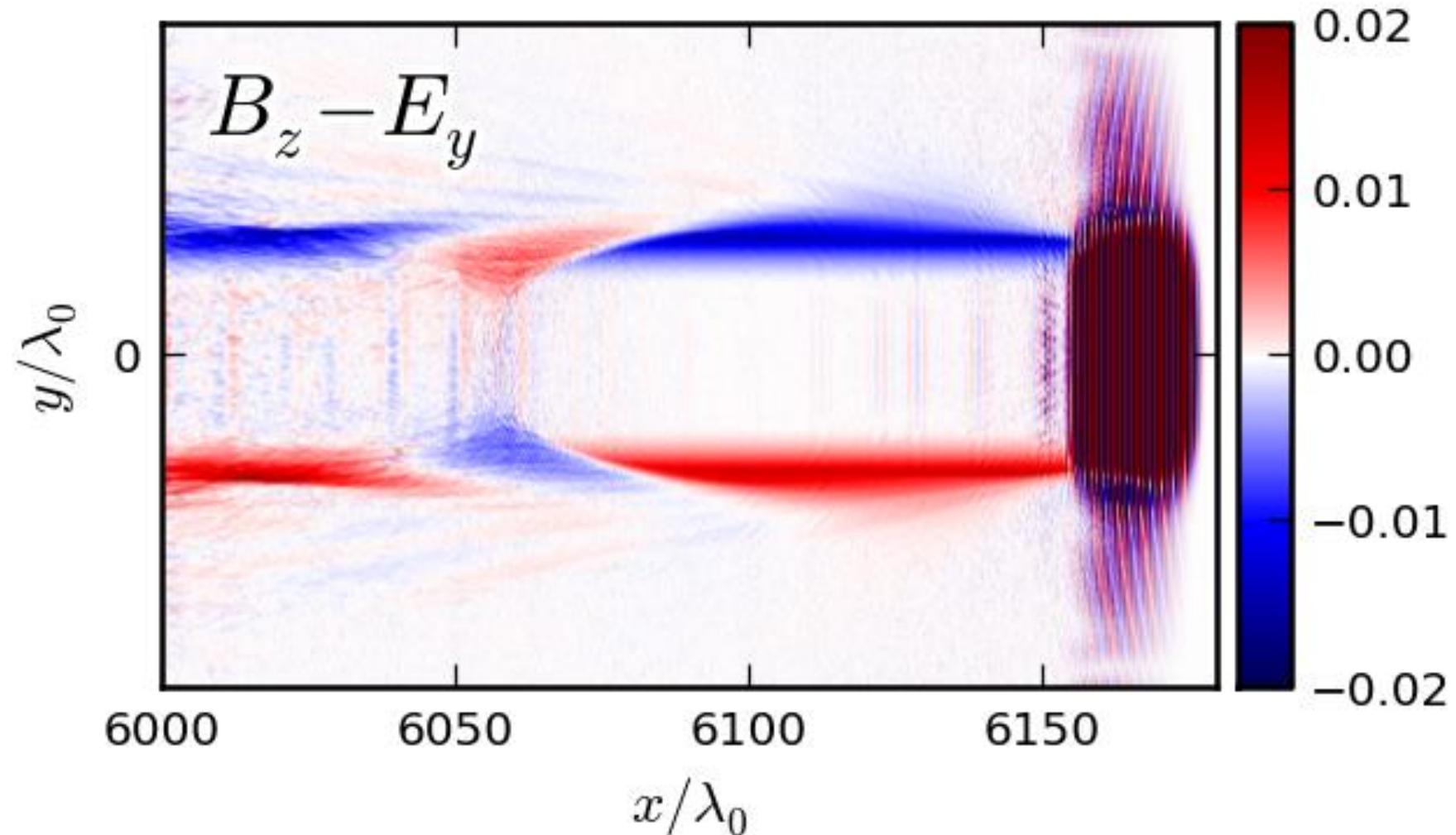
Reversed radial electric field in the bubble

uniform

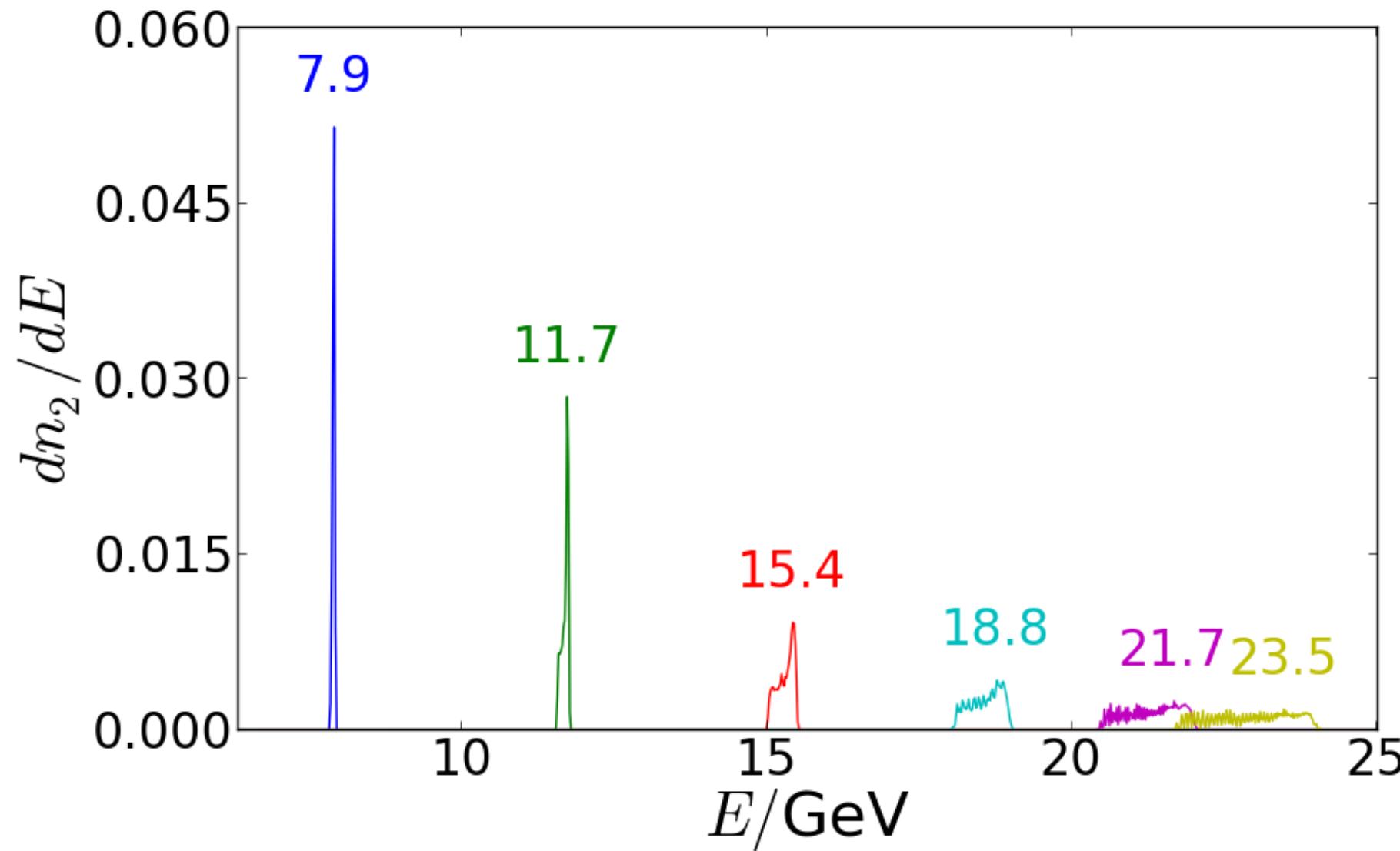
channel



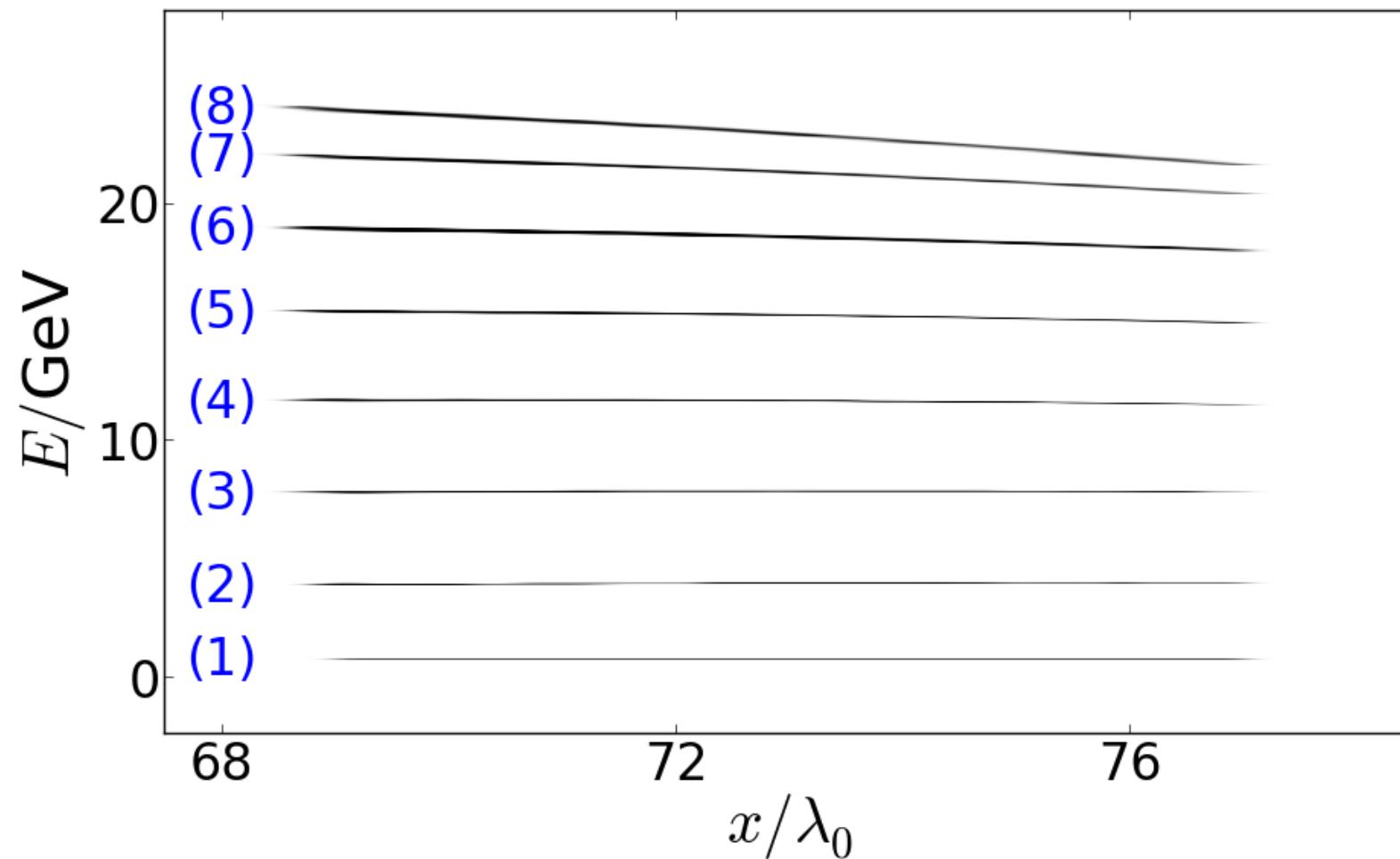
Focusing force in the channel walls only
No net transverse force in the void region.
No betatron resonance!



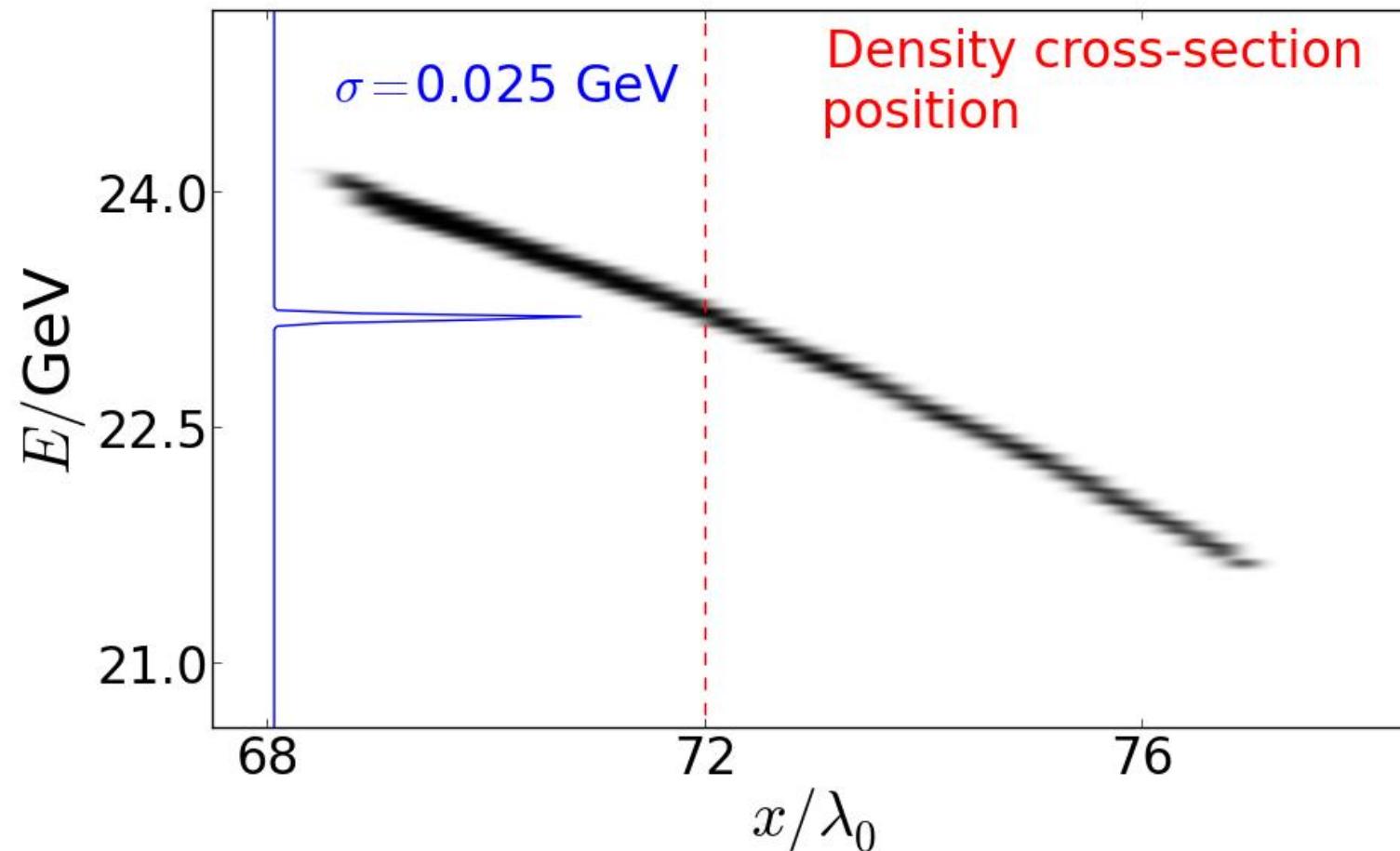
Channel: Mono-energetic spectra



Longitudinal phase space of the witness bunch



r.m.s. energy uncertainty in each slice 10^{-3}
limited by numerical resolution only



Scale to higher energies

Simulated

W_L , J	2.2	17.6	141
τ , fs	4	8	16
a_0	10	10	10
$R, \mu\text{m}$	8	16	32
n_0 , $1/\text{cm}^3$	$5 \cdot 10^{18}$	$1.25 \cdot 10^{18}$	$0.31 \cdot 10^{18}$
L_A , cm	1.6	12.8	100
$\mathcal{E}_{\max}^{\text{dc}}$, GeV	1.5	6	24

Scaled

1.1 kJ	10 kJ
32 fs	70 fs
10	10
64 μm	140 μm
$8 \cdot 10^{16}$	$2 \cdot 10^{16}$
8 m	80 m
98 GeV	400 GeV

Summary

- Deep plasma channels generate new similarity scalings
- Deep plasma channels lead to reversed field configuration in the bubble
- Energy gains per Joule of laser energy are much higher in deep channels
Pancake-like pulses optimize energy gain in channels
- High quality particle acceleration in plasma is feasible