Electron Self-Injection and Trapping into Evolving Plasma Bubble:

Towards Optimization of Beam Quality in GeV-Scale Laser Plasma Accelerators

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in collaboration with

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SILMI Workshop on Frontiers in Intense Laser-Matter Interaction Theory

MPQ für Quantenoptik, Garching-bei-München, 3 March, 2010

Plan of the talk:

1. Introduction to laser wakefield accelerators (LWFAs)
    a. Physics of the blowout regime
    b. Parameter scaling for 10 GeV LWFA driven by a petawatt laser
2. Electron self-injection in the expanding bubble – Hamiltonian treatment
3. Periodic self-injection into oscillating bubble driven by a self-guided laser: possible source of dark current
4. Dark-current-free LWFA with a nonlinear plasma lens
5. Summary

Modern laser wake field accelerators: Blowout regime

- Breakdown in RF accelerators → accelerating gradient $E_{\mathrm{RF}} < 20$ MV/m

- Plasma is already broken down → higher accelerating fields

- Peak laser intensity: $> 10^{19}$ **W/cm^2**
  Laser spot size: **a few c/ω_{pe}**

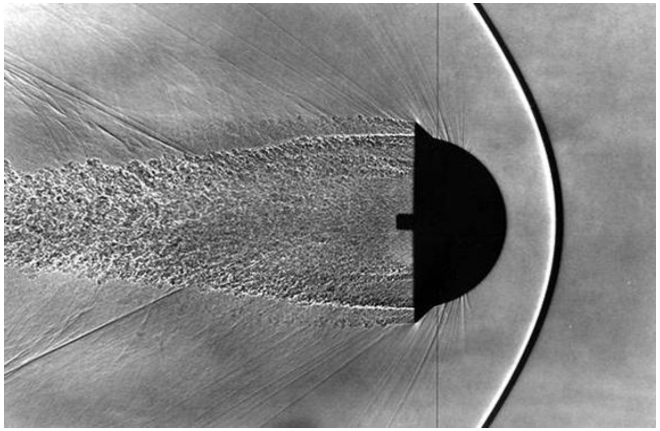
↓ ↓

SINGLE ACCELERATING BUCKET
(**electron density bubble**)
near-luminous phase velocity
accelerating gradient $E_{EPW} > 50$ GV/m

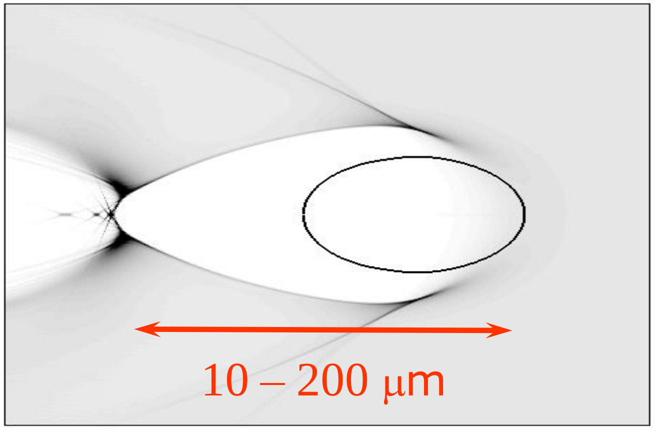
- **Table-top electron accelerator**

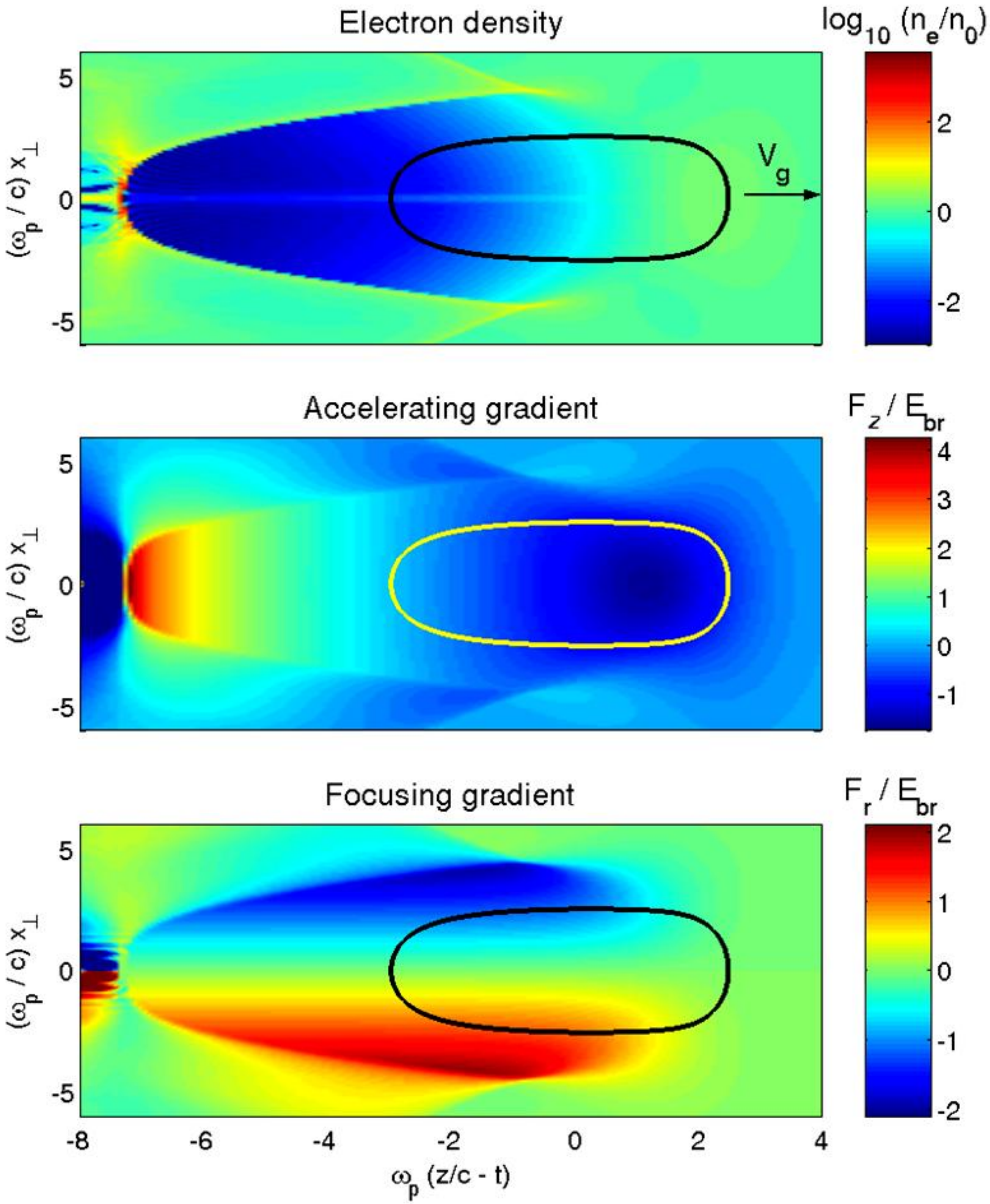
A. Pukhov and J. Meyer-ter-Vehn, *APB* **74**, 355 (2002)

Projectile in gas ($V > v_s$)



Laser pulse in plasma ($V \approx c$ **!!**)





1. Full electron evacuation in the first bucket
2. Multi-stream, mostly transverse electron motion
3. Accelerating gradient:

$$E_{acc} > E_{br} = m_e \omega_{pe} c / |e|$$

4. Accelerating gradient is transversely uniform
5. Entire accelerating bucket is focusing; focusing gradient is *linear* in radius
6. Self-injection (no need of external injection)

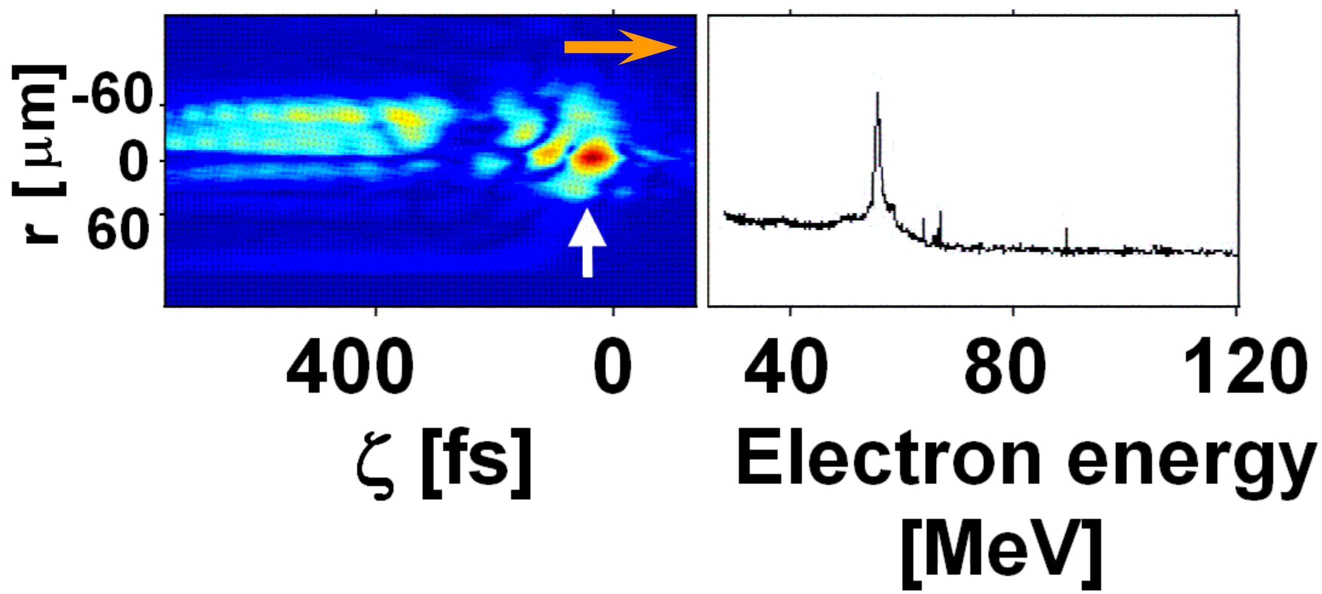
Most popular regime for current experiments!

W. Lu, M. Tzoufras, C. Joshi *et al.*, *Phys. Rev. ST Accel. Beams* **10**, 061301 (2007)

Direct single-shot optical diagnostics is available!

Frequency-Domain Shadowgraphy

Reconstructed
***probe* pulse**



P. Dong, S. A. Reed, S. A. Yi, S. Y. Kalmykov *et al.*, Holographic visualization of laser wakefields

High Energy Density Phys. (2010): doi:10.1016/j.hedp.2009.12.003

Phys. Rev. Lett., to appear;

New J. Phys., to appear

State-of-art LWFAs

Multi-TW ultrashort (< 50 fs) high rep. rate lasers (CPA)

\+ new laser pulse guiding techniques

\+ new high-performance simulation tools (3D PIC and hybrid codes)

\+ rapid progress in theory

$\Downarrow \quad \Downarrow$

"Dream Beam" issue, 30 September 2004

200-300 MeV electron beams

a few % energy spread,

a few tens of pC charge,

a few mrad divergence and pointing stability,

a few % shot-to-shot parameter fluctuations

Petawatt lasers – the way to a fraction of SLAC on top of optical table

$\lambda_0 \sim 1$ **μm**

$P \sim 10^{15}$ **W** (Texas Petawatt, POLARIS, …)

Electron blowout and stable self-guiding $\rightarrow P/P_{cr} < 20$

It is imperative to work at low density:

$n_0 < 3\times10^{17}$ **cm**$^{-3}$

$1 < \tau_L < 2\pi/\omega_{pe}$

$30 < \tau_L < 175$ **fs**

$E_{acc} < 0.55$ **GV/cm**

$L_{depl} \approx 20$ **cm**

Energy gain ~ 11 **GeV**

Electron self-injection at low density: Is it possible?

Bubble is small: $k_p L_b \sim 3 - 5$

and ultra-relativistic: $\gamma \sim \omega_0/\omega_{pe} \sim (20 - 40) k_p L_b$

Criterion (Kostyukov et al., *PRL* 2009) for self-injection into a frozen spherical bubble is violated by a factor of 100

No need to worry!

Evolution of the structure resolves the issue:

Spot and intensity of the self-guided laser vary in time

$\Rightarrow$ bubble shape and size (hence, potentials) vary accordingly

$\Rightarrow$ electrons from the surrounding sheath get self-injected (and even trapped!)

Electron self-injection into evolving plasma bubble: Hamiltonian treatment

Simulation toolbox

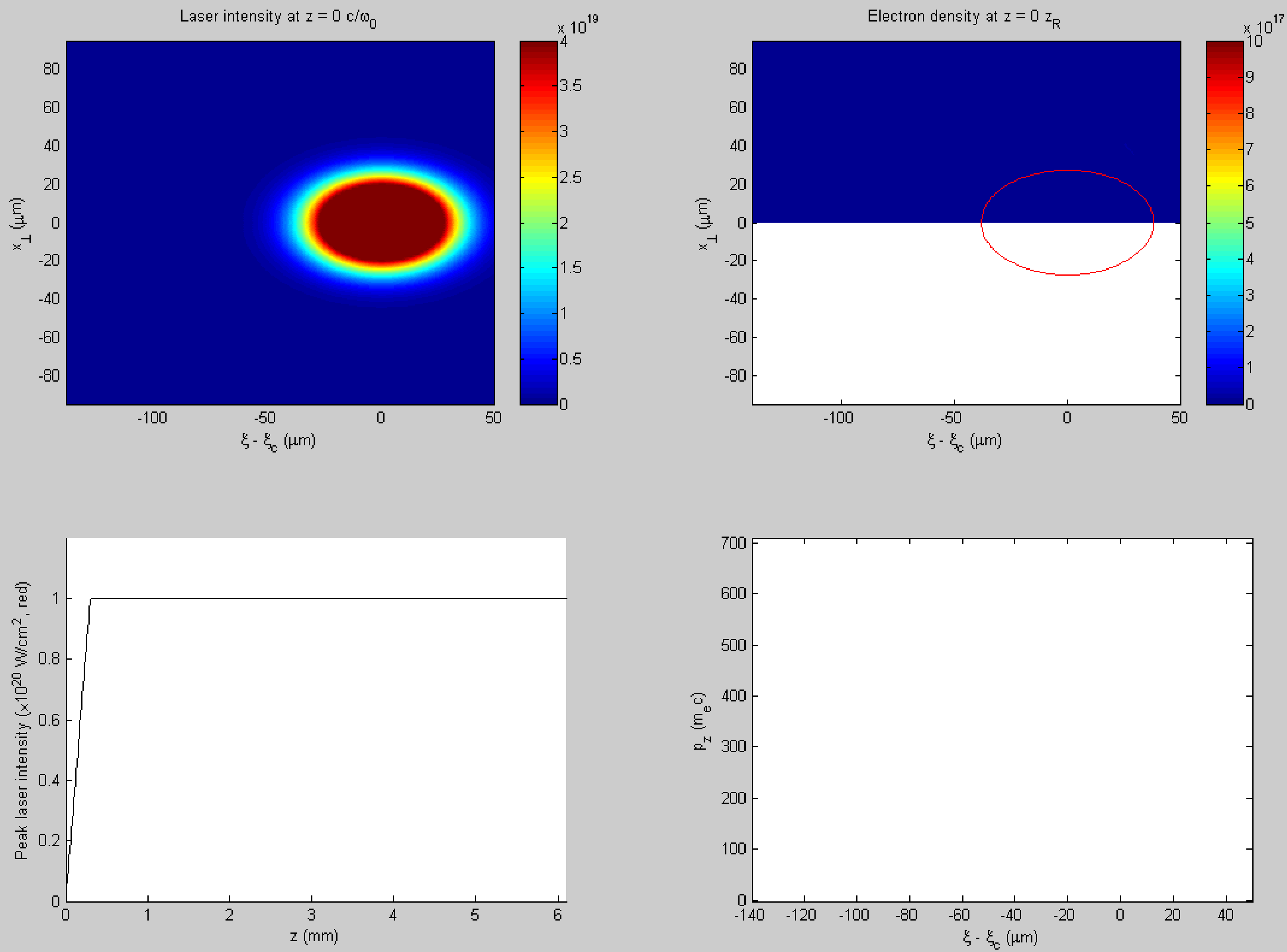
Fully relativistic PIC code *WAKE* + *test electron tracking code*

WAKE: Ponderomotive, axi-symmetric (cylindrical), extended paraxial, quasi-static → no self-injection of WAKE macroparticles

Tracking code: Fully 3-D, dynamic, interaction with non-averaged laser field → models self-injection in the quasi-static wakefield

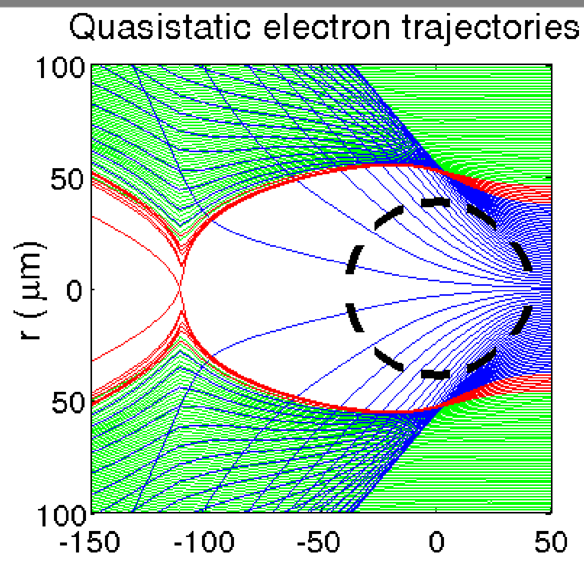
WAKE operates in Hamiltonian variables – Hamiltonian analysis of the test particle dynamics is particularly simple!

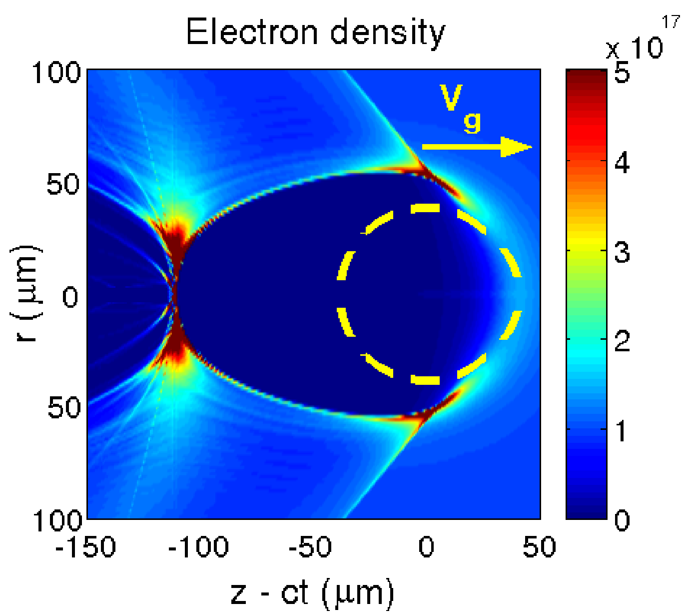
Laser:	150 fs, 1.33 PW, $\lambda_0 = 1.057$ μm		
Focal spot:	$r_0 \approx 25$ μm	→	$k_p r_0 = 1.5$
Peak intensity:	$I_{peak} = 1.1 \times 10^{20}$ W/cm^2	→	$a_0 \approx 10$
Plasma:	$n_0 = 10^{17}$ cm^{-3}	→	$\gamma_g = 100 >> k_p r_0$



Laser intensity at z = 0 c/ω0
x 10^19
x⊥ (μm)
ξ - ξc (μm)
Electron density at z = 0 zR
x 10^17
x⊥ (μm)
ξ - ξc (μm)
Peak laser intensity (x10^20 W/cm^2, red)
z (mm)
pz (me c)
ξ - ξc (μm)

Plasma electrons in a blowout regime





Electron cavity (***"bubble"***) travels over the positive ion background at a relativistic speed

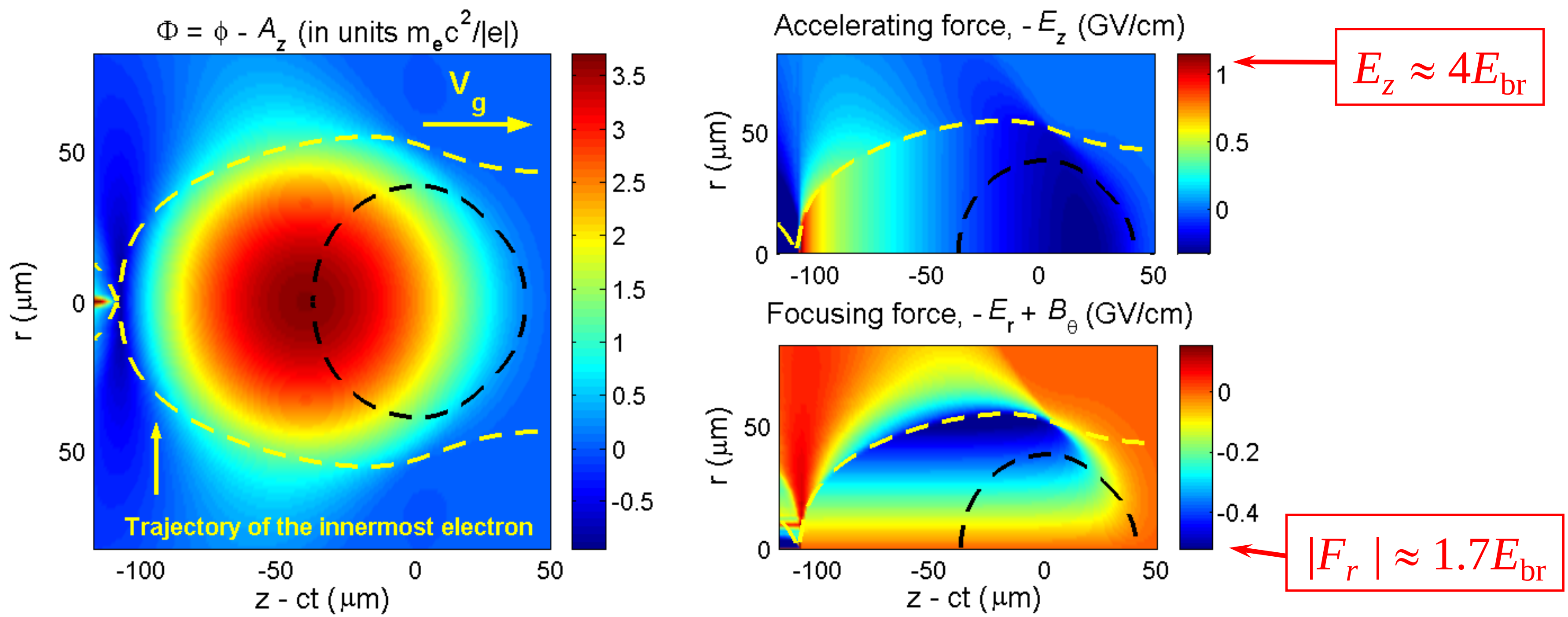
Bubble is essentially a quasi-static structure

Majority of plasma electrons,
expelled by the radiation pressure and
attracted by the charge separation force,
are passing

Electrons forming the dense shell surrounding the bubble are trapping candidates

They follow the bubble for a long time, and become relativistic (QSA is nearly violated)

Lorentz forces acting on electrons - trapping candidates



The innermost electron is exposed to the highest possible wakefields. Wake perturbation around its trajectory during the slippage time,

e.g. due to the slow, quasi-static bubble evolution [S. Kalmykov *et al*., *PRL* **103**, 135004 (2009); *New. J. Phys.* (2010)]

can displace the electron inside the bubble and cause self-injection

Electron self-injection and trapping: Non-stationary Hamiltonian diagnostics

Definitions: $\gamma = (1 + \boldsymbol{p}^2 + \boldsymbol{a}^2/2)^{1/2}$; $\boldsymbol{p} \equiv \boldsymbol{p}/(m_e c)$; $\Phi = |e|(\varphi - A_z)/(m_e c^2)$; $\boldsymbol{a} \equiv |e|\boldsymbol{a}/(m_e c^2)$

Moving-Frame averaged Hamiltonian (z, $\xi = z - ct$, r):

$$H = \gamma + \Phi - p_z$$

For quasi-static WAKE macro-particles MF-Hamiltonian is conserved:

$$H_{\text{QSA}} \approx H(\xi,r) = 1$$

Potentials depend on time $\rightarrow$ MF Hamiltonian of test electron evolves according to $dH/dt = \partial H/\partial t$

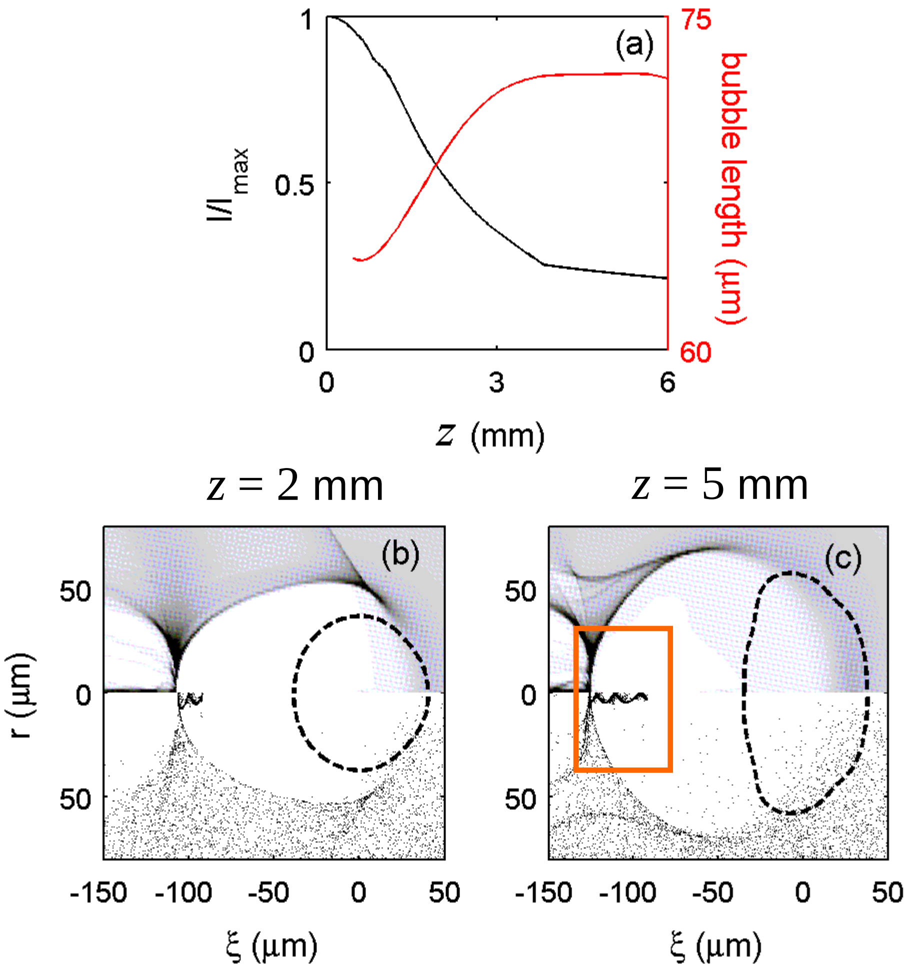
For a test electron moving away from the bubble after the interaction

$$H = \gamma + \Phi - p_z \rightarrow (1 + \boldsymbol{p}^2)^{1/2} - p_z > 0$$

Sufficient condition for trapping

$$\Delta H \equiv \int dt\, (\partial H/\partial t) = \int d\xi\, (c - v_z)^{-1}(\partial H/\partial t) < -1$$

Correlation between the laser defocusing, growth of the bubble, and test electron self-injection



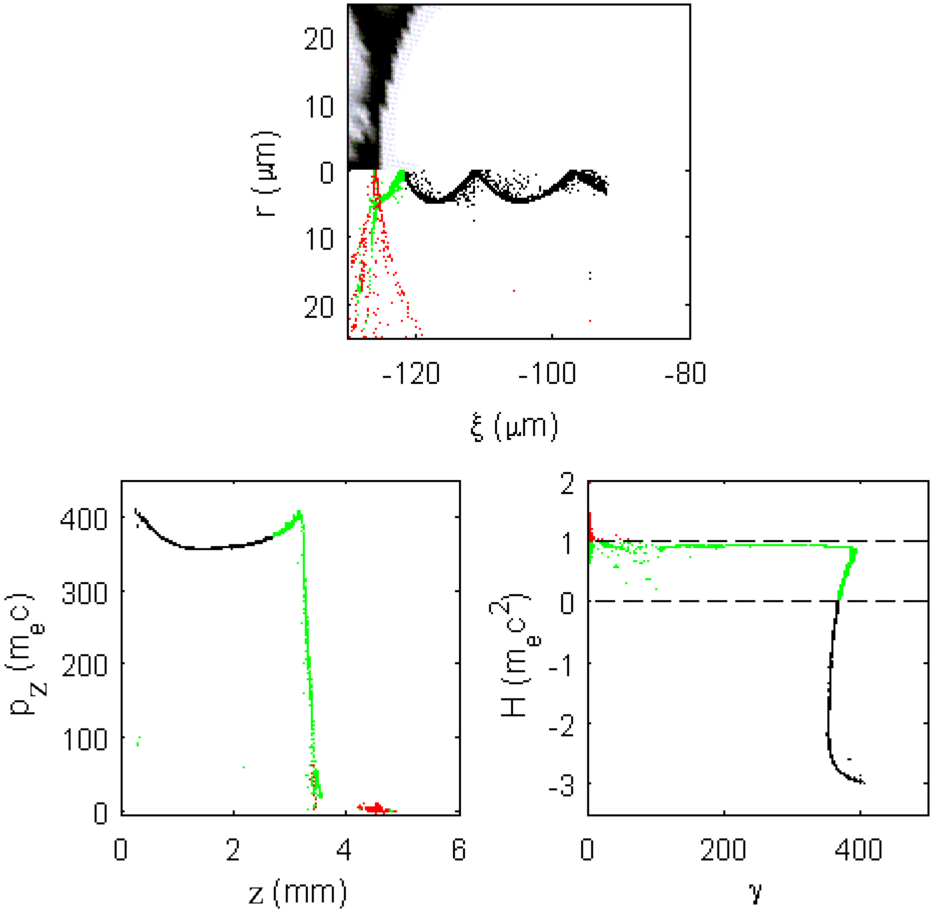
Test electrons are not limited by QSA, hence they can be self-injected, and travel inside the bubble infinitely

1. Once laser diffracts, the bubble grows, injection goes on continuously

2. Bubble stabilizes, injection stops, injected electrons get accelerated

For the frozen laser pulse (non-evolving bubble) self-injection is not the case

S. A. Yi, S. Y. Kalmykov, V. Khudik, and G. Shvets, Hamiltonian analysis of electron self-injection and acceleration into an evolving plasma bubble, **submitted to *Plasma Phys. Control. Fusion***



Once the bubble stabilizes, MF-Hamiltonian of test electrons is conserved

All test electrons can now be divided into 3 groups:

$H < 0$ – trapped electrons (**sufficient condition satisfied**)

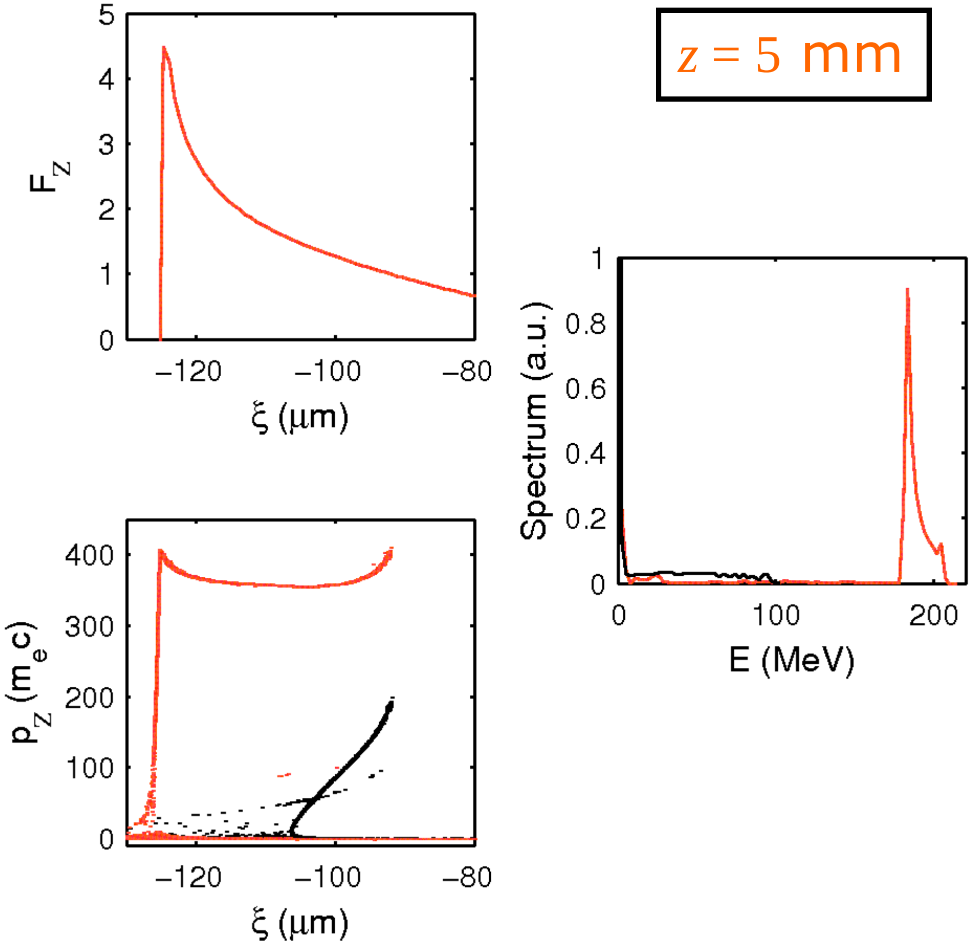
$0 < H < 1$ – injected (accelerated) electrons

$H > 1$ – passing electrons

In this example, electrons with $0 < H < 0.9$ are accelerated as effectively as those which are trapped ($H < 0$); their numbers are roughly the same

For acceleration, $H < 1$ appears to be the necessary condition. In the considered regime with $\gamma_g = 100$, it is almost sufficient!

Phase space rotation and production of mono-energetic electron beam



Bubble stabilizes

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Injected electrons are exposed to the longitudinally non-uniform accelerating gradient

Tail of the bunch ($\mathbf{0 < \mathit{H} < 0.9}$) is exposed to a higher gradient.

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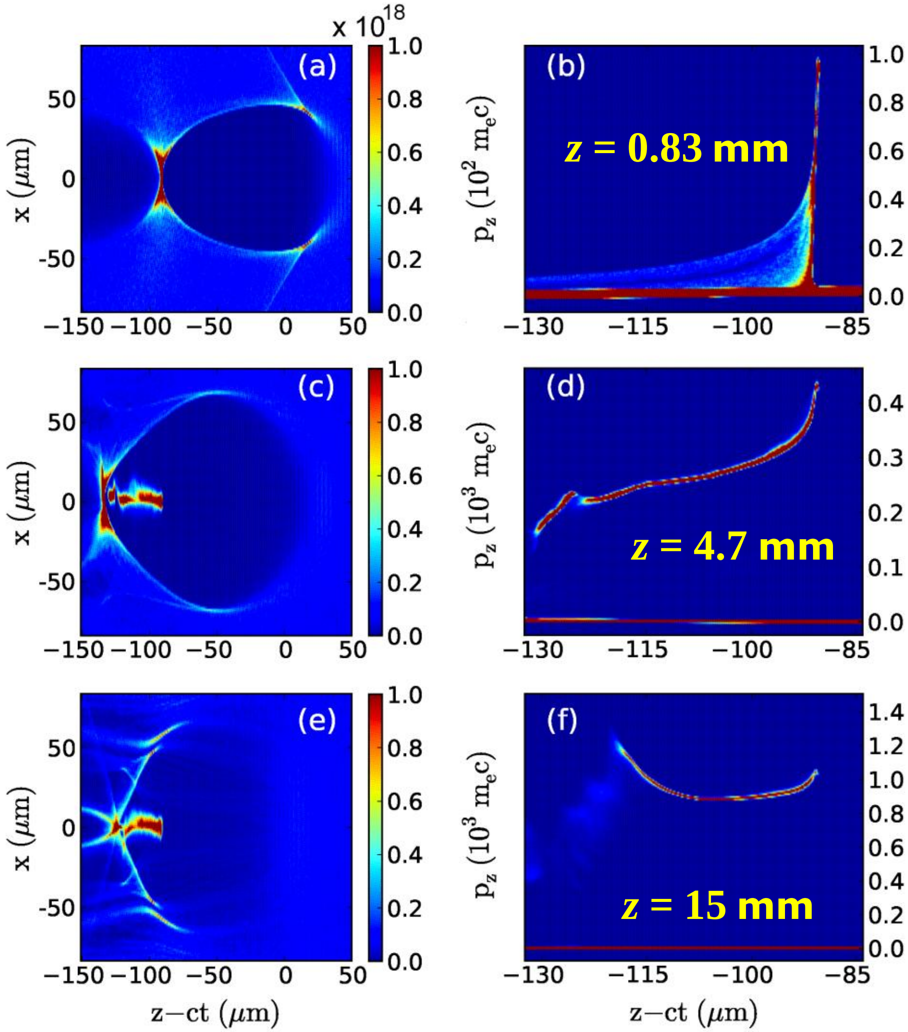
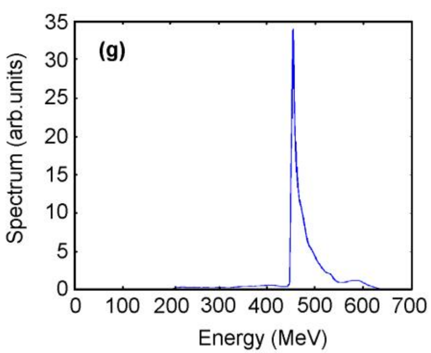
Within 2 mm tail and head equalize in energy

Monoenergetic bunch is produced

3-D CALDER-Circ PIC modeling of electron injection in the growing bubble





Results of test particle modeling are reproduced qualitatively

Beam loading slows down phase space rotation; unable to preclude bucket contraction

$\Downarrow$

Monoenergetic electron beam (average current 13.5 kA) forms with higher energy than in test-particle modeling

S Y Kalmykov, S A Yi, A Beck *et al.*, Numerical modelling of 10 centimetre long multi-GeV laser wakefield accelerator driven by a self-guided petawatt pulse, **to be published in *New J. Phys.* (2010)**

Expanding bubble traps electrons: What are the implications?

Laser spot and intensity oscillate during the self-guiding

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Multiple injection in the same bucket during the laser self-guiding – already observed in experiment – N. A. M. Hafz *et al*., Nucl. Instr. and Meth. A (2010), doi:10.1016/j.nima.2010.02.020

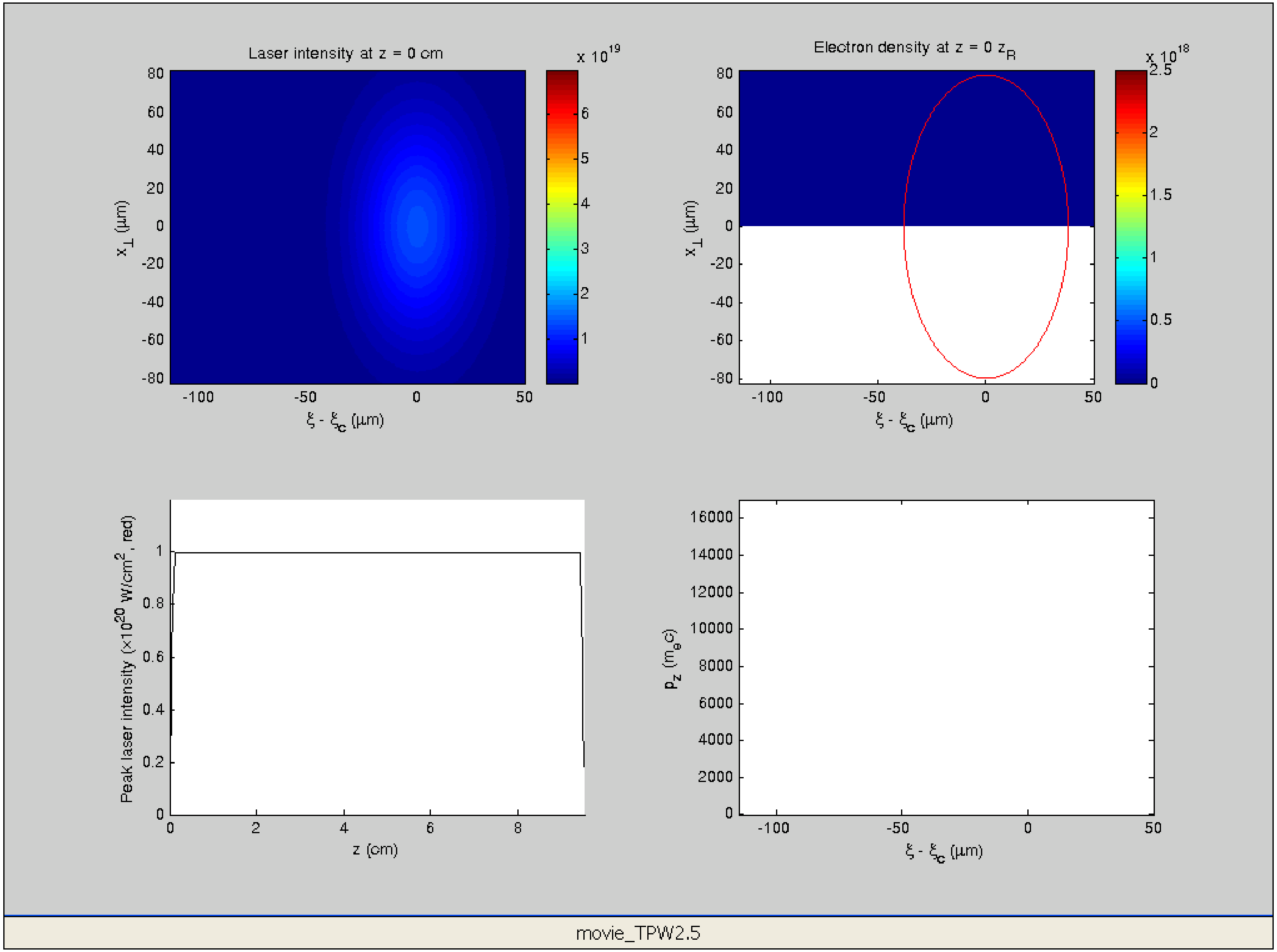
$\Downarrow \quad \Downarrow$

Emittance dilution + increase in energy spread

How to avoid it?

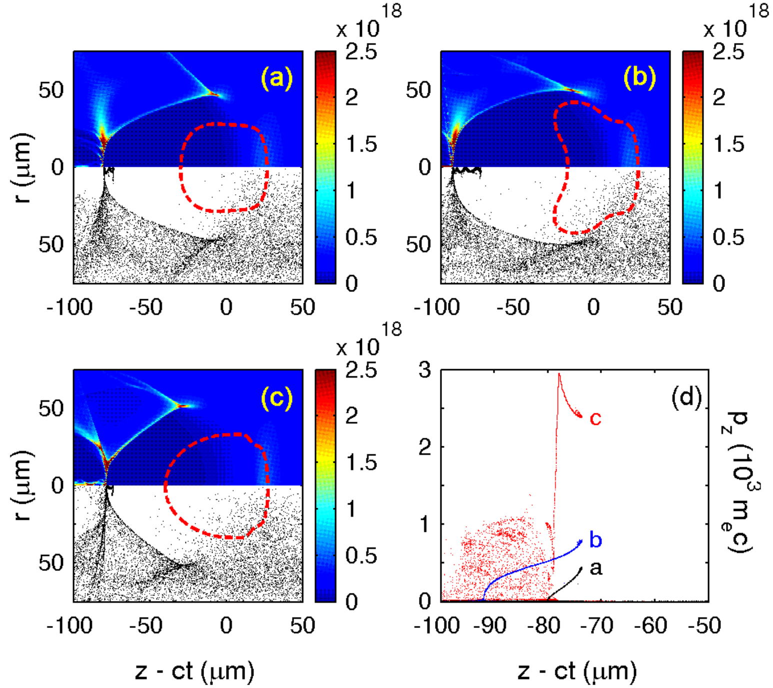
Make self-injection a single time event:
enforce rapid defocusing of the laser and bubble local growth by over-focusing the pulse with a nonlinear plasma lens

Periodic self-injection of test electrons: WAKE modeling



Laser (Texas PW): $\lambda_0 = 1.057$ μm, $P = 1.33$ PW, $\tau_L = 150$ fs, pulse initially mismatched for self-guiding

First period of bubble oscillation



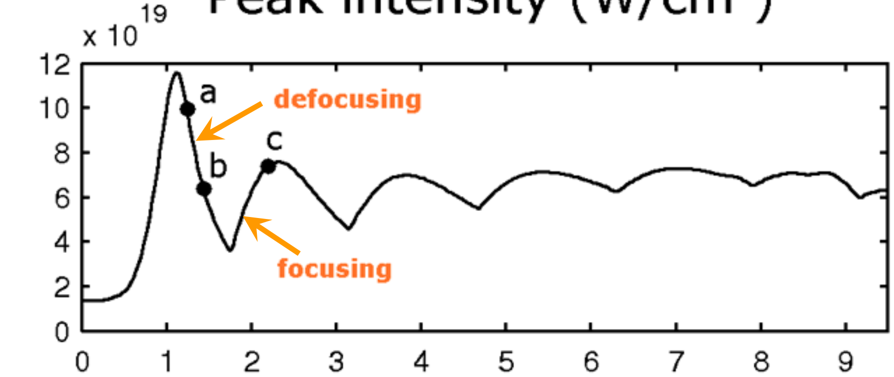
Pulse head – self-guided;
Pulse tail – beats inside the bubble

→ Periodic variations of bubble size

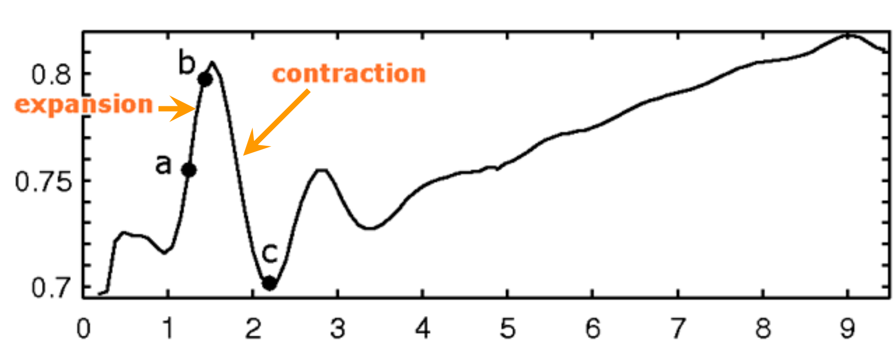
→ Periodic self –injection

→ Large final energy spread +
high emittance ($\varepsilon_{\perp}^{norm} \sim 7\pi$ mm mrad)

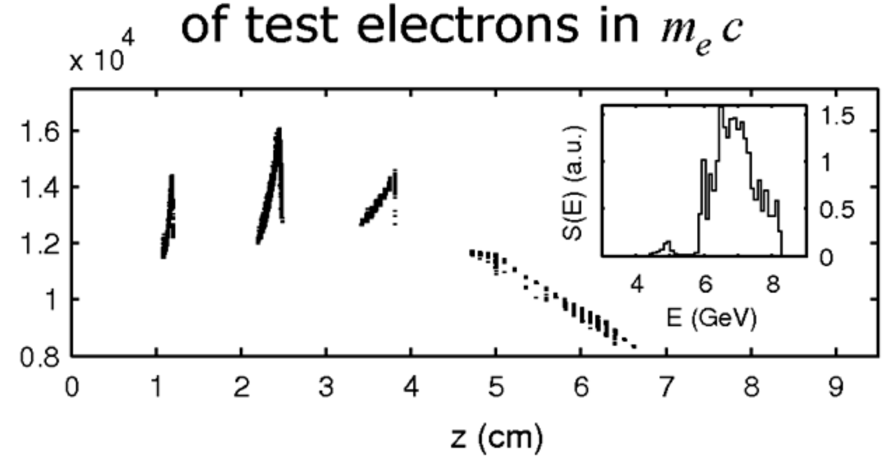
Peak intensity (W/cm^2)



Bubble length in λ_p^{-1}



Longitudinal momentum
of test electrons in $m_e c$



Dark-current free acceleration in low-density plasma

Low density ($\approx 10^{17}$ cm^{-3}) plasmas

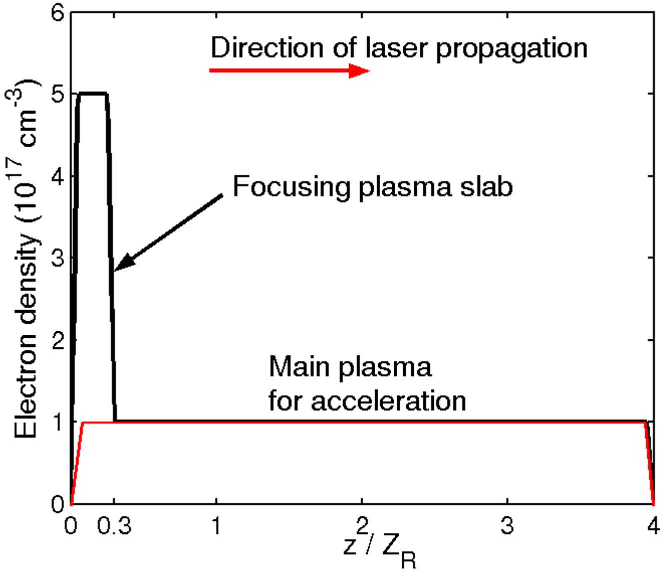
$\Downarrow$

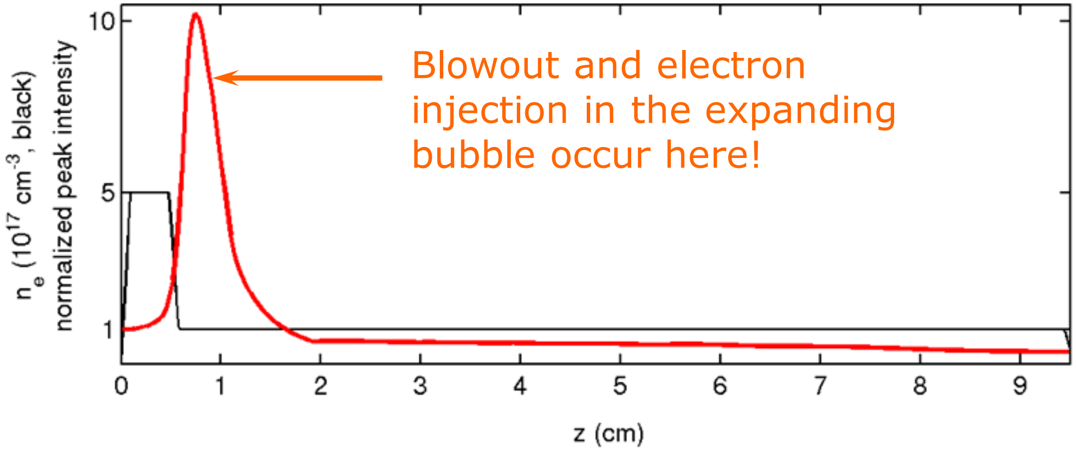
Evolution of matched laser and bubble is too steady

$\Downarrow$

PW laser pulse must be over-focused to cause self-injection *– practically difficult*!

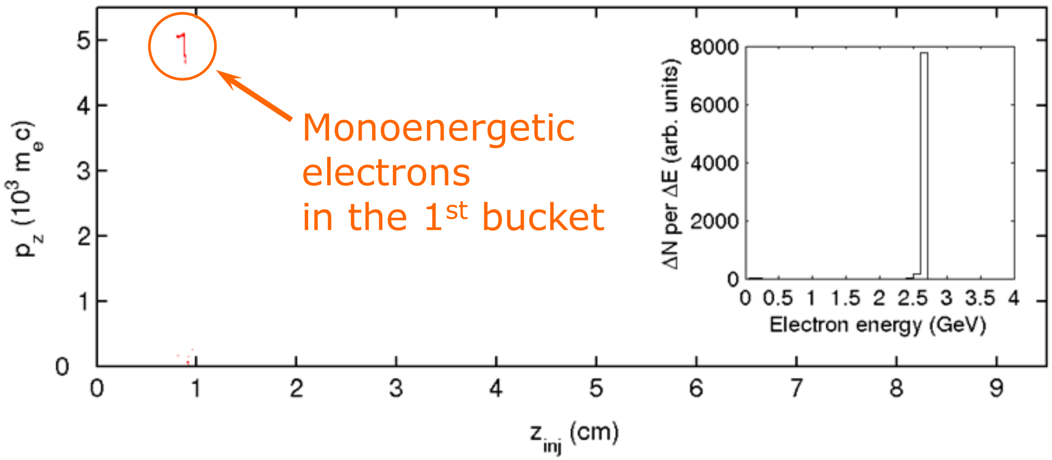
Strong focusing and blowout can be enforced using the plasma lens!



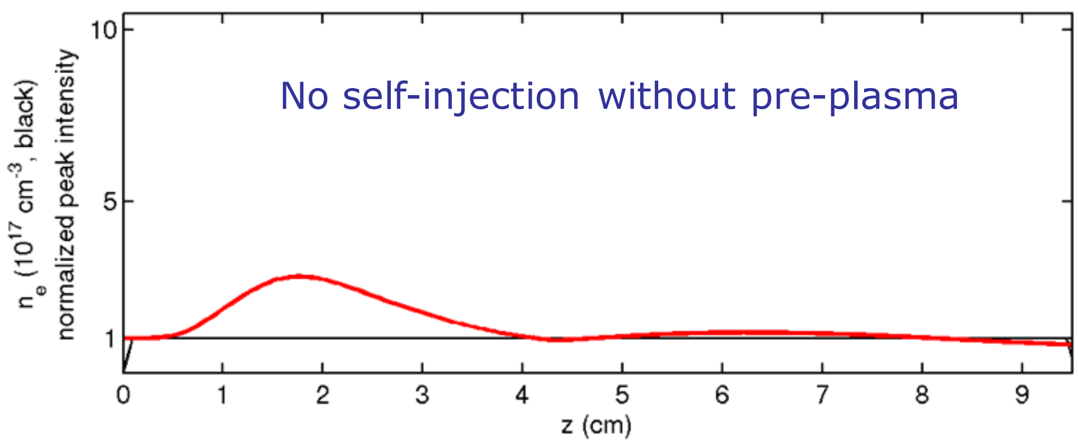


Pre-plasma slab acts as a short focal length thin lens (no focusing and blowout inside the dense slab):

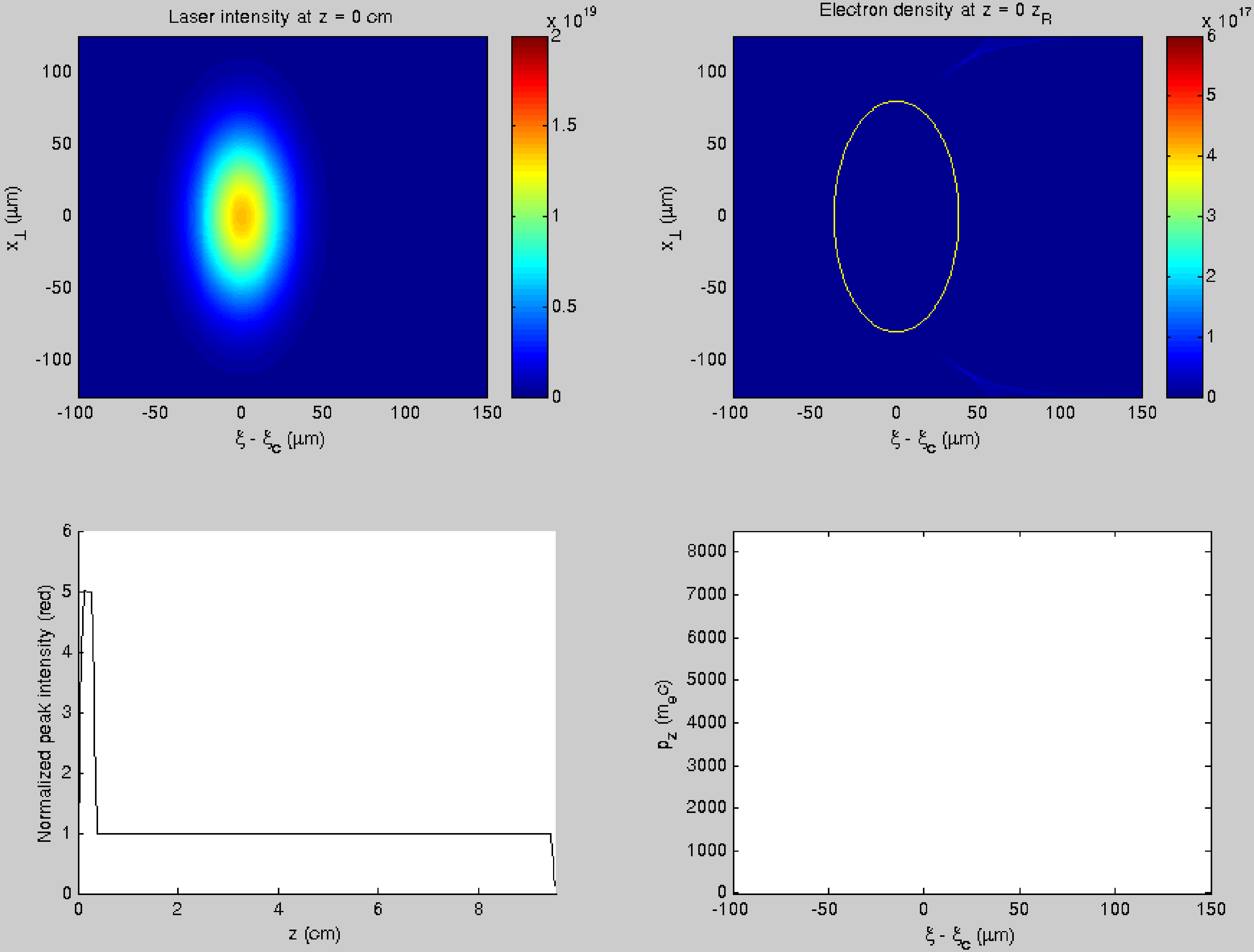
$$L_{nlpl} < (Z_{R0}/2)(a_0/2)^2(P/P_{cr})^{-1/2} \approx 5 \text{ mm}$$



After defocusing laser is guided; energy losses due to nonlinear aberrations are < 40%



S Y Kalmykov, S A Yi, A Beck *et al*., Dark-current-free petawatt LWFA…, **submitted to *Plasma Phys. Control. Fusion***



Laser intensity at z = 0 cm
x 10^19
Electron density at z = 0 z_R
x 10^17
x_⊥ (μm)
ξ - ξ_c (μm)
Normalized peak intensity (red)
z (cm)
p_z (m_e c)

Conclusions

In plasmas of density $n_0 \sim 10^{17}$ cm^{-3}, which are the guiding and accelerating media of laser-plasma accelerators driven by $100 - 200$ fs, 1 - 2 PW pulses (TPW, POLARIS) electron self-injection and monoenergetic acceleration critically depends on the nonlinear dynamics of the self-guided laser pulse.

Electron density bubble, which expands during the periods of laser defocusing, effectively traps background plasma electrons. Self-injection ceases during the periods of bubble stability and contraction.

At the same time, phase space rotation (long before the dephasing is reached) produces a quasi-monoenergetic electron beam.

Single event of self-injection (which means no dark current and emittance dilution during further acceleration over ~ 10 cm plasmas) can be organized in a specially designed target (two-section differentially pumped cell) with a front compartment containing high-density plasma (nonlinear plasma lens).

Summary of publications

Injection in wakes in blowout regime

[1] S. Y. Kalmykov, S. A. Yi, V. Khudik, G. Shvets, *Electron self-injection and trapping into an evolving plasma bubble*, **Phys. Rev. Lett. 103**, 135004 (2009)

[2] S. Y. Kalmykov, S. A. Yi, A. Beck, A. F. Lifschitz *et al.*, *Dark current-free petawatt-laser-driven wakefield accelerator based on electron self-injection into the expanding plasma bubble*, submitted to **Plasma Phys. Control. Fusion** (2009).

[3] S. A. Yi, S. Y. Kalmykov, V. Khudik, and G. Shvets, *Hamiltonian analysis of electron self-injection and acceleration into an evolving plasma bubble*, submitted to **Plasma Phys. Control. Fusion** (2009).

Modeling 10 GeV scale self-guided LWFA

[4] S. A. Reed, S. Kalmykov, E. Gaul *et al.*, *Preparation for laser wakefield experiments driven by the Texas Petawatt Laser system*, **AIP Proc. 1086**, 177-183 (2009).

[5] S. Y. Kalmykov, S. A. Reed, S. A. Yi , A. Beck *et al.*, *LWFA with the TPW: towards GeV electron energy in a single self-guided stage*, to be published in **High Energy Density Phys.** (2010) doi:10.1016/j.hedp.2009.11.002.

[6] S. Y. Kalmykov, S. A. Yi, A. Beck, A. F. Lifschitz *et al.*, *Numerical modelling of 10 centimetre long multi-GeV laser wakefield accelerator driven by a self-guided petawatt pulse*, to be published in **New J. Phys.** (2010).

Optical diagnostics of wakes in the blowout regime

[7] P. Dong, S. A. Reed, S. A. Yi, S. Kalmykov *et al.*, *Formation of optical bullets in laser-driven plasma bubble accelerators*, to be published in **Phys. Rev. Lett.** (2010)

[8] Same authors, *Visualization of plasma bubble accelerators using Frequency-Domain Shadowgraphy*, to be published in **High Energy Density Phys.** (2010) doi:10.1016/j.hedp.2009.12.003.

[9] Same authors, *Holographic visualization of laser wakefields*, to be published in **New J. Phys.** (2010)

End of the talk…

but not of the story!

Texas Petawatt experiment coming soon!

It is on the cutting edge of short-pulse laser technology:

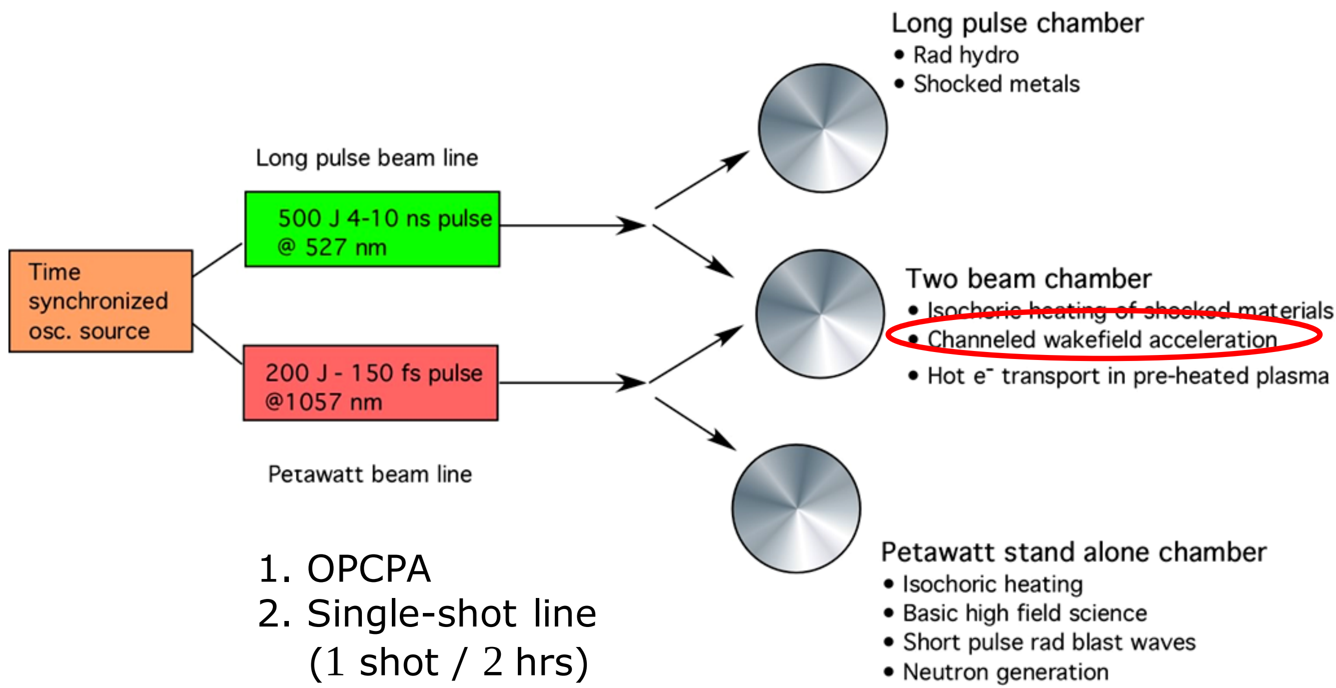
Facility	Amplifier	Wavelength /Power/pulse duration/ repetition rate	Year commissioned
Texas Petawatt (UT Austin)	Nd:glass OPCPA	1.057 μm/ 1.25 PW/ 150 fs/ 1 shot per 2 hours	March 2008
POLARIS (U. Jena, Germany)	Diode pumped CPA, Yb^{3+}:glass; 5 stages	1.042 μm/ 1 PW/ 150 fs/ 0.03 - 0.1 Hz	2007: 4 out of 5 amplification stages realized including compressor (8 J, 150 fs)

Also ~100 TW high-rep. rate lasers (Ti:Sapphire, CPA): HERCULES (U. Mich.), Astra Gemini (RAL), ALLS-Quebec, DRACO (FZD-Rosendorf), DIOCLES (U. Nebraska) …

Low-density gas/plasma targets: differentially pumped cell, slit jet (no channels! – plasma density is too low…)

Texas Petawatt (TPW): The shortest Petawatt laser in the world

Conceptual block diagram of the Texas Petawatt Laser



1. OPCPA
2. Single-shot line
   (1 shot / 2 hrs)

http://www.ph.utexas.edu/~utlasers/tpp.php

Sketch of the experiment