Multi-scale simulations for Laser Wakefield Acceleration experiment on the Texas Petawatt laser

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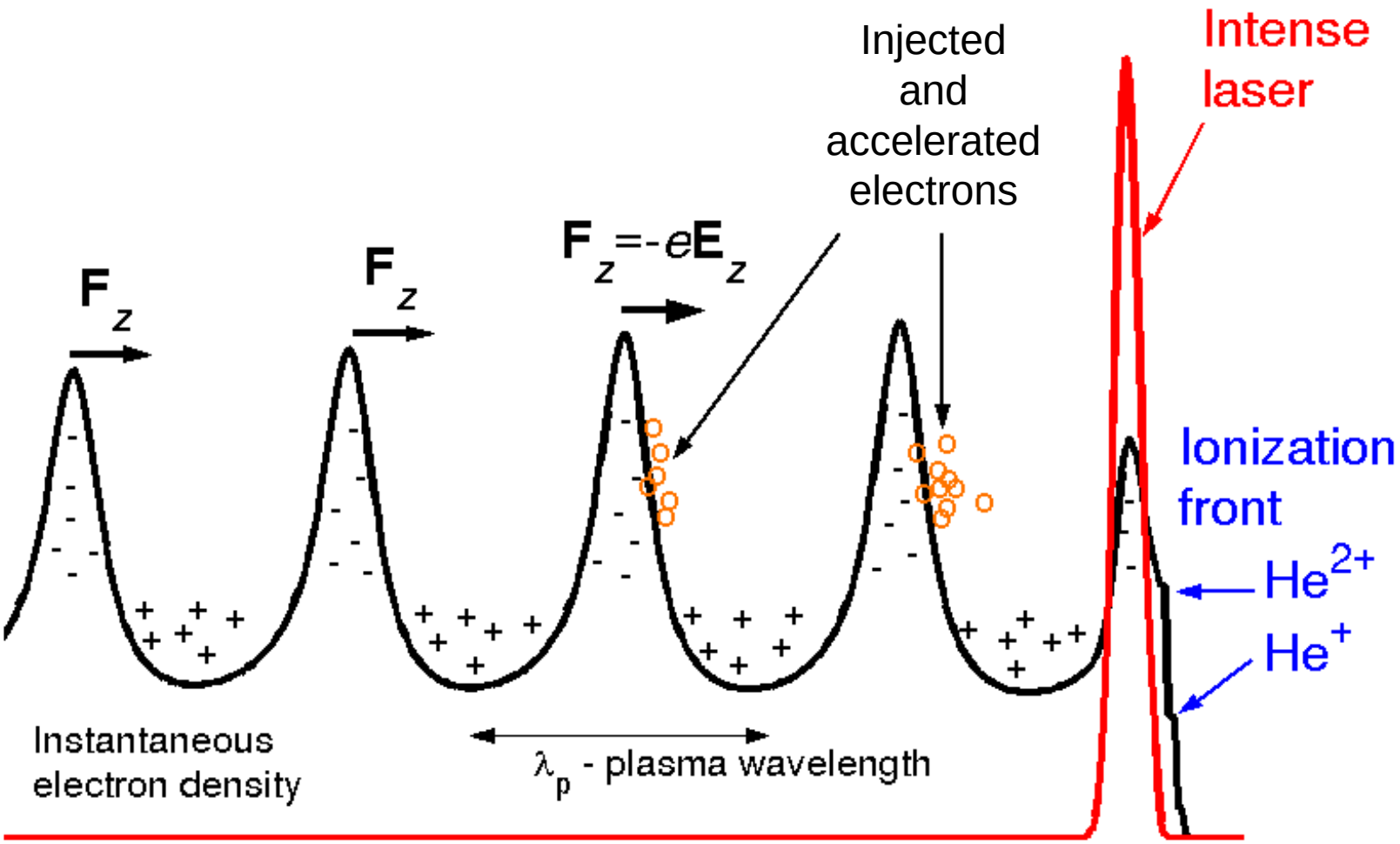
Outline

- Laser wakefield accelerators (LWFA) in the petawatt regimes – physical aspects
- Texas Petawatt – parameters of the laser system and experimental configuration
- Brief review of simulation tools
- Stability of the TPW laser beam and plasma wake: reduced PIC simulations
- Electron injection: reduced 3D and full 2D PIC simulations

Introduction to laser wakefield accelerators (LWFA)

Laser Wakefield Accelerator



T. Tajima and J. M. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979)

Why doing LWFA with a Petawatt laser?

Petawatt power (~10^{15} W) +
pulse duration $\leq$ 150 fs ($\leq 2\pi/\omega_{pe}$)

Self-guiding over cm-long plasmas of density ~10^{17} cm^{-3}

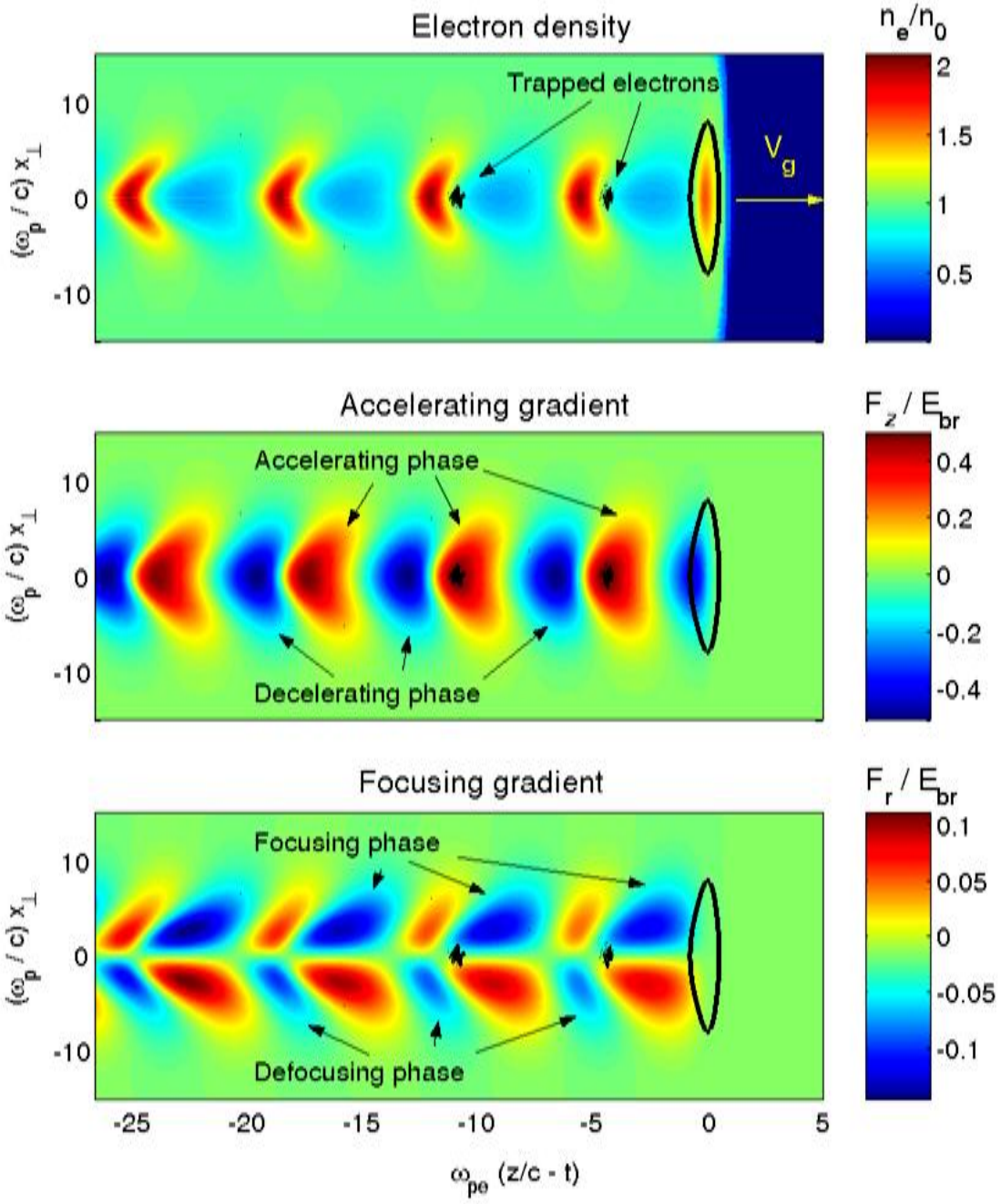
Peak intensity above 10^{19} W/cm^2 even with the large focal spot (>50 μm)

Maintaining the accelerating gradient
$E_{acc} \sim E_{br} \approx (n_e[\text{cm}^{-3}])^{1/2}$
~ tens of GV/m

GeV electrons from cm-long plasmas without external guiding

How well we can do in terms of accelerated charge?

5% of energy transferred from a 200 J, 150 fs laser pulse to a 3 GeV mono-energetic electron bunch implies 3 nC of accelerated charge (actual charge may be smaller due to beam loading or inefficient injection).



LWFA with Petawatt laser: Standard Scheme:

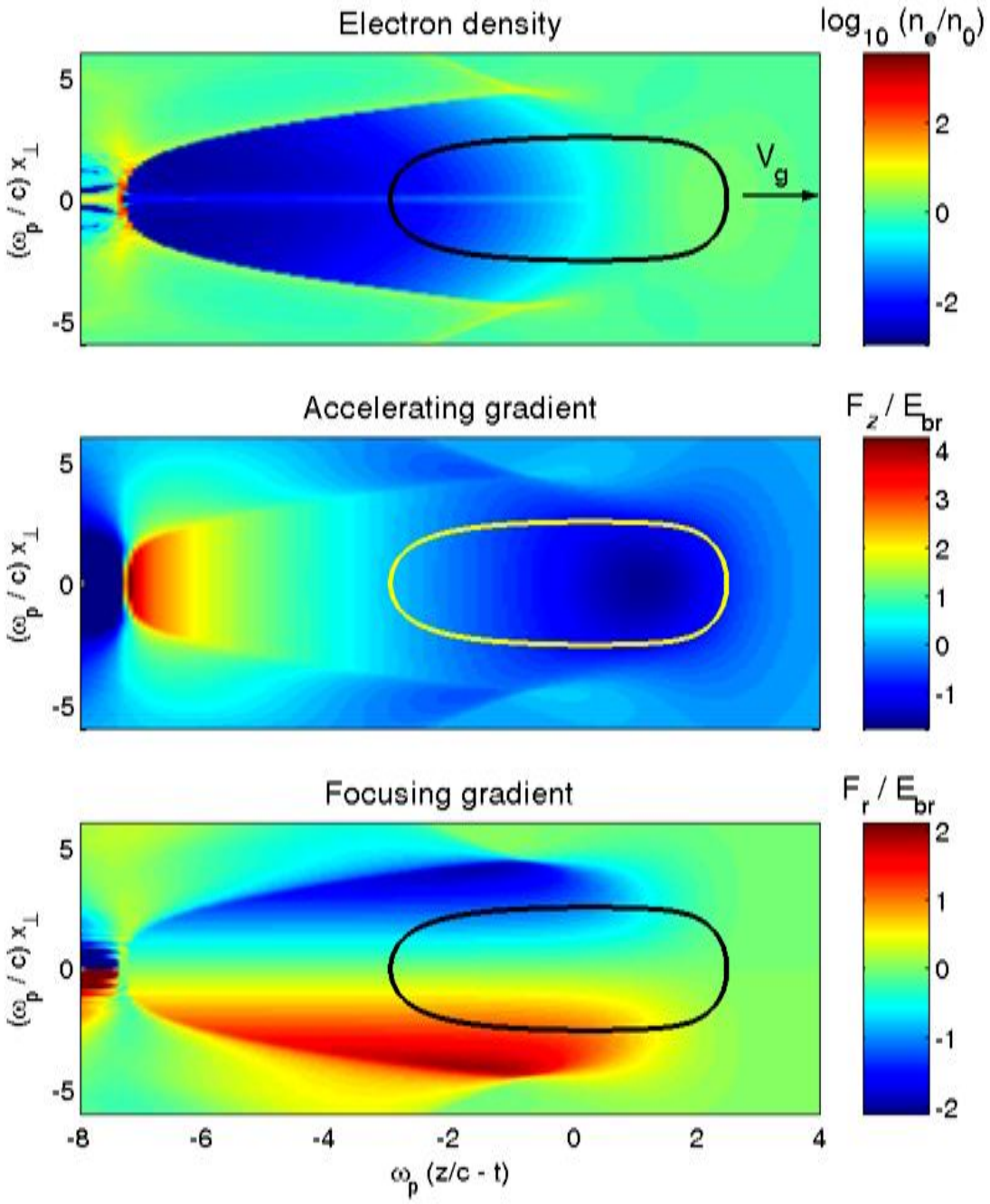
1. Non-broken plasma wave
2. Mostly laminar electron flow
3. Accelerating gradient:

$$E_{\mathrm{acc}} \le E_{\mathrm{br}}$$

$$E_{\mathrm{br}} \approx 0.96 (n_0[\mathrm{cm}^{-3}])^{1/2}\ \mathrm{V/cm}$$

4. Almost entire accelerating bucket is focusing
5. External injection (RF gun, optical methods, density tapering…)

S. Yu. Kalmykov, L. M. Gorbunov, P. Mora, and G. Shvets, *Phys. Plasmas* **13**, 113102 (2006)



LWFA with Petawatt laser: Blowout regime:

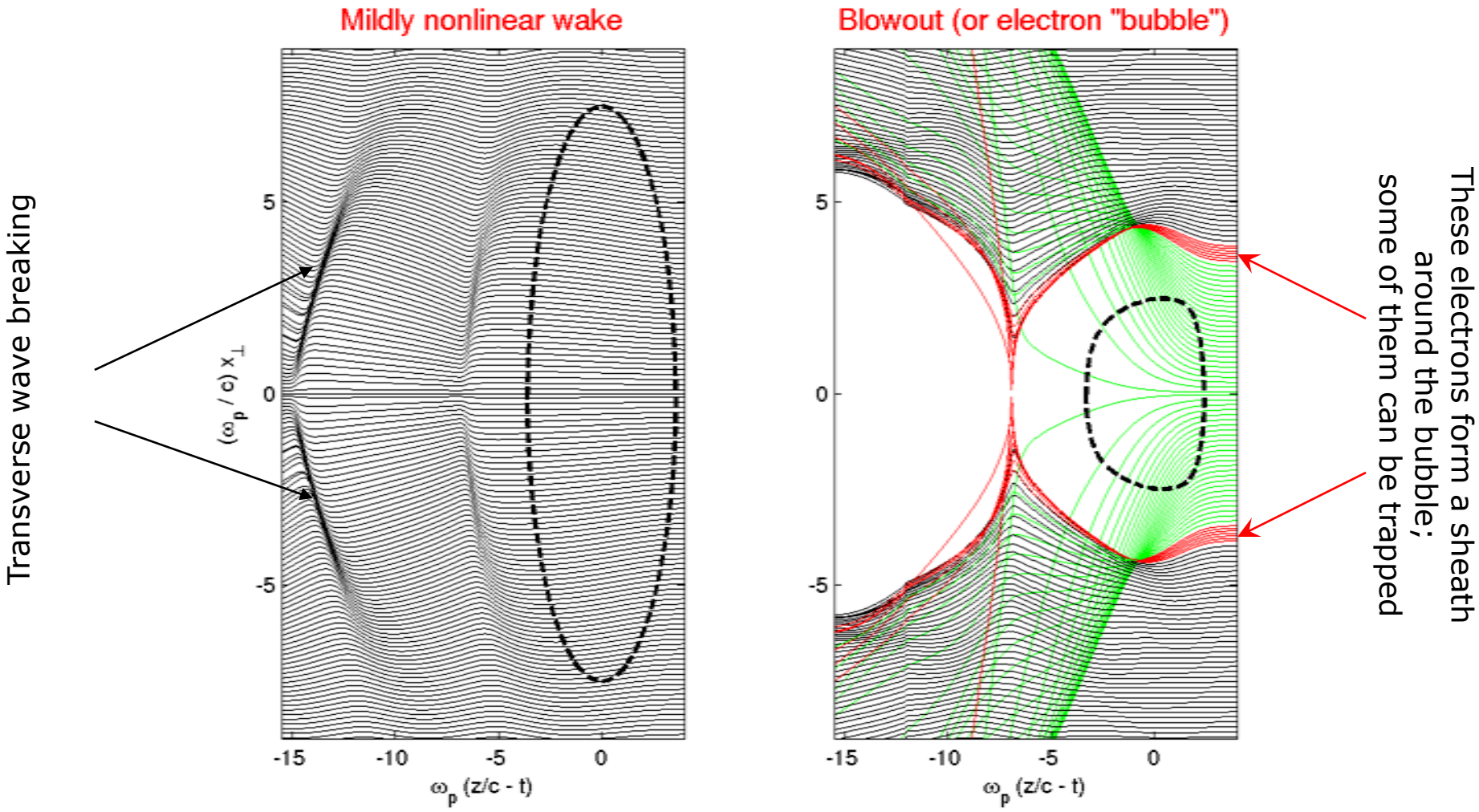
1. Full electron evacuation in the first bucket
2. Multi-stream, mostly transverse electron motion
3. Accelerating gradient:

$$E_{\mathrm{acc}} > E_{\mathrm{br}}$$

4. Entire accelerating bucket is focusing
5. Self-injection (no need of external injection)

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

Dynamics of plasma electrons in nonlinear laser wakes



Maps of electron trajectories are from the same simulation for TPW-LWFA parameters

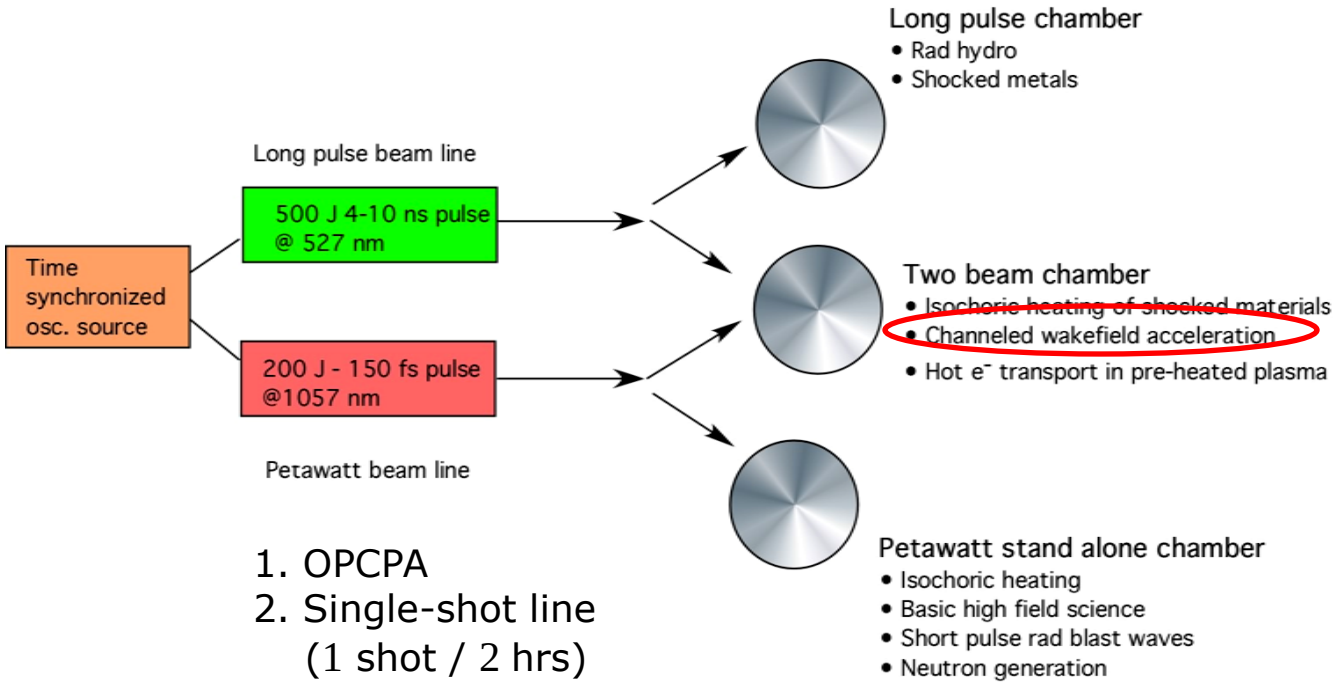
Left: $z = 0$ (laser focal plane, start of the simulation),

Right: $z = 9.5$ mm ($\approx 0.5\ Z_R$)

Texas Petawatt:
parameters of the laser system and experimental configuration

Texas Petawatt: The shortest true Petawatt laser in the world

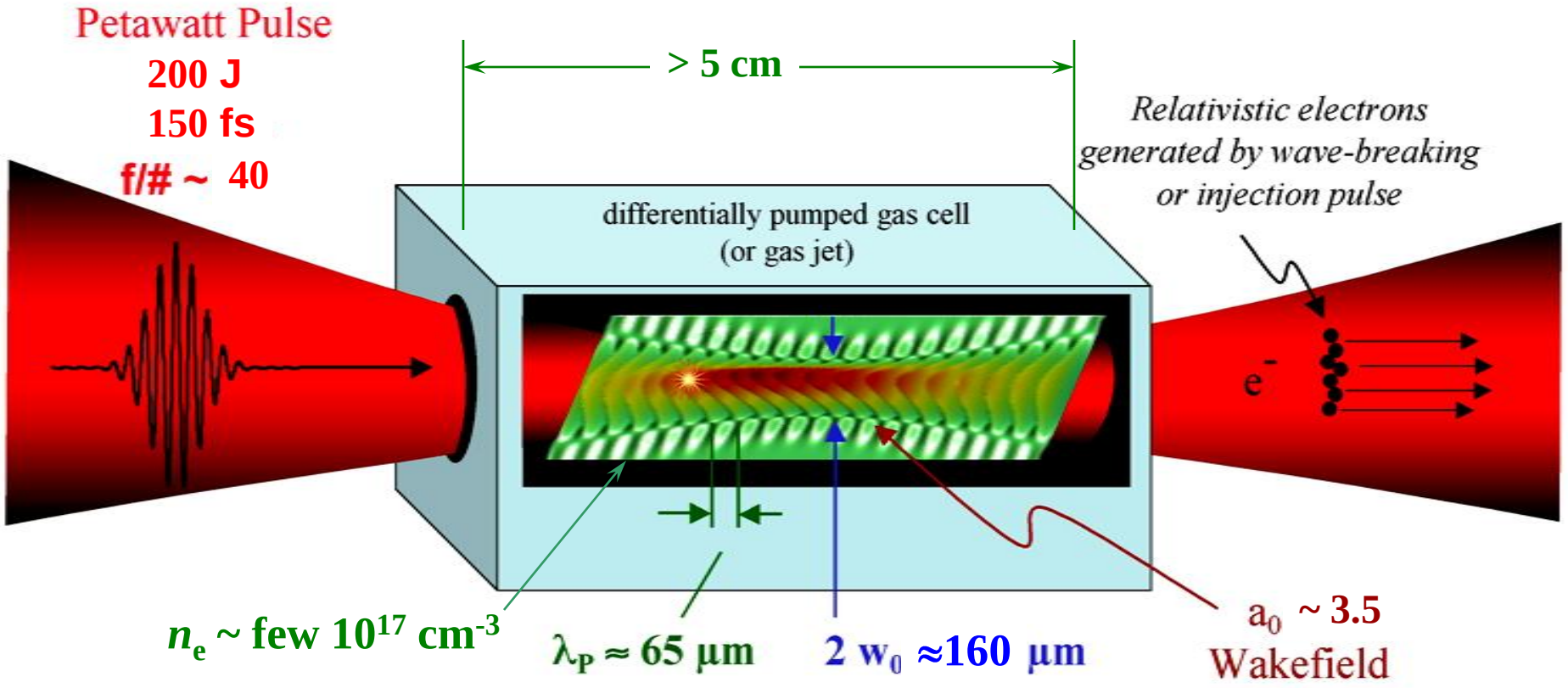
Conceptual block diagram of the Texas Petawatt Laser



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

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

Sketch of TPW-LWFA experiment



(Courtesy M. C. Downer)

The regime is unique:

1. All the LWFA's with self-injection operated so far at $n_e > 5\ 10^{18}$ cm^{-3}
2. Non-guided LWFA's were limited to few mm propagation

Challenge: Because of the huge domain, reduced simulation models must be used!

Experimental strategy

- Maximize the energy of electrons, minimize the energy spread.

- Rely on laser beam self-guiding

- Minimize the number of laser pulses in the interaction region

- Rely on the electron self-injection from ambient plasma instead of external injection: regime with the electron blowout is the most favorable

- Redundancy: explore options of external injection for low plasma densities ($\sim 10^{17}$ cm^{-3}) when the "bubble" formation and self-injection are unlikely.

Parameter optimization is pursued with the
aggressive PIC modeling
using both reduced (WAKE) and full (VLPL) relativistic 3D codes.

Brief review of simulation tools

I. Simulation tools

WAKE [P. Mora and T. M. Antonsen, Jr., Phys. Plasmas **4**, 217 (1997)]

- Fully relativistic particle-in-cell code, "moving window"
- Quasi-paraxial solver for radiation beam propagation (group velocity dispersion of radiation in plasma included)
- Quasi-static electron response to the time-averaged (over laser period) ponderomotive force excludes electron self-injection; enormously speeds-up particle pushing
- 2D planar or 3D axi-symmetric geometry
- Fully 3D test particle tracking code (allows to model self-injection)

WAKE is perfect for fast optimization of the laser and plasma wake dynamics

II. Simulation tools

Virtual Laser Plasma Lab (**VLPL**) [A.Pukhov, J. Plasma Physics **61**, 425(1999)]

- Fully electromagnetic explicit relativistic 3D PIC code; moving window

- Maxwell solver with the eliminated numerical group velocity dispersion in the direction of propagation;

  preserves accuracy with coarse meshes and large time steps (~10 grid points per radiation wavelength, ~8-10 ppc) over cm-long propagation distance in rarefied plasmas

- Parallelized (MPI, domain decomposition); we run it on the Lonestar cluster on >200 processors

  linear performance scaling with the number of processors

We use VLPL to self-consistently model the electron injection from ambient plasmas.

Accelerating structure stability: Reduced PIC simulations

Self-guiding – the key point of TPW-LWFA experimental strategy

Self-guiding is a multi-faceted process at high laser power:

1. Relativistic self-focusing
2. Ponderomotive channeling (including plasma wave induced guiding)
3. Longitudinal effects (e.g., nonlinear phase self-modulation due to the relativistic mass effect and electron density perturbations and subsequent temporal pulse compression due to the GVD of plasma)

The planned experiments will demonstrate all these effects to the full extent!

I. Regime with compensated nonlinearities

$$\omega_{pe}\tau_{laser} < 1, \qquad P_{laser} >> P_{cr}$$

MAIN FEATURES:

- Relativistic mass effect due to electron oscillation in the laser field cancels with the ponderomotive nonlinearity (electron density perturbation)
- Plasma lensing is drastically reduced $\Rightarrow$ enhanced laser stability
- Strongly overcritical pulse propagates (diffracts) in plasma as in vacuum

POTENTIAL DISADVANTAGES FOR TPW-LWFA:

- Too low plasma density for 150 fs laser ($< 5\ 10^{16}$ cm^{-3}) $\Rightarrow$ low accelerating gradient $\Rightarrow$ large propagation distance is needed
- Large acceleration distance in homogeneous plasma can only be achieved at the expense of initially large focal spot $\Rightarrow$ low accelerating gradient
- External electron injection is required.

P. Sprangle, E. Esarey, and A. Ting, *Phys. Rev. A* **41**, 4463 (1990)
L. M. Gorbunov, S. Yu. Kalmykov, and P. Mora, *Phys. Plasmas* **12**, 033101 (2005)

II. Regime with stationary ponderomotive cavitation

$$\omega_{pe}\tau_{laser} >> 2\pi, \qquad P_{laser} \geq 1.1 P_{cr}$$

MAIN FEATURES:

- Relativistic mass effect results in a pulse collapse
- Transverse ponderomotive force creates a co-moving channel devoid of electrons in the region occupied by laser beam
- Laser is guided by the channel over many Rayleigh lengths.

POTENTIAL DISADVANTAGES FOR TPW-LWFA:

- Electrons trapped in the channel can experience a direct laser acceleration. This mechanism, however, is not suitable because the acceleration is not monoenergetic
- Threat of stimulated Raman side-scattering/filamentation because of the large pulse duration: the laser beam can break up before collapse.

G.-Z. Sun, E. Ott, Y. C. Lee, and P. Guzdar, *Phys. Fluids* **30**, 526 (1987)
P. Mora and T. M. Antonsen, Jr., *Phys. Plasmas* **4**, 217 (1997)

III. Regime with dynamic ponderomotive cavitation (blowout, or "bubble" regime) – the operating regime for TPW-LWFA

$$1 < \omega_{pe}\tau_{laser} < 2\pi, \qquad k_p r_0 \approx 2\sqrt{a_0}, \qquad P_{laser} >> P_{cr}$$

MAIN FEATURES:

- Radial ponderomotive force expels all the electrons and creates the region devoid of electrons ("bubble") in the wake of the laser pulse
- Focusing by the transverse density gradient in the bubble and temporal compression guide the laser pulse over many Rayleigh lengths.

ADVANTAGES FOR TPW-LWFA:

- Acceleration of self-trapped electrons is quasi-monoenergetic. Self-trapping is facilitated by density gradients and the effects of nonlinear laser evolution
- Threat of SRS/filamentation is greatly reduced because of the small pulse duration $\Rightarrow$ insensitivity to the quality of the focal spot.

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

Some remarks on the bubble regime simulations for TPW-LWFA

$$1 < \omega_{pe}\tau_{laser} < 2\pi, \qquad k_p r_0 \approx 2\sqrt{a_0}, \qquad P_{laser} >> P_{cr}$$

- The **only** parameter that can be easily changed in the experiment is electron density
- Simulations are being made in plasmas of density $0.5 < n_e < 5\ 10^{17}$ cm^{-3} (the first condition satisfied)
- PW beam is imperfect

⇓

focal spot size exceeds 80 microns in the experiment

⇓

second condition is **never** satisfied initially

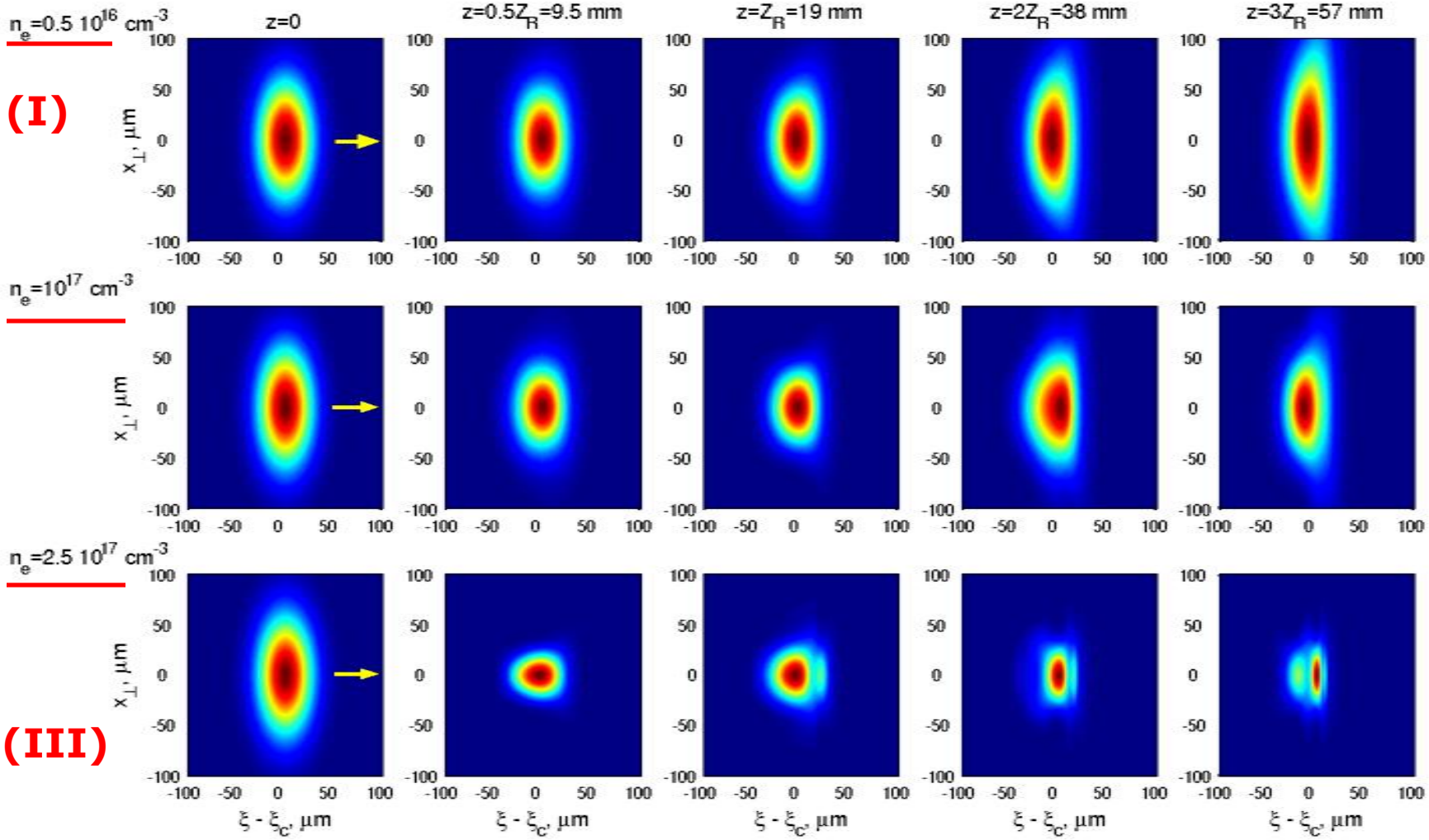
⇓

inception of self-guided propagation is seen only after ~ 1 cm propagation

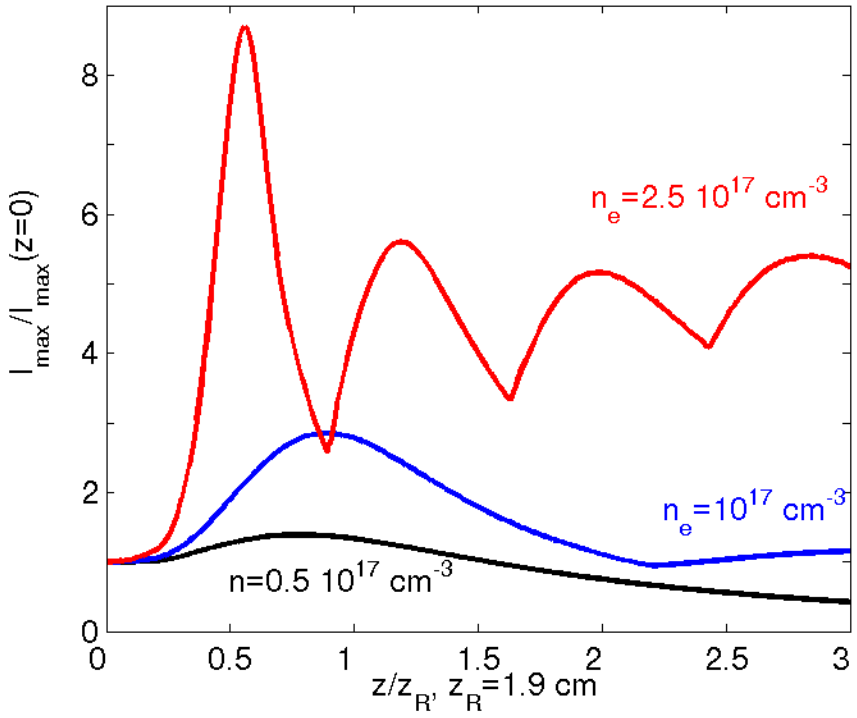
⇓

Self-guided stage is inaccessible for the direct full PIC modeling (**only reduced PIC!**)

Nonlinear guiding in the TWP-LWFA: WAKE simulations



Nonlinear guiding – peak intensity



$n_e = 0.5\ 10^{17}$ cm^{-3} → regime (I)

$n_e = 10^{17}$ cm^{-3} → transition from (I) to (III)

$n_e > 2.5\ 10^{17}$ cm^{-3} → regime (III)

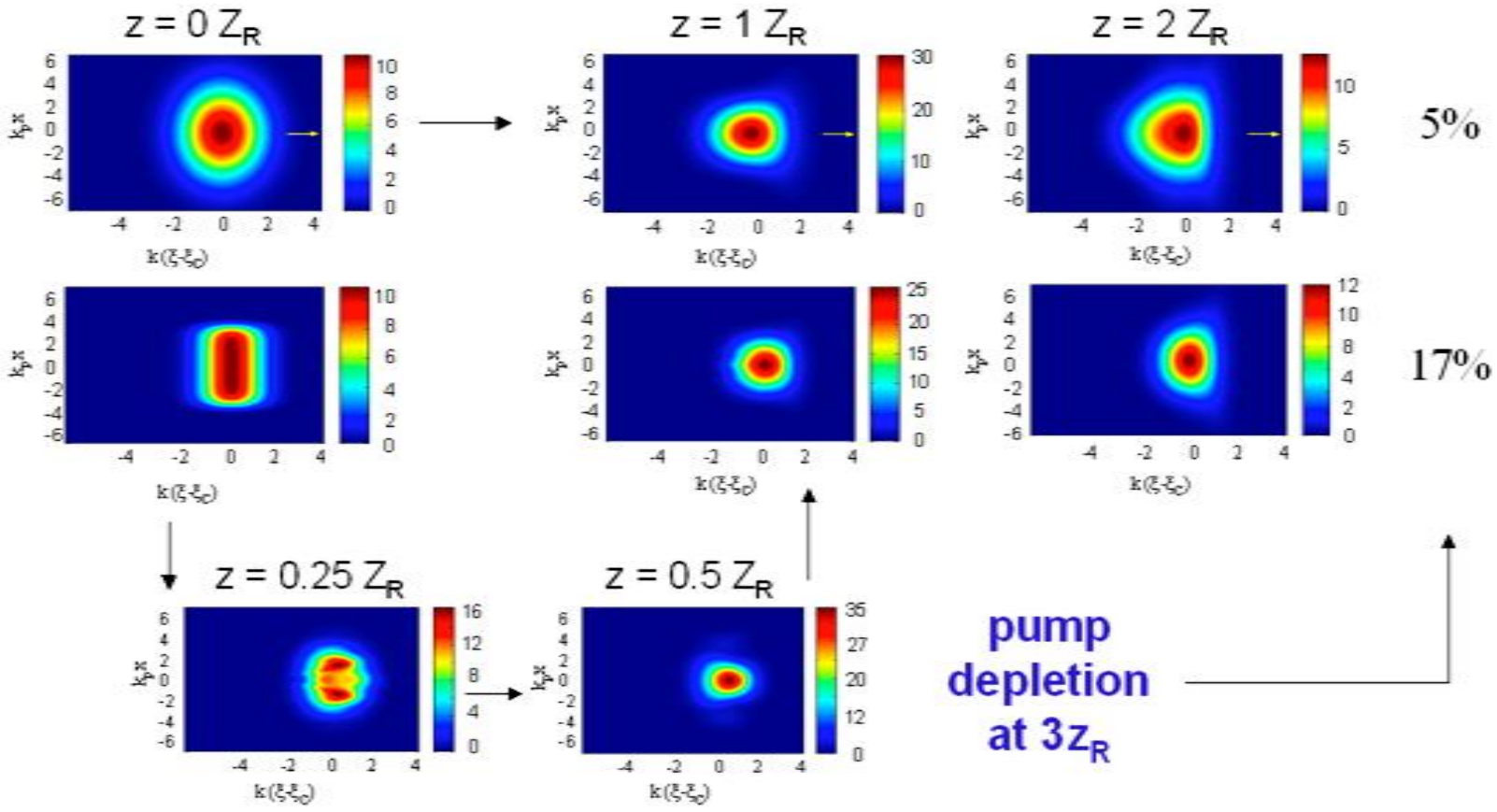
Laser stability against non-ideal (non-Gaussian) spot profile

$n_e = 10^{17}$ cm^{-3}:

$P_{laser}/P_{cr} = 7.7$

Gaussian:

Super-Gaussian 4th order



Laser stability against the localized spot perturbations in the TPW-LWFA

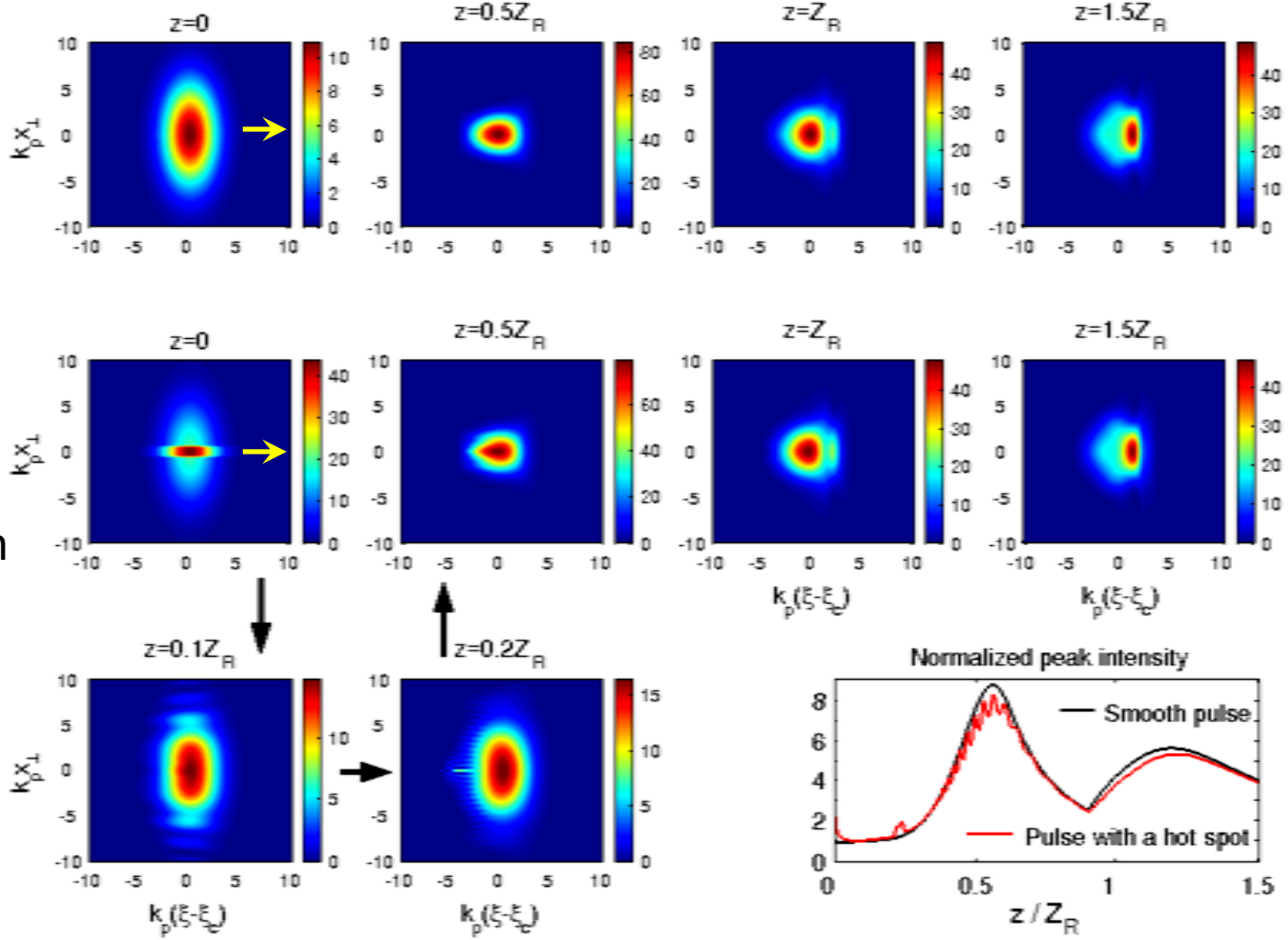
$n_e = 2.5\ 10^{17}$ cm^{-3}: $P_{laser}/P_{cr} \approx 20$

Gaussian:

Gaussian +

super-Gaussian hot spot +

localized phase perturbation:



Bubble stability against the localized laser spot perturbations

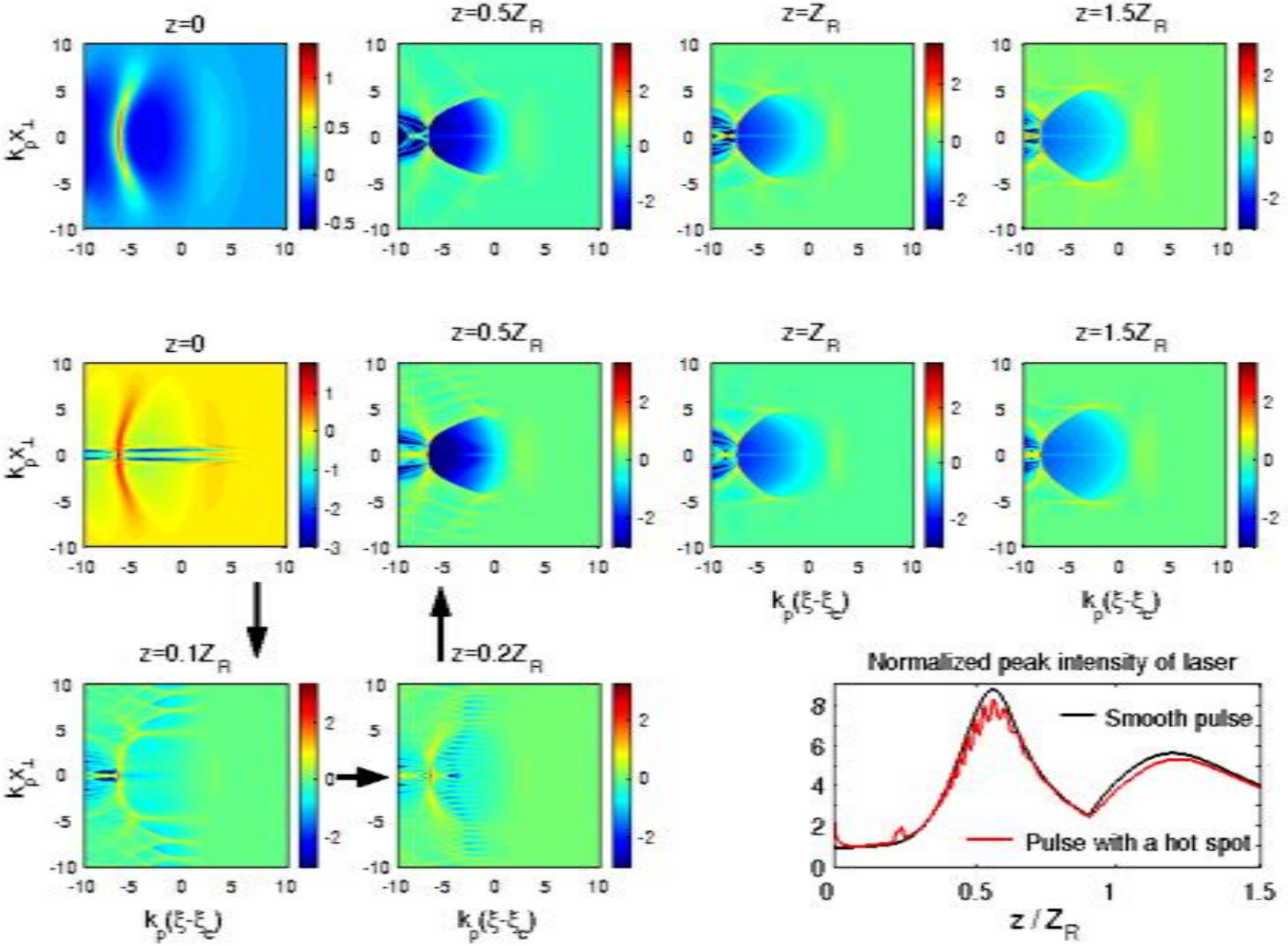
$n_e = 2.5\ 10^{17}$ cm^{-3}: $P_{laser}/P_{cr} \approx 20$

Gaussian:

Gaussian +

super-Gaussian hot spot +

localized phase perturbation:



Electron injection: Reduced 3D and full 2D PIC simulations

Acceleration of electrons – Towards multi-GeV energies

The laser beam and the plasma "bubble" are remarkably robust

Injected electrons can experience monoenergetic acceleration:

Energy gain ~ 3 GeV over 7.6 cm of plasma with a density 10^{17} cm^{-3}

Normalized r.m.s. emittance

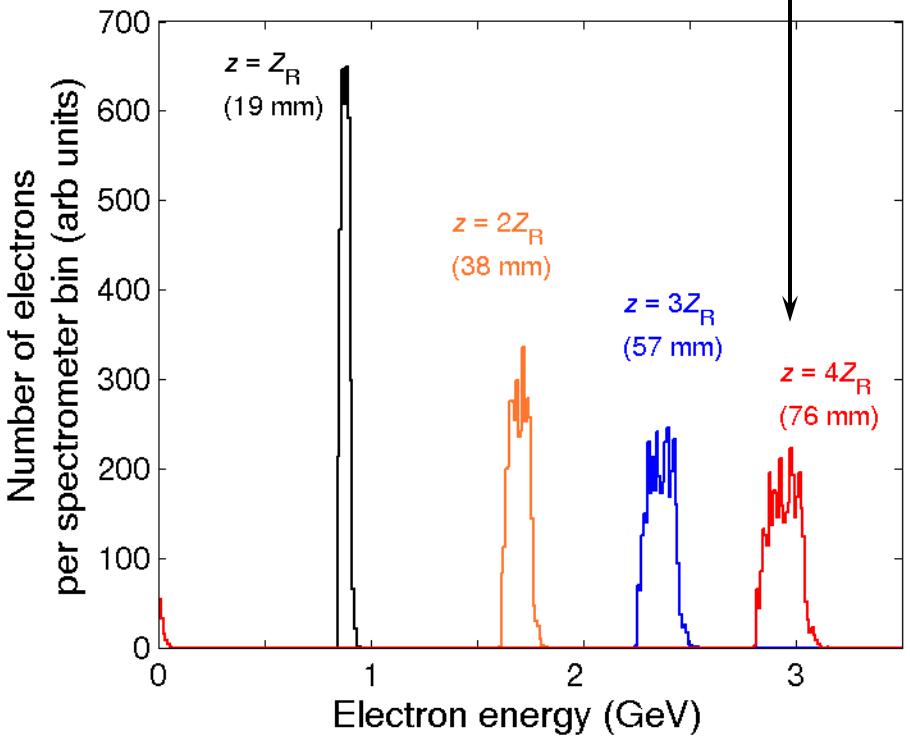
$\gamma\varepsilon_{\perp} < \pi$ mm mrad

Average accelerating gradient:

$E_z \approx 0.4$ GV/cm

$E_z > E_{br} \approx 0.3$ GV/cm

How do the electrons get injected???



Self-injection:

1. Self-injection in the longitudinally uniform plasmas (transverse wave breaking *etc*.)

2. Plasma density tapering/longitudinal density gradients:
   dense thin pre-plasma slab/gas jet in front of/embedded into the main plasma

3. Exotic targets:
   cluster plasma, nano-targets of solid-state density: foams, nano-wires…

All-optical injection:

1. Counter-propagating pulses: head-on collision

2. Co-propagating pulses: artificially created hot spot

3. Injection by transverse ponderomotive force: LILAC

I. Self-injection in the uniform plasmas

To cause the electron self-injection in the density range $n_e < 5\ 10^{17}$ cm^{-3} the first wake bucket must evolve during the time of electron passage through/around it

Problems: a) Initially Gaussian pulse evolves too steadily to cause self-injection in plasmas with $n_e < 2.5\ 10^{17}$ cm^{-3} (*even in the blowout regime*!)

b) Self-focusing of the Gaussian pulse (80 μm spot) takes about 1 cm of propagation. This excludes direct full multi-dimensional PIC simulations

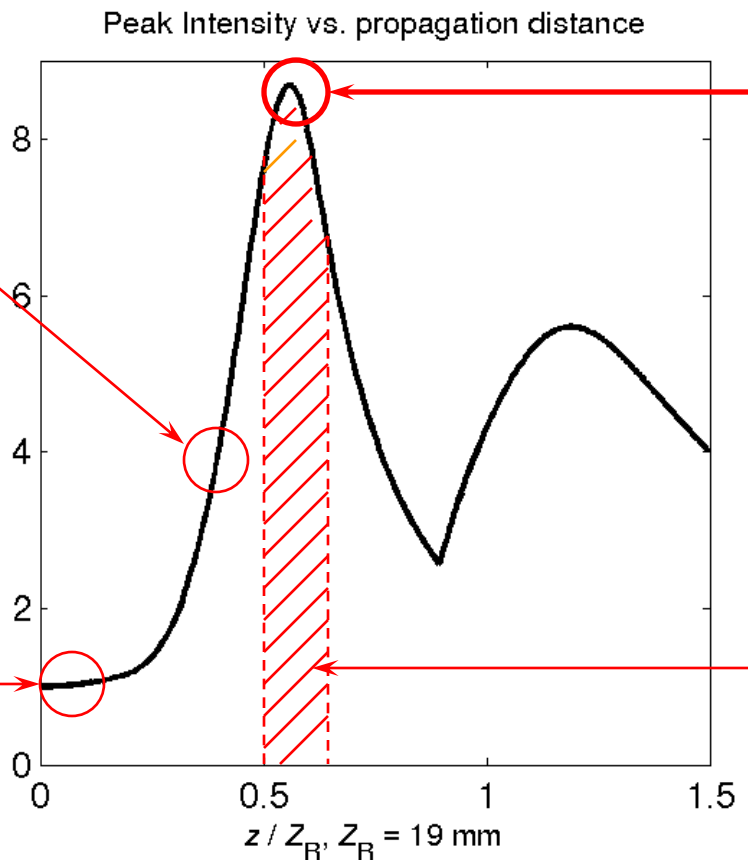
***We resort to the hybrid incremental approach*:**

1. 3D WAKE run gives the evolution of laser intensity and spot with z
2. We establish the suspicious regions (i.e., those where the full electron blowout occurs) along the laser path
3. We put quiescent ($\gamma = 1$) test electrons at each time step ahead of the laser pulse in the suspicious region.
4. If the test electron trapping is observed, we use the laser parameters from the vicinity of this point as the initial condition for the 2D VLPL run.
5. We run 2D VLPL for a few millimeters and validate the self-consistent injection.

II. Self-injection in the uniform plasmas

Electron density: $n_e < 2.5\ 10^{17}\ cm^{-3}$

WAKE result:



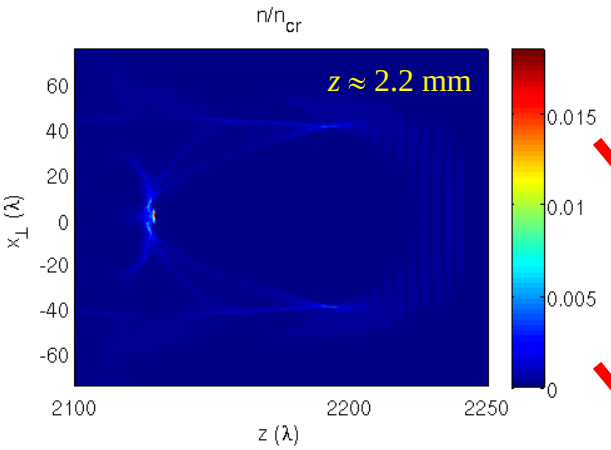
$a_0 \approx 6.6$
$r_0 \approx 40\ \mu m$
Wake is strongly broken:
Still no injection

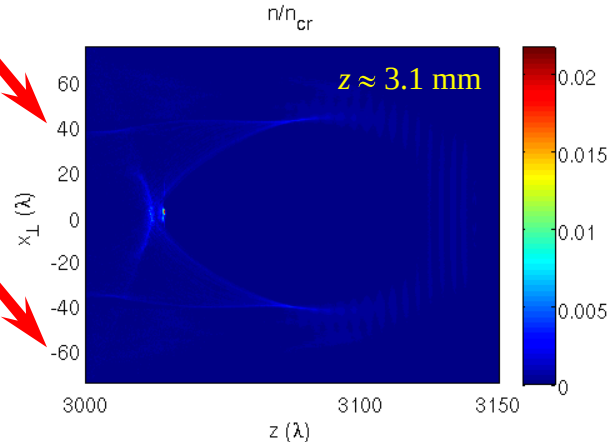
$a_0 \approx 3.3$
$r_0 \approx 80\ \mu m$
Wake is mildly non-linear:
2D VLPL gives no injection

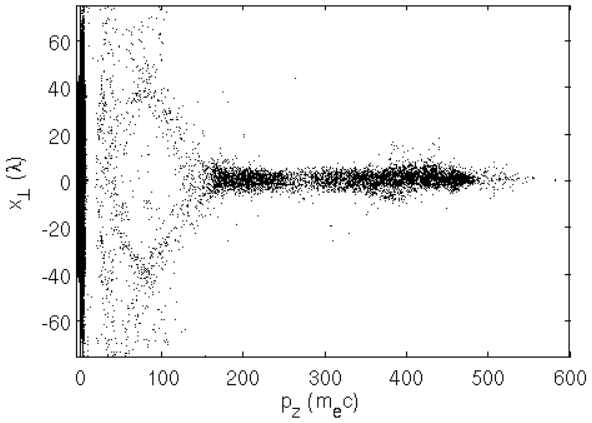
$a_0 \approx 9.9$
$r_0 \approx 27\ \mu m$
Laser diffracts, "bubble" grows
⇓ ⇓
Injection begins!!!

Total blowout ($n_e = 0$) is achieved here;
this zone is suspicious of injection

Self-injection at the point of strongest focusing: VLPL 2D (planar) modeling





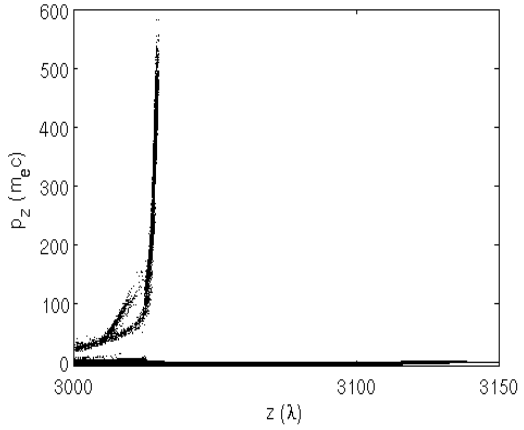


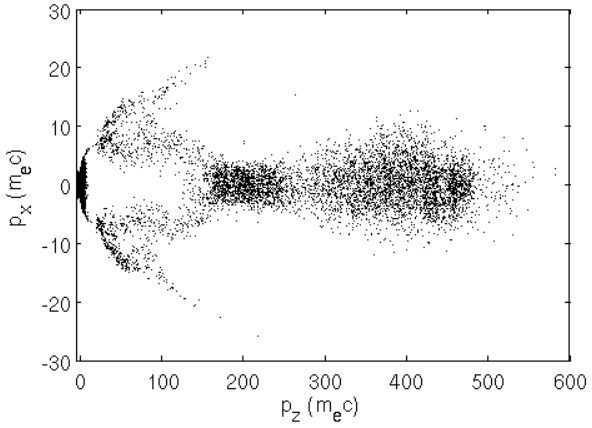
$n_0 = 2.5\ 10^{17}$ cm^{-3}

$a_0 = 3.3 \times 3 = 9.9$

$r_0 = 80\ \mu m / 3 \approx 27\ \mu m$

$P = 1.25$ PW





Self-injection can be expected in plasmas of higher density ($n_e \geq 2.5\ 10^{17}$ cm^{-3}) around the point of tightest laser focus

Injection due to the imperfection of the focal spot

Reaching the blowout regime with the large-spot transversely Gaussian pulse requires at least 1 cm of propagation. In very tenuous plasmas ($\sim 10^{17}$ cm^{-3}) the self-injection is unlikely even in the blowout regime.

Imperfection of the focal spot (a single bright hot spot) can break the wake from the very beginning and keep it broken until the blowout occurs naturally due to laser self-focusing.

The hot spot diffracts (also seeds some filamentation*), but, in the long perspective, keeps the accelerating structure unaffected*. Rapid evolution of the broken wake causes electron trapping almost immediately after the laser entrance into plasma even at $n_e = 10^{17}$ cm^{-3}.

Hint: A hot spot can be created artificially! (by another, low-energy, tightly focused pulse coaxially propagating with the main driver)

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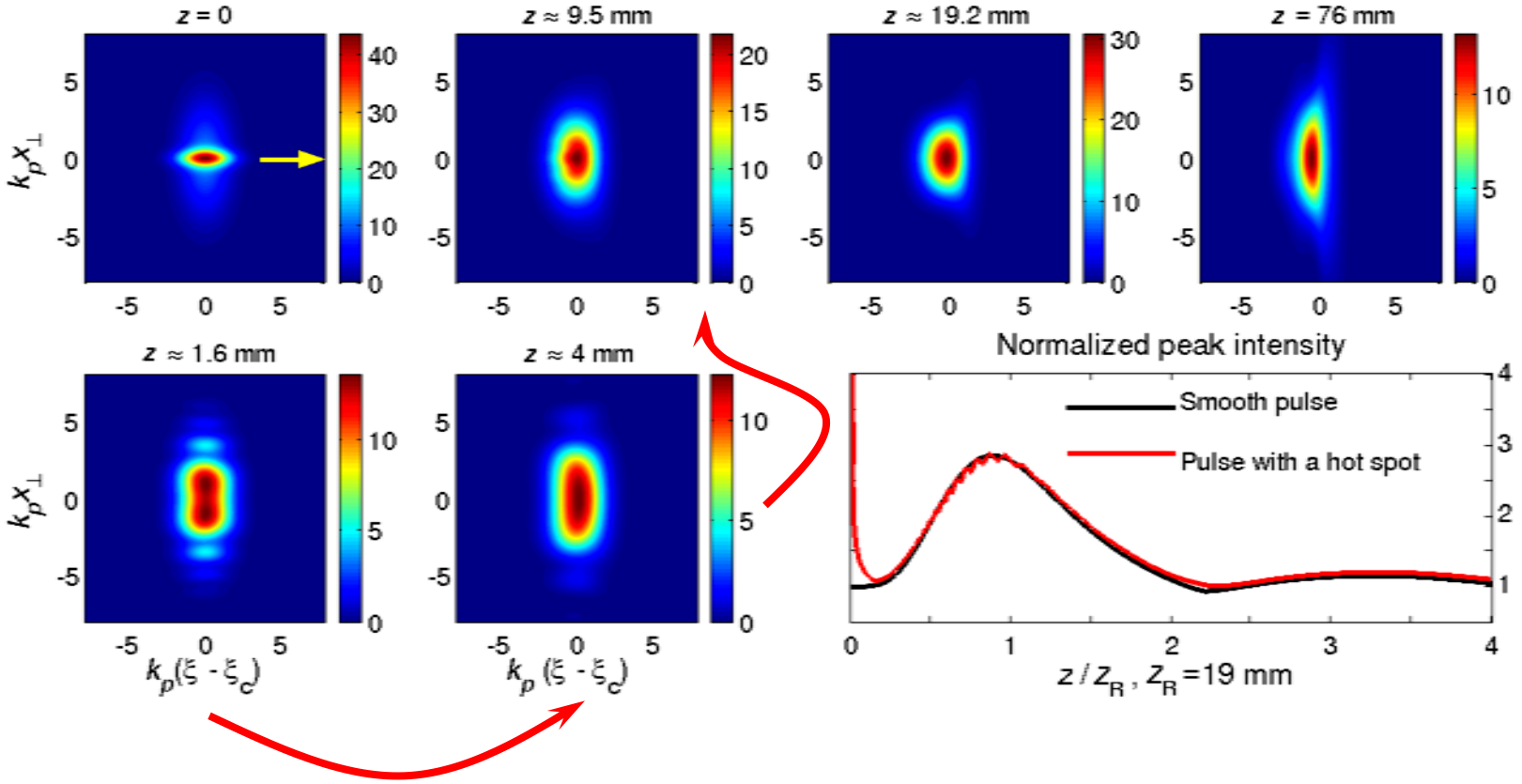
*N. E. Andreev, L. M. Gorbunov, P. Mora, and R. R. Ramazashvili, *Phys. Plasmas* **14**, 083104 (2007)

Hot-spot-triggered injection: 3D WAKE simulation

Normalized laser intensity, $|a(x_\perp,\xi)|^2$:

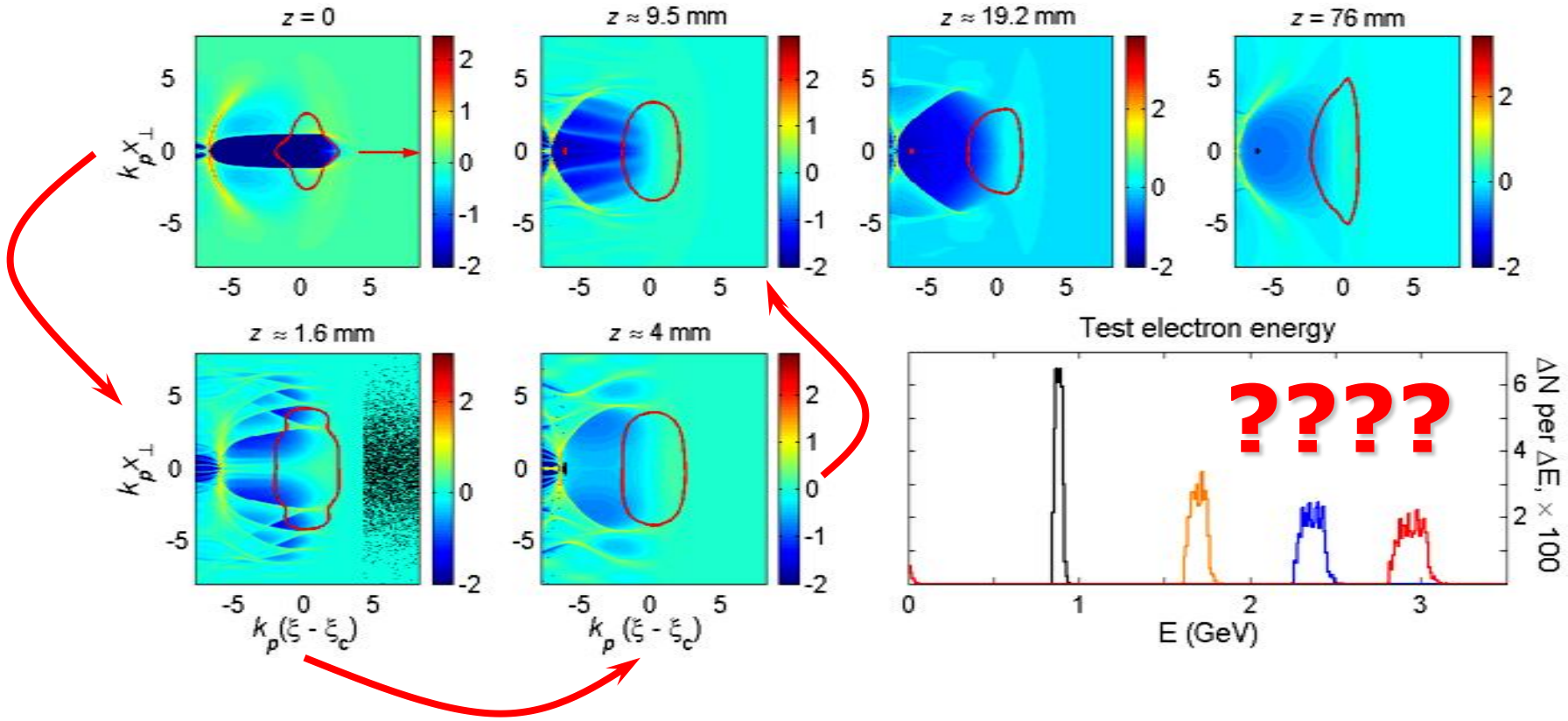


$n_0 = 10^{17}$ cm^{-3}

$a_0 = 3.3$ $r_0 = 80$ μm $Z_{R0} = 19$ mm

$a_1 = 3.3$ $r_1 = 10$ μm $Z_{R1} = Z_{R0}/64 = 0.300$ mm

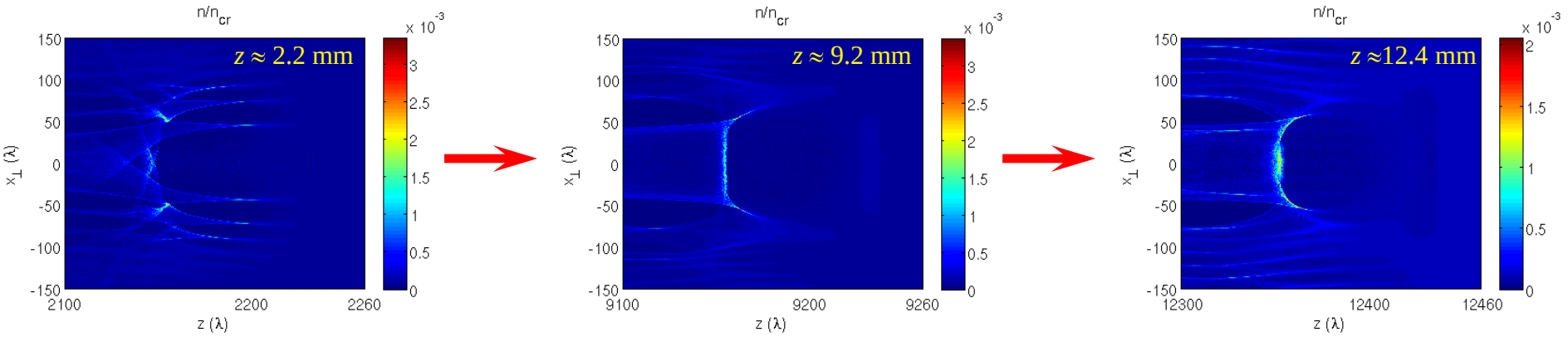
Electron density (on the logarithmic scale)



1. Slab of quiescent ($\gamma = 1$) test electrons is set on the laser path (slab length 0.7 mm)
2. Nonlinear broken wake rapidly evolves as the laser crosses the cloud of test electrons $\Rightarrow$ some electrons get trapped
3. Injection terminates as soon as the test electron slab is expired; monoenergetic acceleration ensues

This picture is not exactly the same as in a full PIC simulation, where the trapping is saturated by beam loading!!!

Hot-spot-triggered injection: 2D-VLPL run



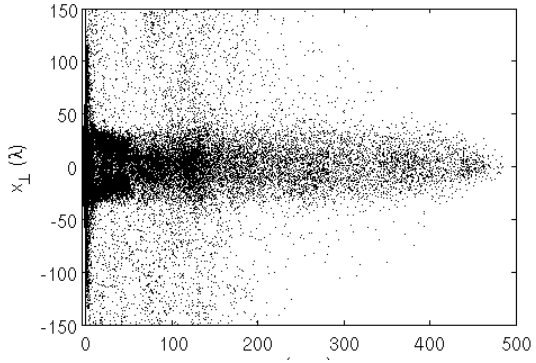
$$\frac{a_1}{a_0} = \frac{1}{\sqrt{2}}$$

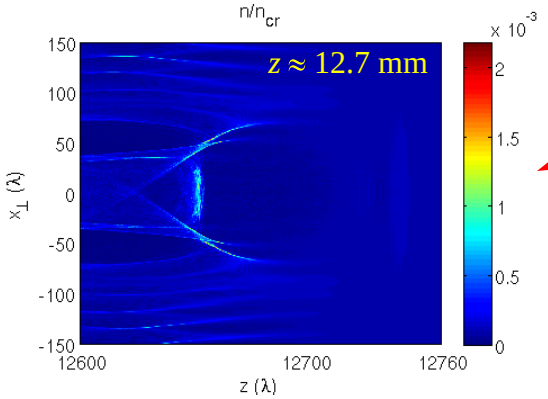
$$\frac{r_1}{r_0} = \frac{1}{8}$$

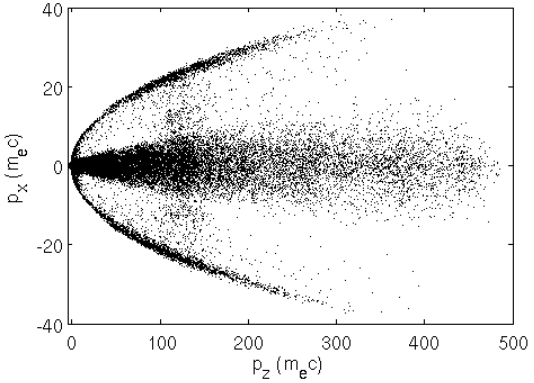
$a_0 = 3.3$

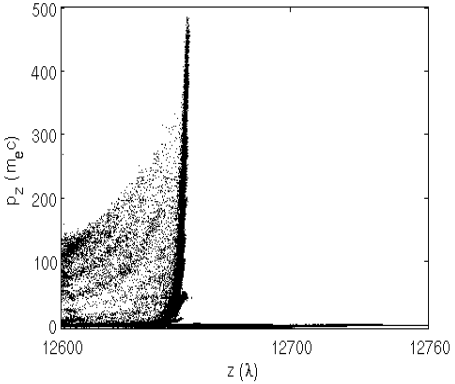
$r_0 = 80\ \mu\text{m}$

$Z_{R_0} = 19\ \text{mm}$









Density down-ramp assisted injection

Phase mixing on the density down-ramp

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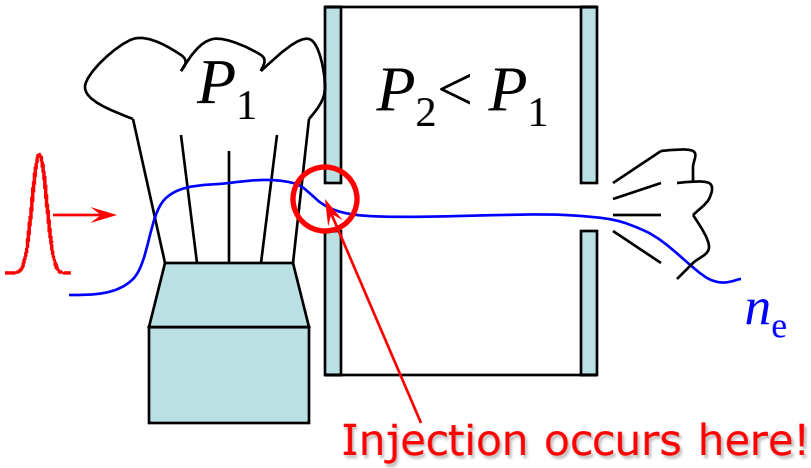
Some electrons end up
in the accelerating-focusing phase
of the first bucket



Problems: Quasi-monoenergetic injection requires

a) small ($< \times 2$) difference between the pre-plasma and main plasma density

b) fine control over the density gradient shape with < 100 μm precision

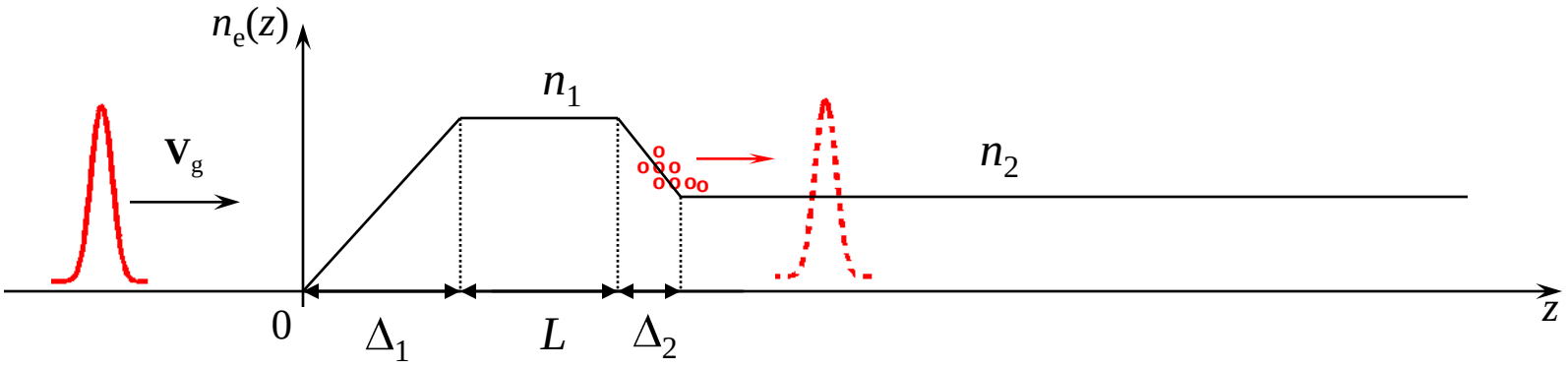
Technically challenging – difficult to produce a controllable density profile on the sub-mm scale at the density $n_e \sim 1 - 5\ 10^{17}$ cm^{-3}.

S. V. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, *Phys. Rev. E* **58**, R5257 (1998)

H. Suk, N. Barov, J. B. Rosenzweig, and E. Esarey, *Phys. Rev. Lett.* **86**, 1011 (2001)

A. V. Brantov, T. Zh. Esirkepov, M. Kando *et al.*, *Phys. Plasmas* **15**, 073111 (2008)

2D-VLPL simulations of the ramp-assisted injection



$\Delta_1 = 250\ \lambda_0$

$L = 250\ \lambda_0$

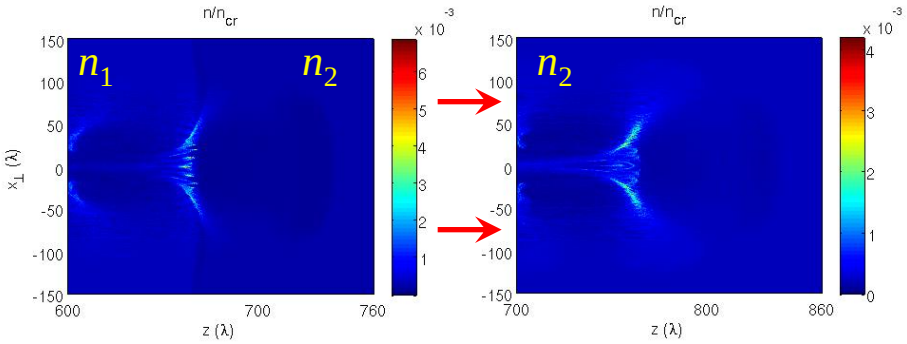
$n_2 = 2.5\ 10^{17}\ \mathrm{cm}^{-3}$

$\Delta_2 = \lambda_0$ or $100\ \lambda_0\ (\approx 1.5\ \lambda_{p2})$

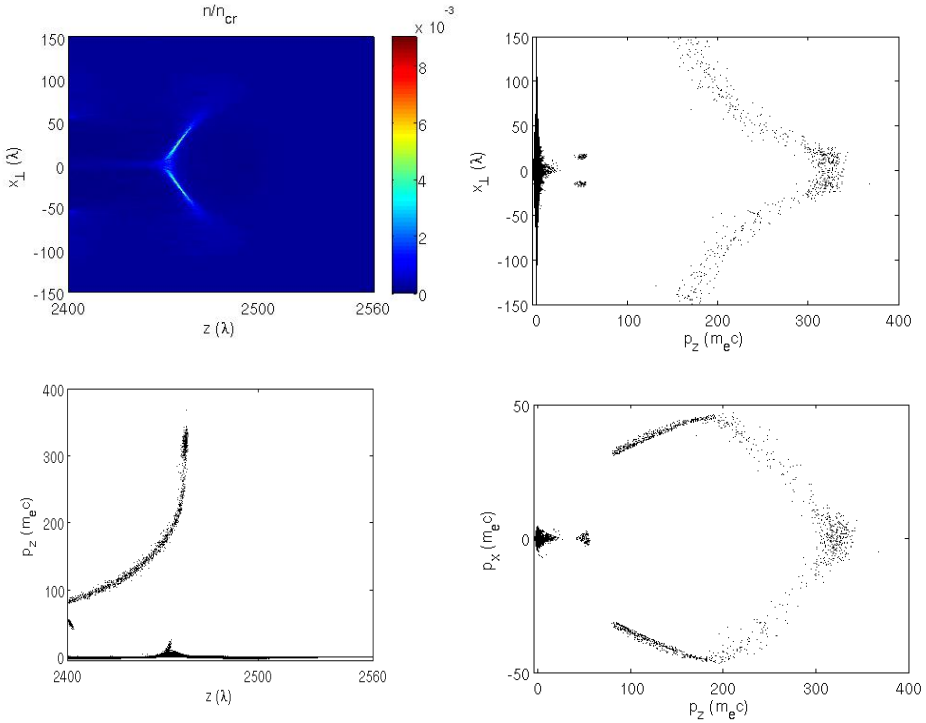
$n_1 = 4$ or $5\ 10^{17}\ \mathrm{cm}^{-3}$

Ramp: down-step by a factor 1.6

Plasma wake near density transition

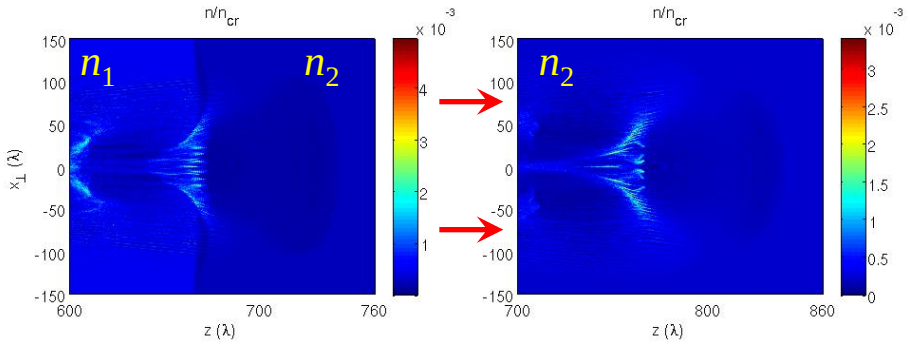


Plasma density around z = 2.5 mm

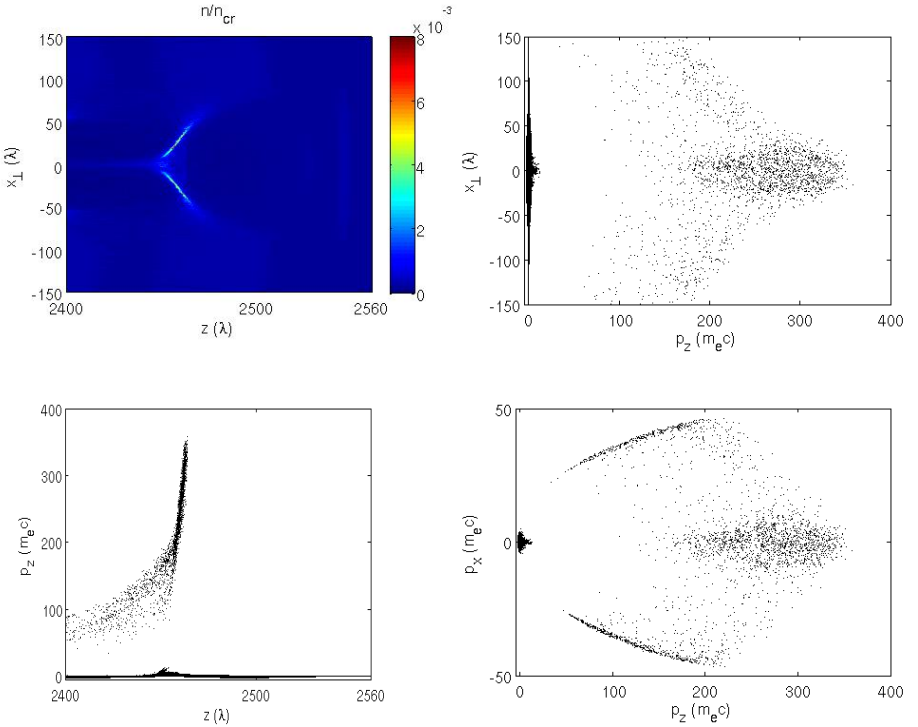


Down-step by a factor 2

Plasma wake near density transition

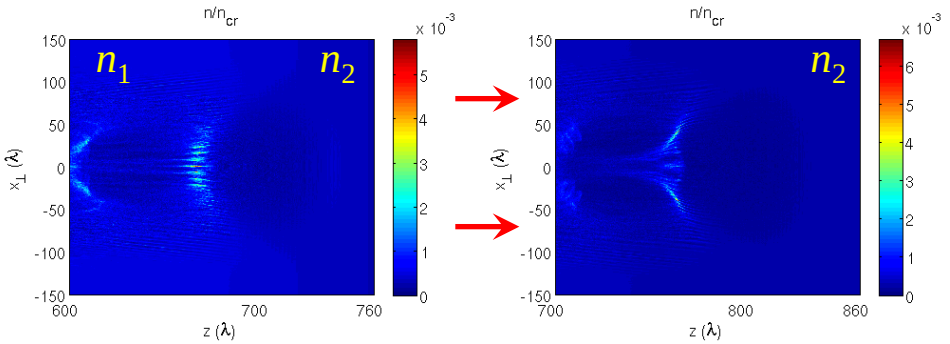


Plasma density around z = 2.5 mm

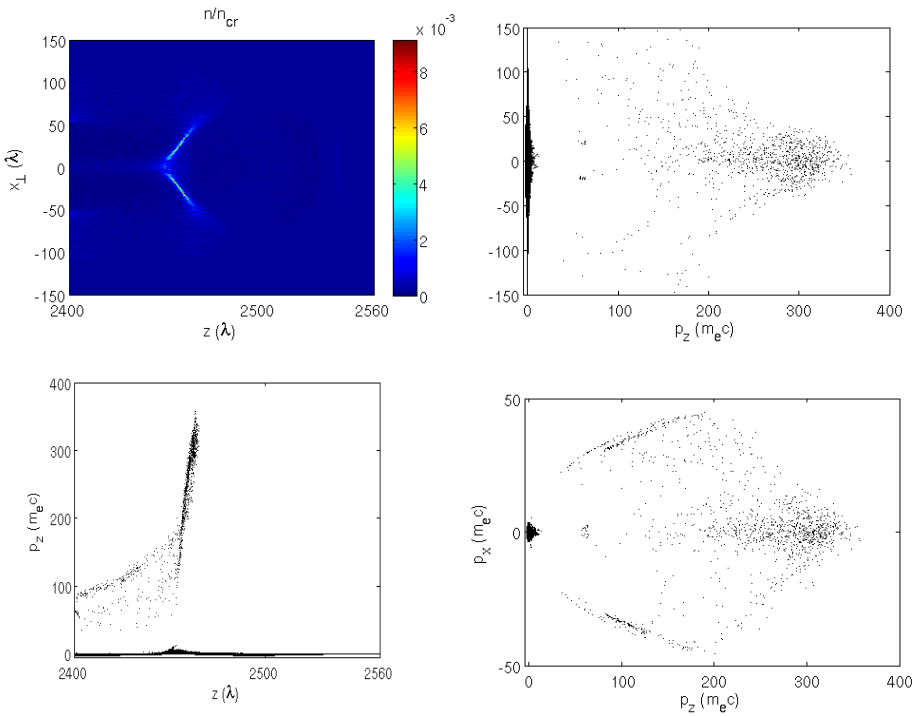


Down-ramp 100 μm, density ratio 2

Plasma wake near density transition

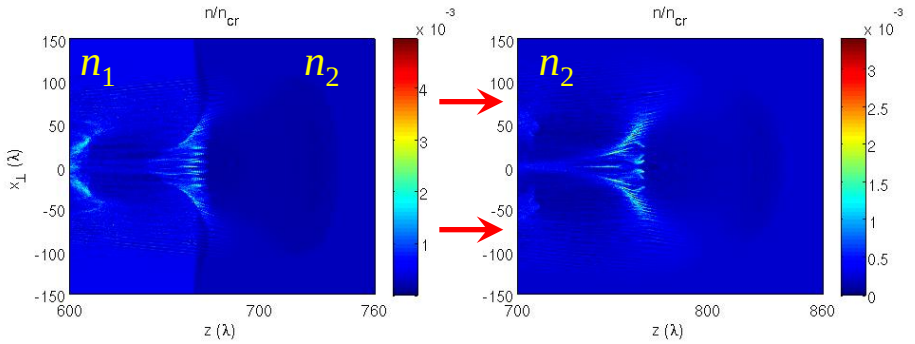


Plasma density around z = 2.5 mm

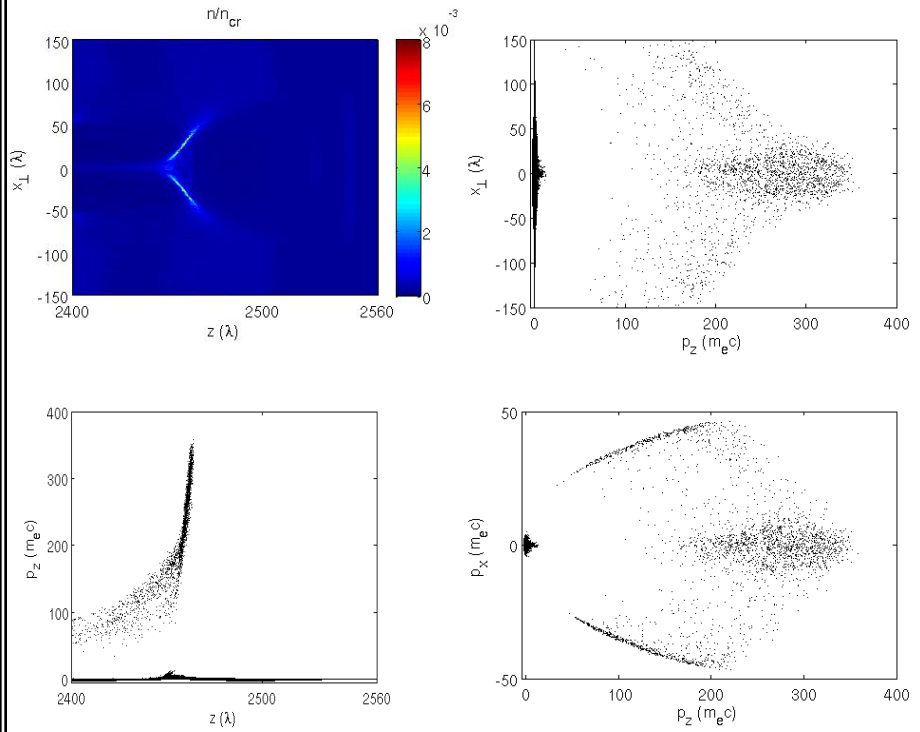


Down-step by a factor 2

Plasma wake near density transition



Plasma density around z = 2.5 mm



Conclusions

1. Nonlinear guiding of the TPW laser pulse can rely on either compensation of nonlinearities (at low densities, ~ 10^{17} cm^{-3}) or the dynamic ponderomotive blowout (at densities $\geq 2.5\ 10^{17}$ cm^{-3}).

2. In both regimes, the long-term evolution of the TPW beam is robust: i.e., quite insensitive to the non-Gaussian intensity profile across the focal spot (e.g., to the presence of hot spots).

3. For smooth, initially Gaussian, beam the electron self-injection in the broken nonlinear wake ("bubble") is expected in dense plasmas only ($\geq 2.5\ 10^{17}$ cm^{-3}).
   Presence of intense hot spots (e.g., created artificially) speeds up the wave breaking and facilitates injection even at low densities (~ 10^{17} cm^{-3}).

4. Additional injection tool (technically demanding, though) is tapering the plasma density (making a sharp density down-ramp on the laser path).

5. Other injection options (head-on colliding laser pulses and nano-targets) are being explored.

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Slides in reserve

Maxwell solver of VLPL: Numerical Dispersion Free in the Z direction explicit multi-dimensional finite difference scheme:

τ - time step

h_z - step in the direction of propagation

$h_x \geq h_z$ - step in the transverse direction

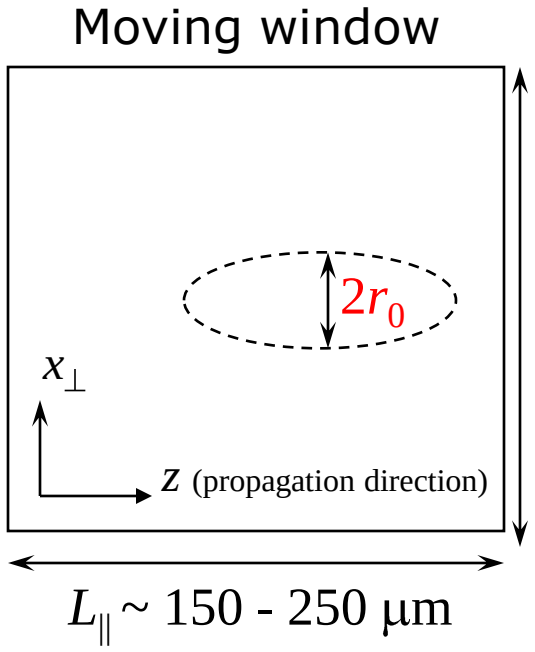
$$\beta_z = 3/4 \qquad \beta_x = 1 - 0.25(h_z / h_x)^2 \qquad \alpha_i = 0.5(1 - \beta_i)$$

$$\frac{1}{\tau^2}\sin^2\frac{\omega\tau}{2} = \frac{1}{h_z^2}\sin^2\frac{k_z h_z}{2}(\beta_x + 2\alpha_x \cos k_x h_x) + \frac{1}{h_x^2}\sin^2\frac{k_x h_x}{2}(\beta_z + 2\alpha_z \cos k_z h_z)$$

Scheme is stable (in vacuum!) even if $c\tau = h_z$; in this limit, using NDFZ removes numerical dispersion for waves running along Z axis ($k_x = 0$, laser propagation direction).

In plasmas of density ~$2.5\ 10^{17}$ cm^{-3} ($n_0/n_c = 2.5\ 10^{-4}$), steps $c\tau = 0.07999\ \lambda_0$, $h_z = 0.08\ \lambda_0$ give a stable propagation of the laser pulse over at least 1.5 cm

Grids and boxes for the TPW simulations



WAKE:

20 grid points per k_p^{-1} in the z direction

12 g. p . per k_p^{-1} in the radial direction

24 particles per radial cell near axis

8 to 3 p. p. c. in the outer areas

Transverse boundaries are absorbing for radiation

VLPL with NDFZ Maxwell solver:

$12 - 30$ g. p. per laser wavelength in the z direction

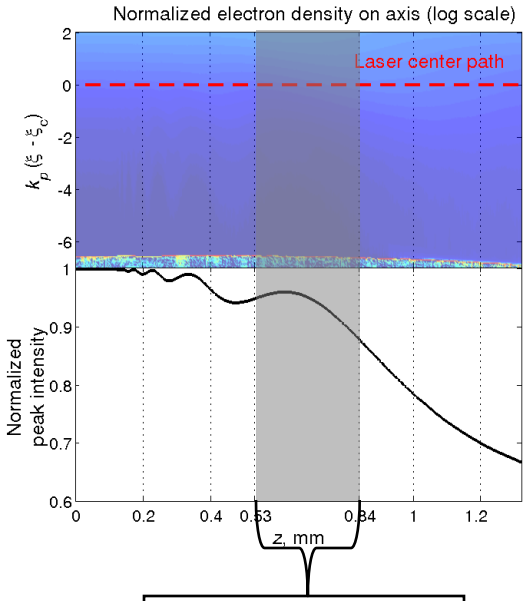
2.5 g. p. per λ_0 in the radial direction

$8 - 10$ p. p. c.

Transverse boundaries are periodic for particles and radiation

$\lambda_0 \sim (0.063 - 0.14)\, k_p^{-1}$
for $n_e \sim (1 - 5)\ 10^{17}$ cm^{-3}

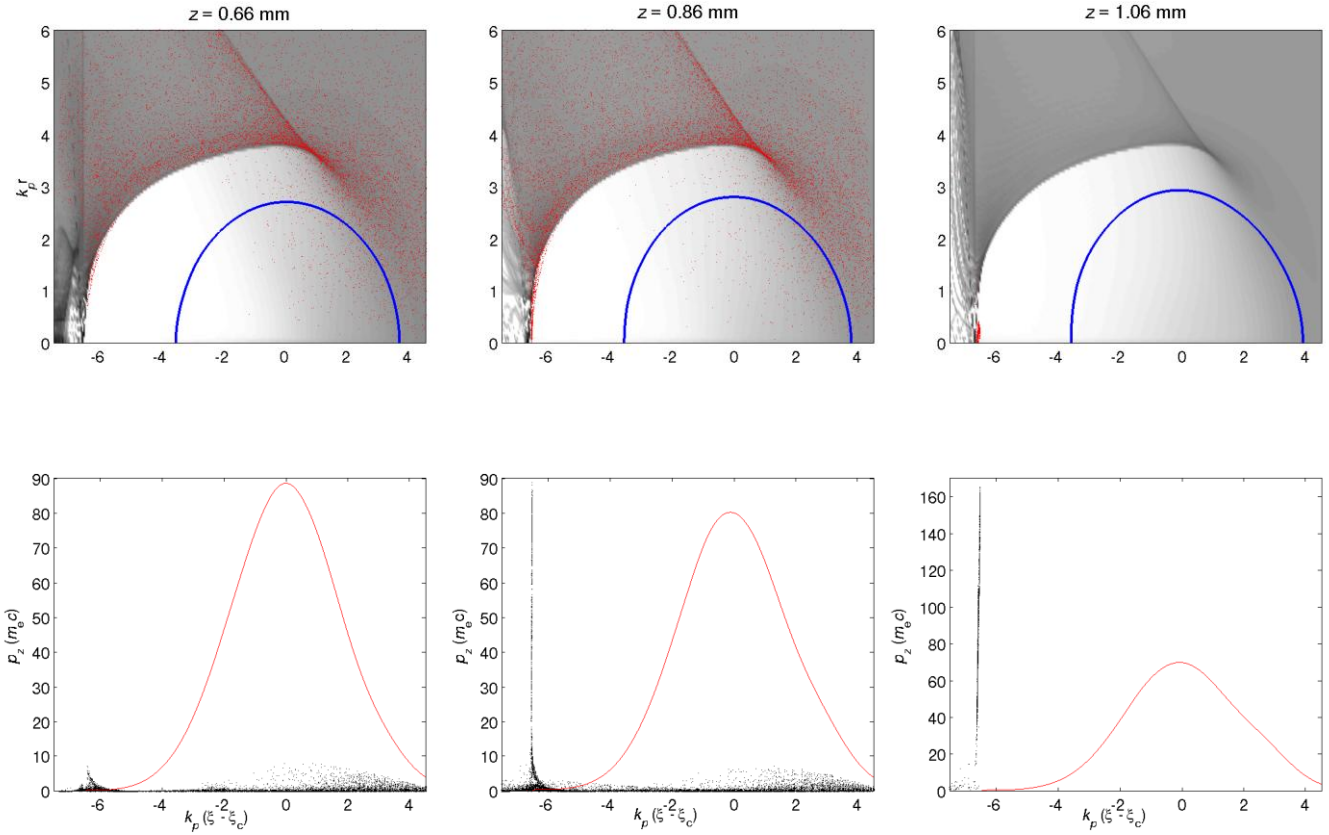
Test particle modeling (WAKE) of self-injection at the place of strongest focus



Test electrons with $\gamma = 1$ are placed here

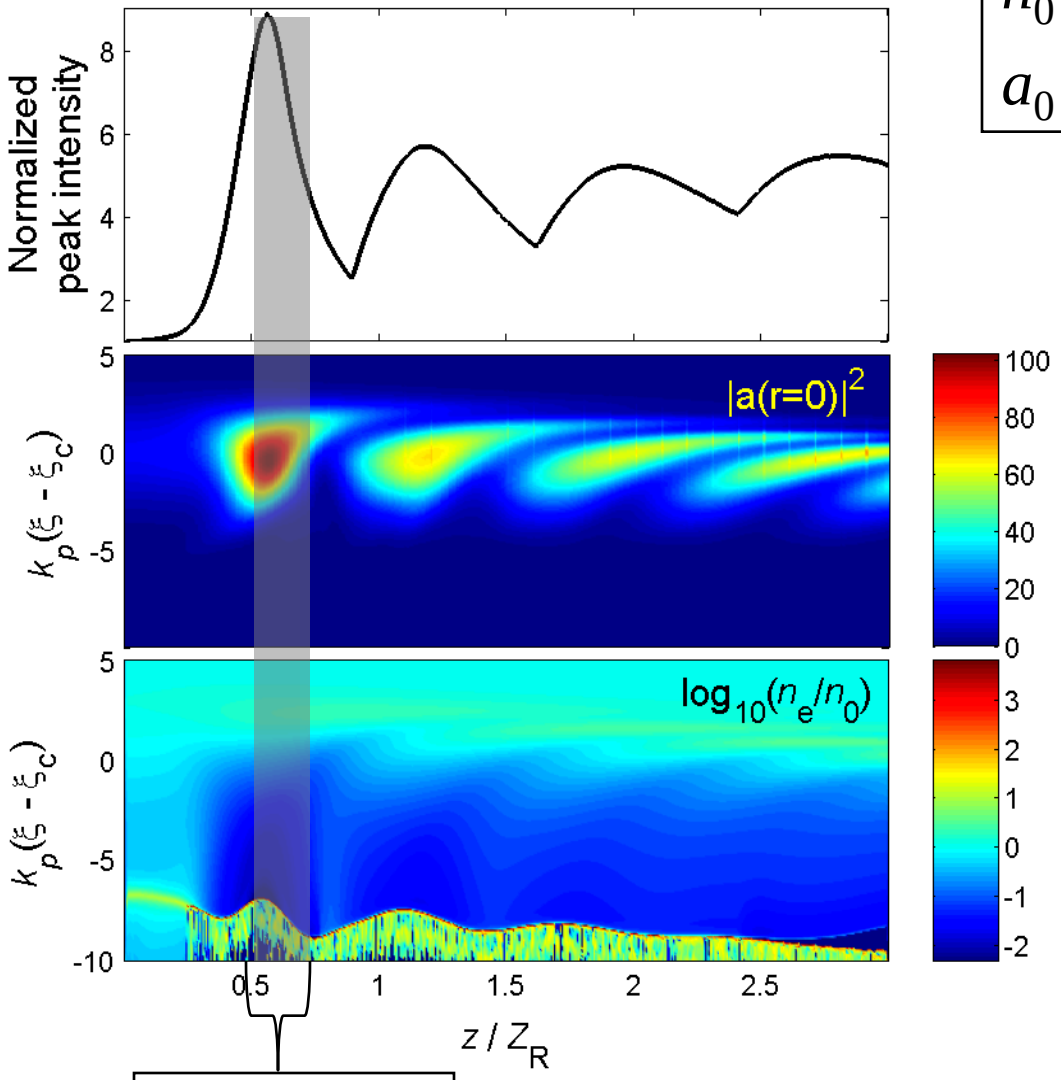
$n_0 = 2.5\ 10^{17}\ \mathrm{cm}^{-3}$ $P = 1.25$ PW

$a_0 = 3.3 \times 3 = 9.9$ $r_0 = 80\ \mu\mathrm{m} / 3 \approx 27\ \mu\mathrm{m}$

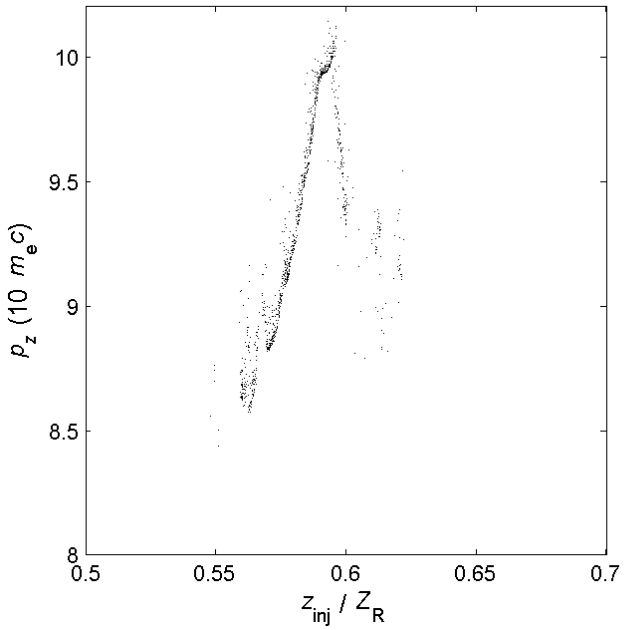


$n_0 = 2.5\ 10^{17}\ \mathrm{cm}^{-3}$ $P = 1.25$ PW

$a_0 = 3.3$ $r_0 = 80\ \mu\mathrm{m}$



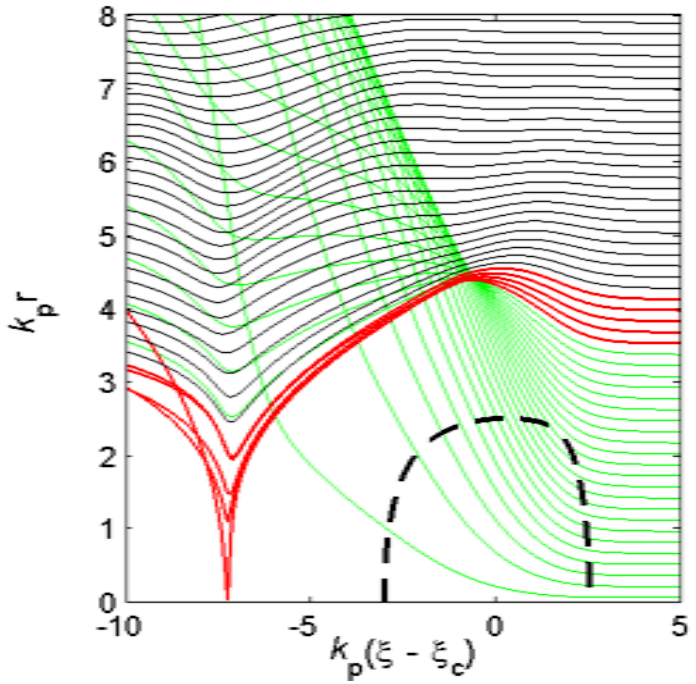
Longitudinal electron momentum vs. its initial position



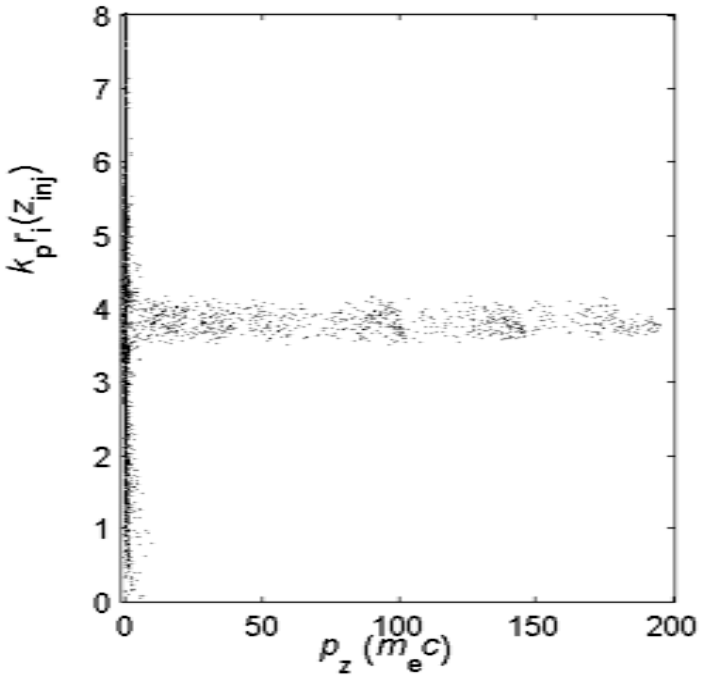
Test electrons with $\gamma = 1$ are placed here

Only narrow central part of this interval actually contributes to the accelerated electron bunch

Trajectories of plasma electrons at $z = 0.6Z_R$



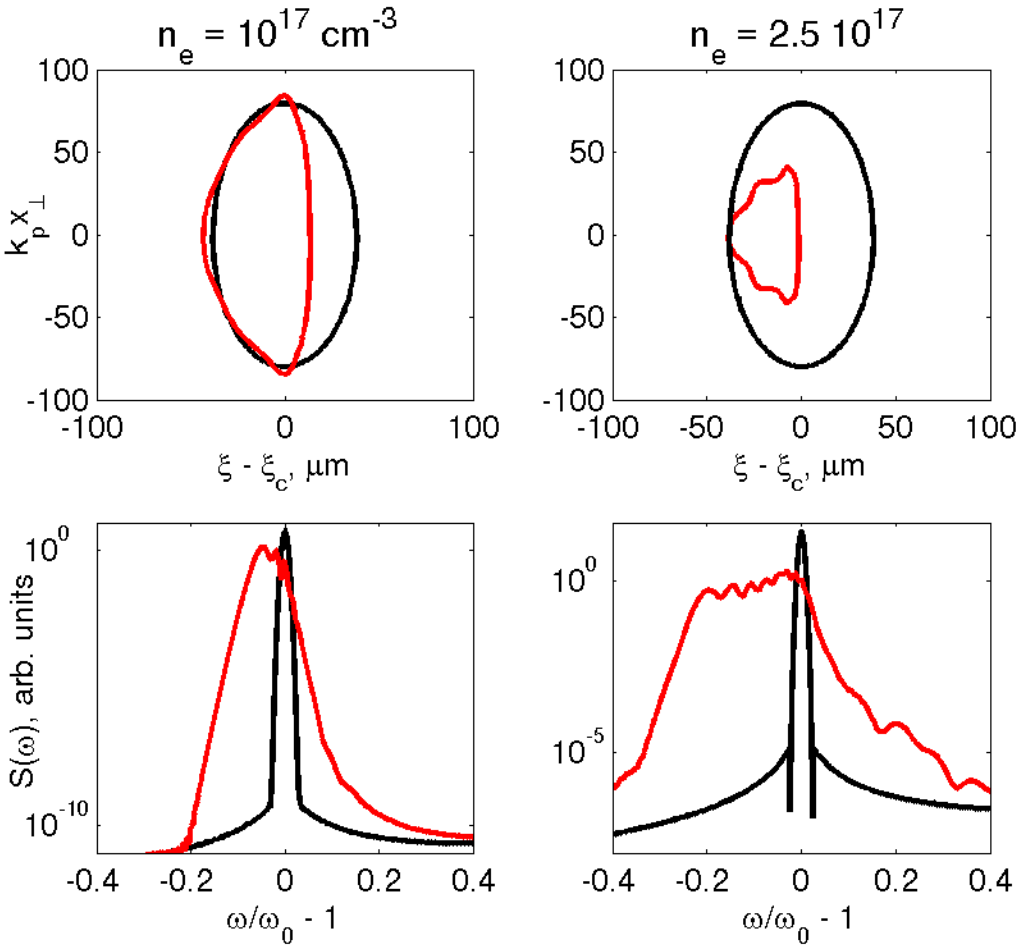
Longitudinal momentum of test electrons injected in the box at and before $z = 0.6Z_R$



Laser pulse compression and red-shift in the TWP-LWFA: WAKE simulations

$P_{laser}/P_{cr} = 7.7$ $P_{laser}/P_{cr} = 20$

Normalized intensity at I_{max}/e^2:

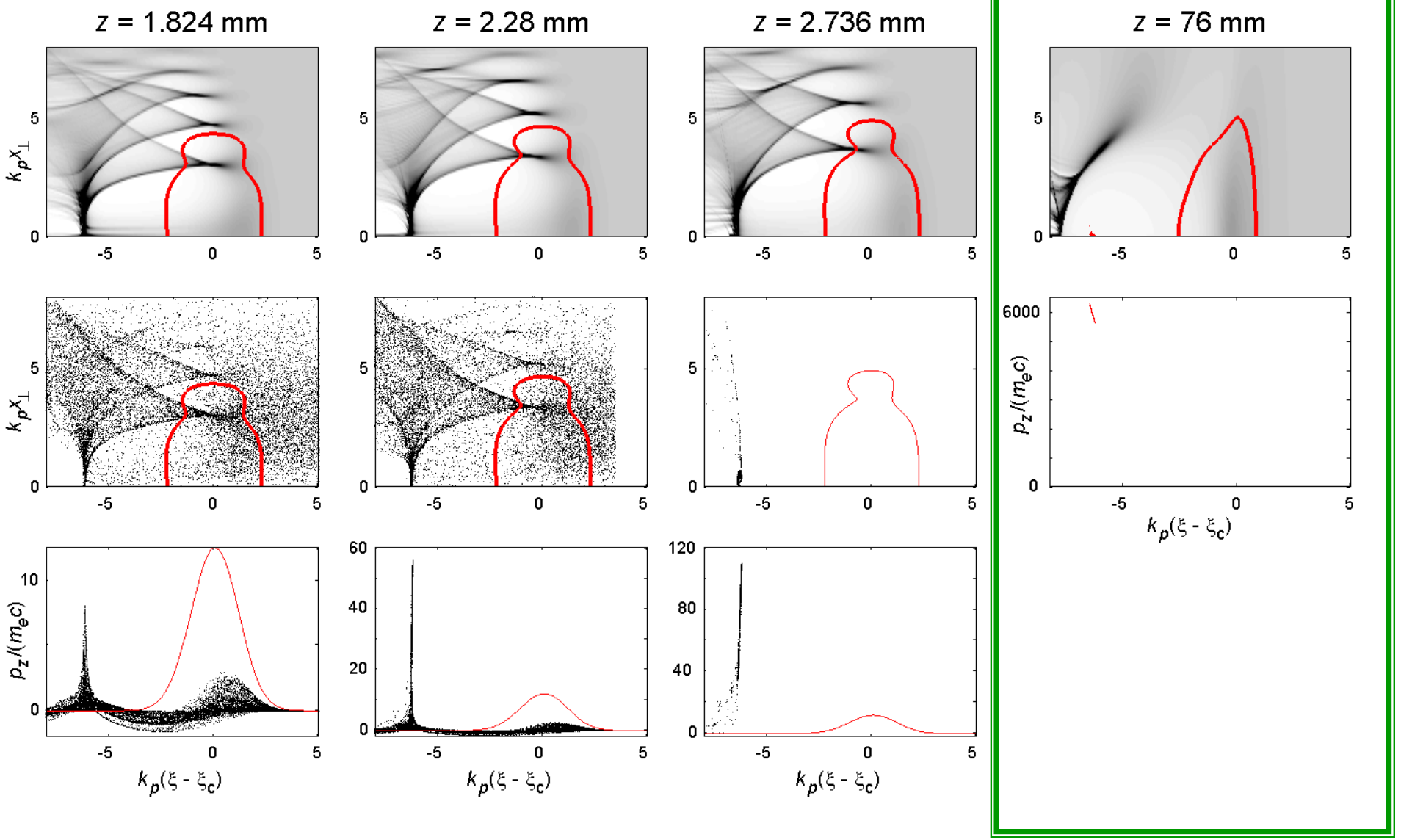


Frequency spectrum:

—— $z = 0$

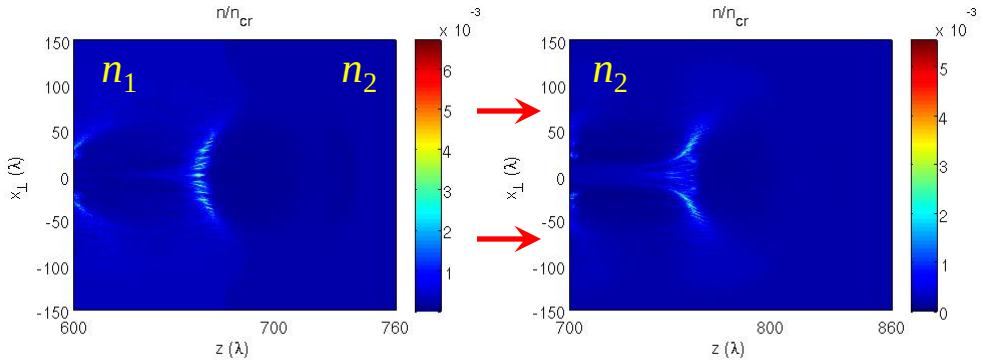
—— $z = 4Z_R$ (≈ 7.6 cm)

Test particle modeling (WAKE) of the hot-spot-assisted injection



Linear density down-ramp: $\Delta_2 = 35\lambda_0$, $n_1/n_2 = 1.6$

Plasma wake near density transition



Plasma density around $z = 2.5$ mm