Difficulties of positron acceleration known from theory

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This is a brief reminder of known facts that were earlier clarified and published

My report is based on two papers:

PHYSICS OF PLASMAS **14**, 023101 (2007)

Acceleration of positrons by electron beam-driven wakefields in a plasma

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(Received 15 September 2006; accepted 21 December 2006; published online 7 February 2007)

Plasma wakefield acceleration of positron beams in the wake of a dense electron beam (in the blowout regime) is numerically analyzed. The acceleration is possible only if the energy content of the wakefield is not very high. This is in contrast to electron acceleration, for which the optimum performance requires driver currents and wave energies to be as high as possible. For positrons, the efficiency of plasma-to-witness energy exchange can amount to several tens percent, but high efficiencies require precise location of the positron beam and sophisticated beam shapes. Unlike an electron witness, the positron always gets an energy spread of about several percent caused by the transverse inhomogeneity of the accelerating field.
[DOI: 10.1063/1.2434793]

PHYSICS OF PLASMAS **24**, 023119 (2017)

Radial equilibrium of relativistic particle bunches in plasma wakefield accelerators

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Drive particle beams in linear or weakly nonlinear regimes of the plasma wakefield accelerator quickly reach a radial equilibrium with the wakefield, which is described in detail for the first time. The equilibrium beam state and self-consistent wakefields are obtained by combining analytical relationships, numerical integration, and first-principles simulations. In the equilibrium state, the beam density is strongly peaked near the axis, the beam radius is constant along most of the beam, and longitudinal variation of the focusing strength is balanced by varying beam emittance. The transverse momentum distribution of beam particles depends on the observation radius and is neither separable nor Gaussian. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4977058]

Problem 1: Narrow area of acceleration + focusing

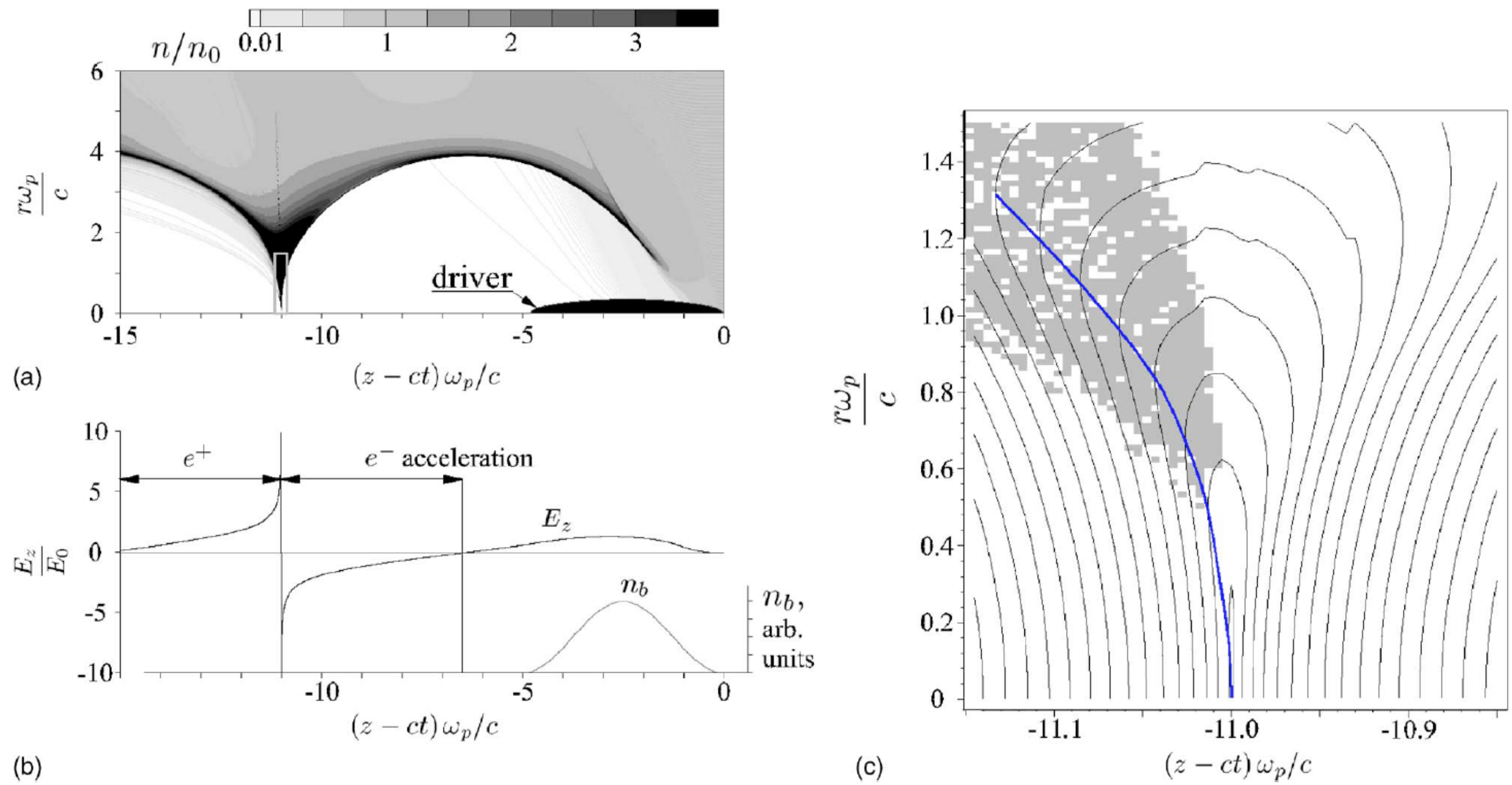
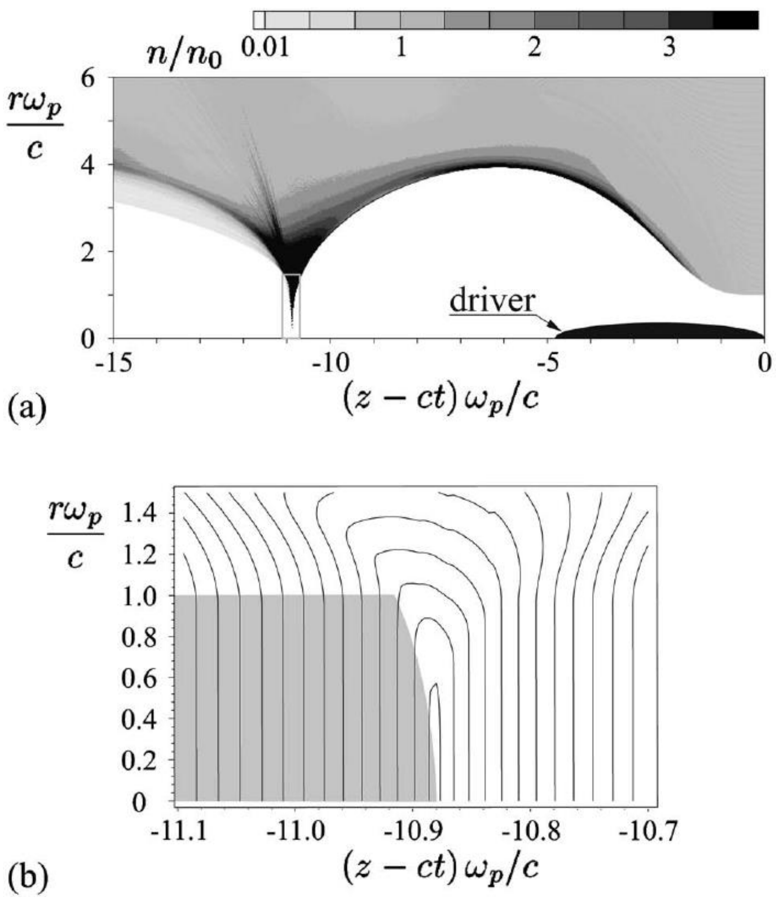


FIG. 1. (Color online) (a) Bubble shape at a high energy content of the wave (map of the plasma electron density at $\tilde{\Psi}=70$); (b) corresponding profiles of the on-axis electric field and driver density; (c) contour lines of the force potential $\tilde{\Phi}$ showing the shape of the potential well near the end of the first bubble [in the area marked in (a) by the gray rectangle]. The thick line in (c) shows the local minima of $\tilde{\Phi}$ at z=const; gray shading is the equilibrium location of relativistic test particles initially placed near the axis.

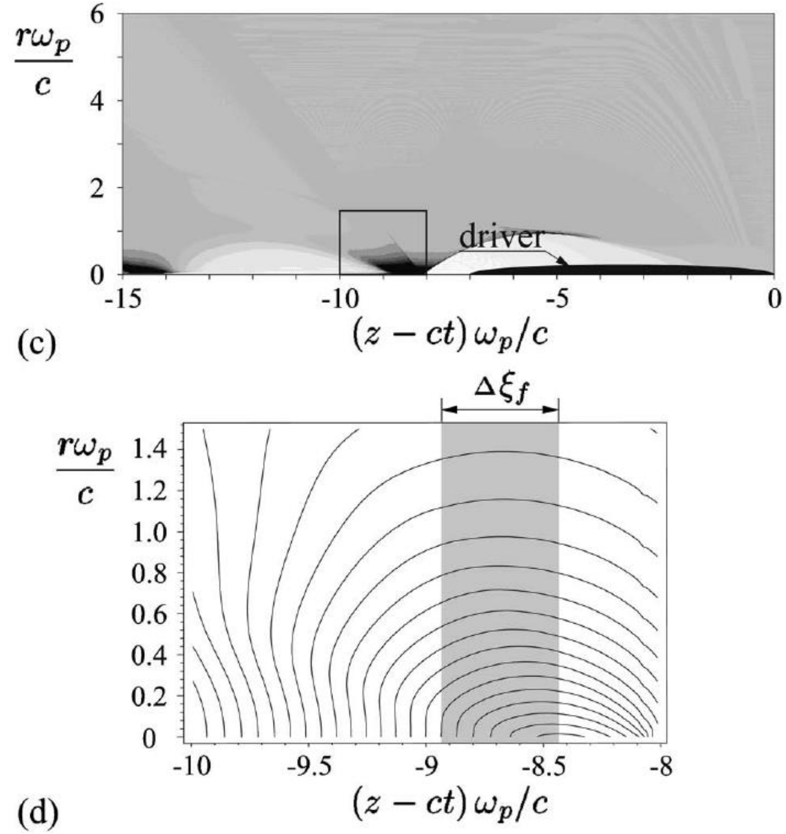
(Not a problem for linear wakes, but those have lower fields and lower efficiencies)

Possible solutions to Problem 1

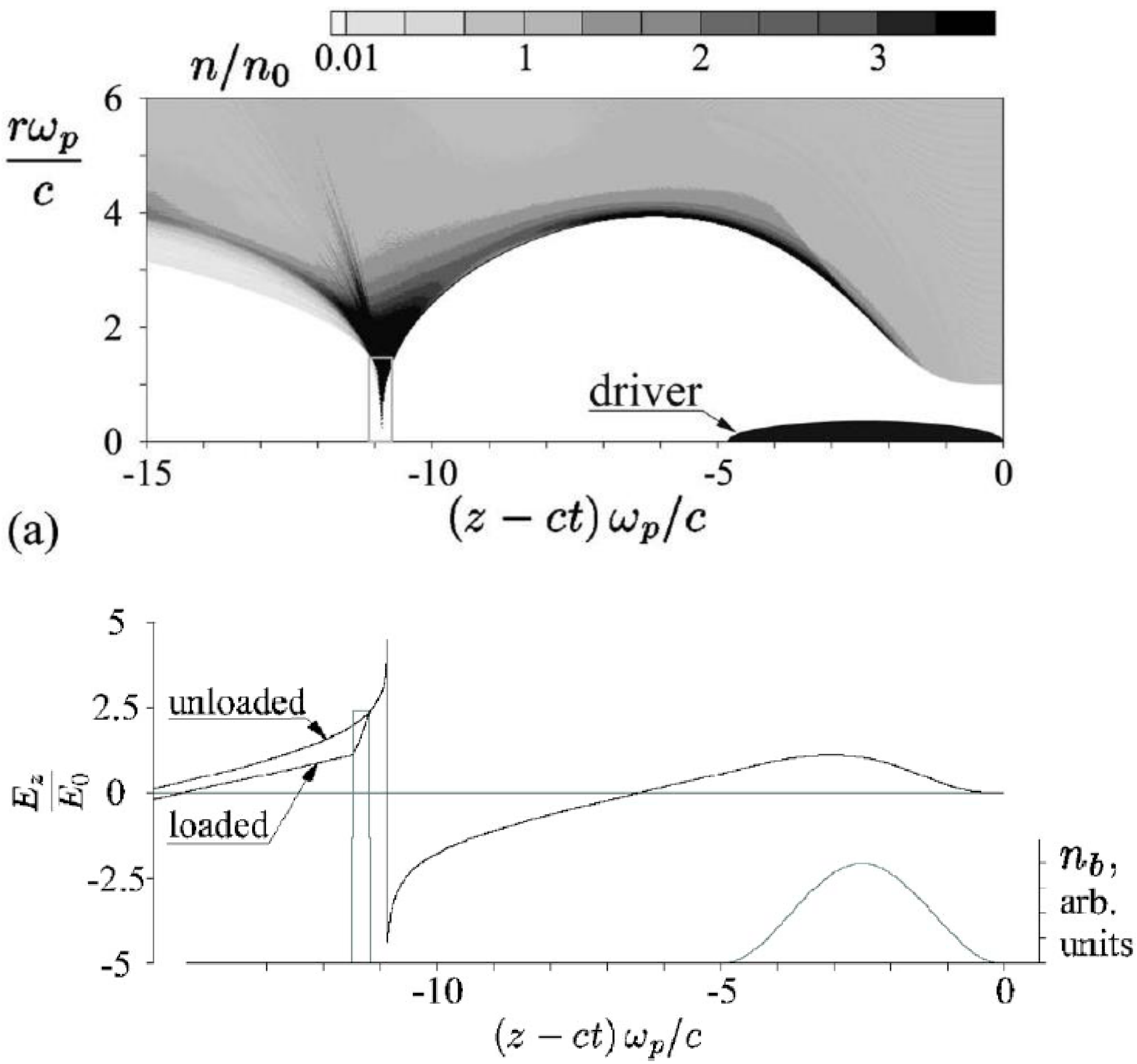
Hollow channel (no ions inside that defocus e+)



Narrow bubble (quasi-nonlinear regime)



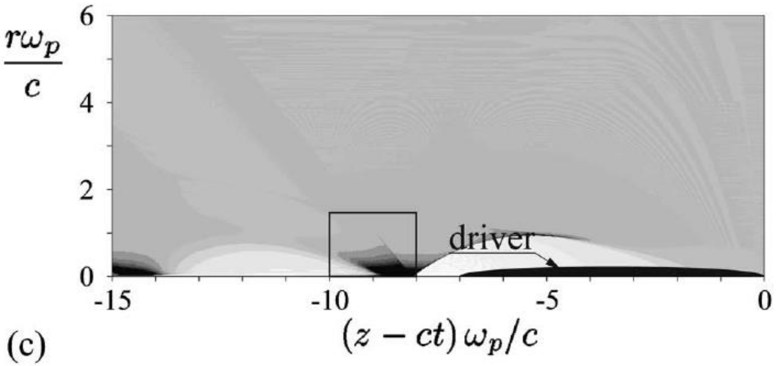
Problem 2: Unfavorable slope of E_z(z-ct)



Even if defocusing problem is solved with a hollow channel,

the beam loading increases the energy spread

Problem 3: Efficiency needs fantastic precision

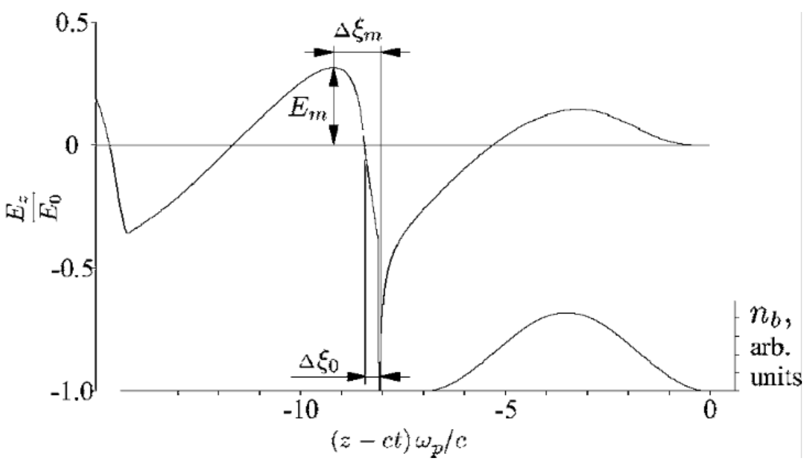


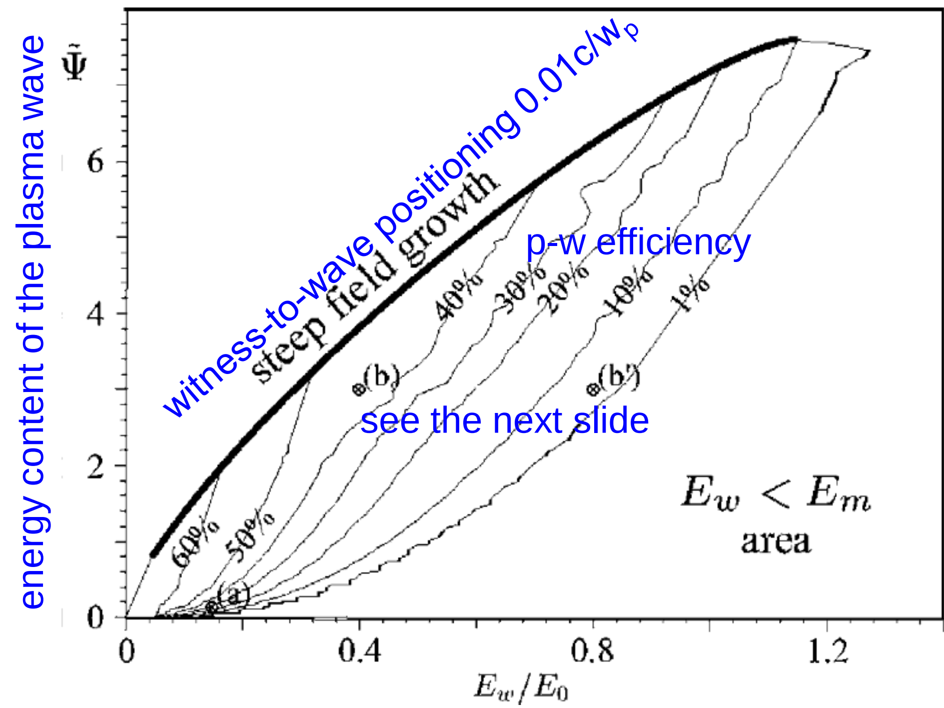
(c)

In the case of quasi-nonlinear regime, the efficiency is low (too much energy left in the plasma).

High efficiency needs very precise positioning of the witness bunch and a complicated witness shape.

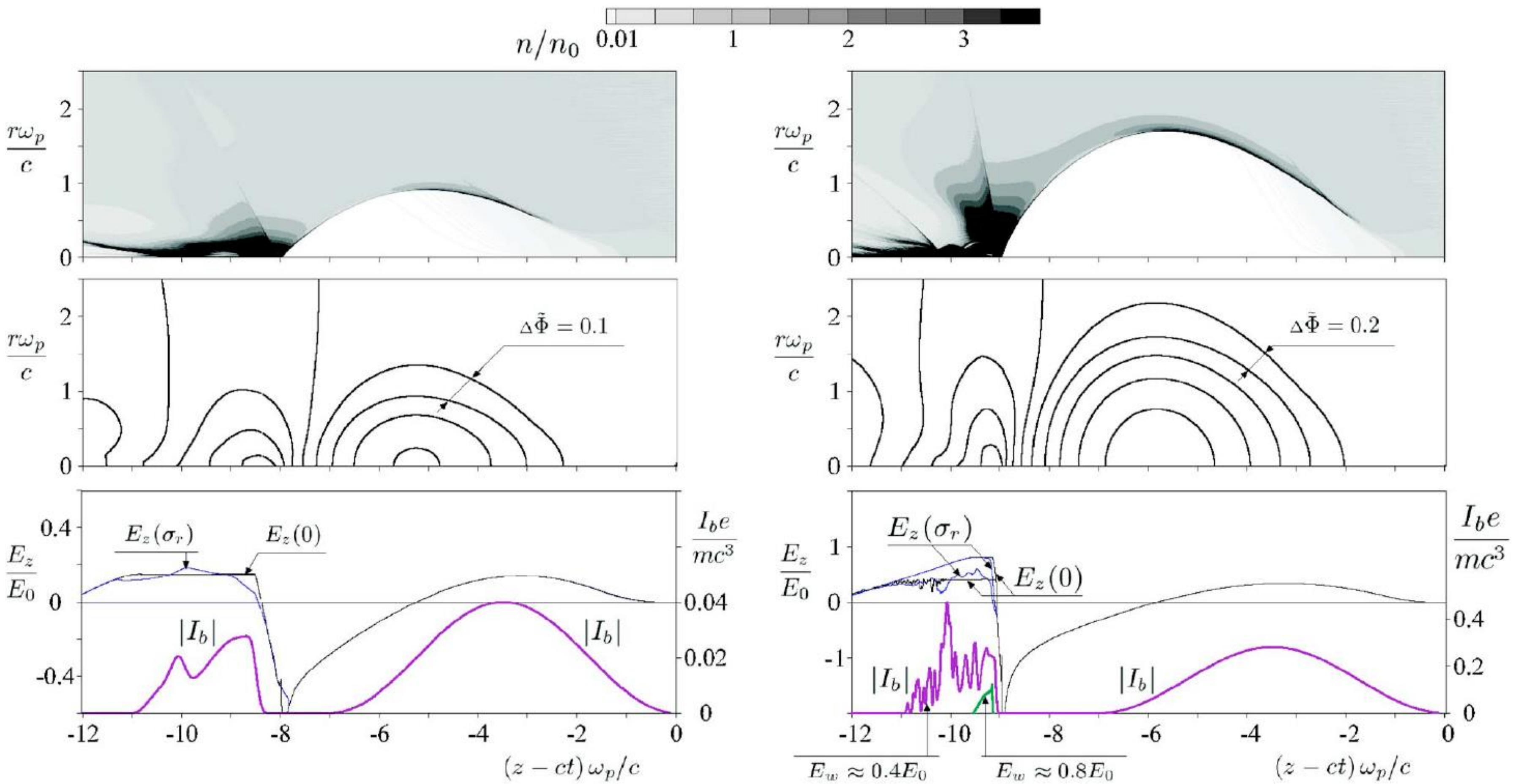
How to preserve this match along the whole interaction distance is an open question.





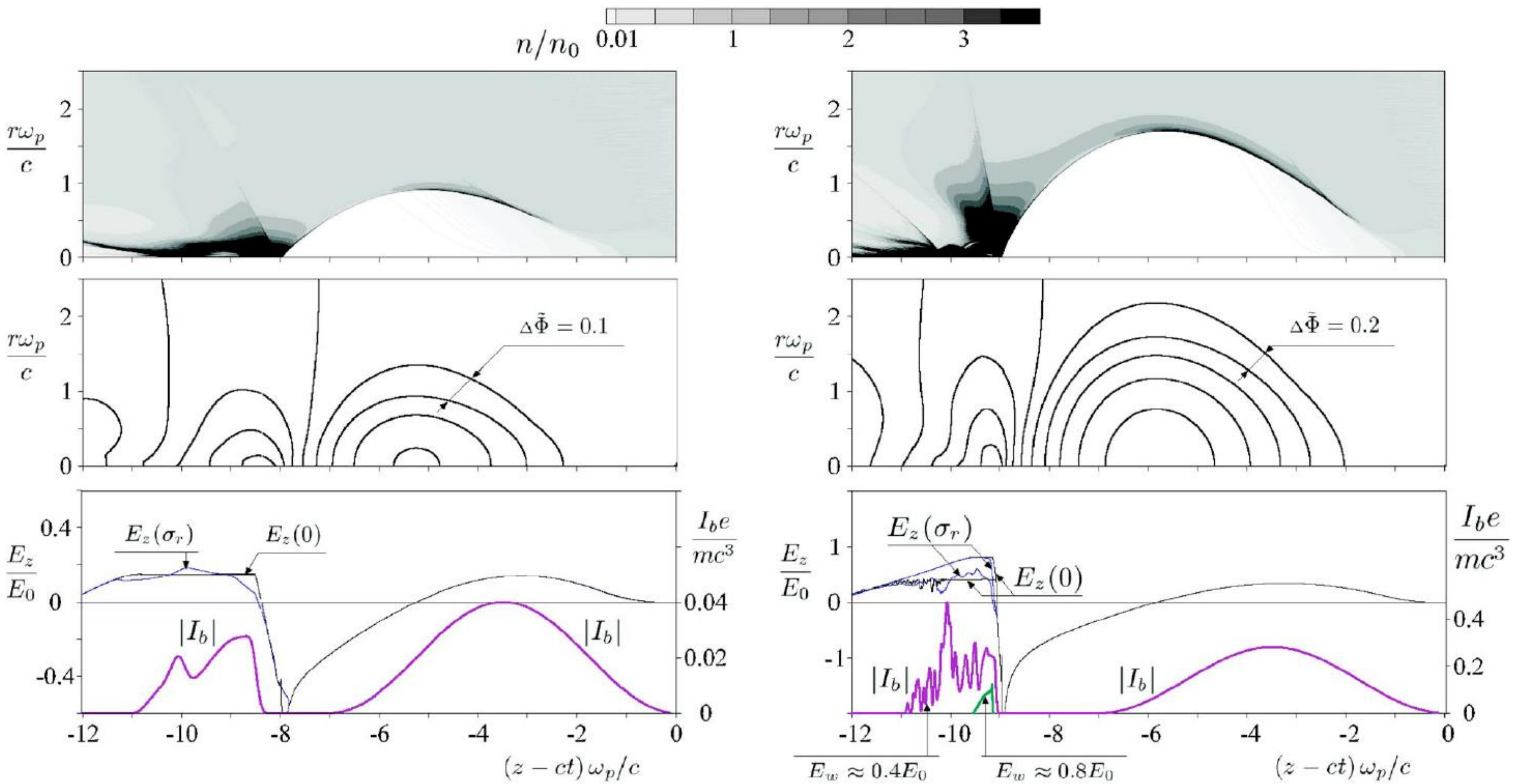
accelerating field (for a matched witness shape)

Problem 3: Efficiency needs fantastic precision



The witness shape that provides a constant accelerating field on the axis is rather exotic.

Problem 4: Accelerating field is not constant across the witness



Problem 4: Accelerating field is not constant across the witness

The problem is of a fundamental nature, as indicated (but not proven) by the theory of beam equilibria.

We have a beam:

$$n_b(r,\xi) = n_{b0} f(r) g(\xi)$$

It drives the wakefield:

$$\vec{F} = -e(\vec{E} + [\vec{e}_z, \vec{B}]) = -\nabla\Phi$$

$$\Phi(r,\xi) = mc^2 \frac{n_{b0}}{n_0} R(r) G(\xi),$$

$$R(r) = -k_p^2 \int_0^r dr' r' I_0(k_p r') K_0(k_p r) f(r') - k_p^2 \int_r^\infty dr' r' I_0(k_p r) K_0(k_p r') f(r'),$$

$$G(\xi) = k_p \int_\xi^\infty d\xi' \sin(k_p(\xi' - \xi)) g(\xi'),$$

$$D(r_a)$$

$$f(r) = \frac{\sigma_r^2}{r} \int_r^\infty \frac{D(r_a)\, dr_a}{\tilde{\tau}(r_a)\sqrt{R(r_a) - R(r)}}$$

$$\tilde{\tau}(r_a) = \int_0^{r_a} \frac{dr}{\sqrt{R(r_a) - R(r)}}$$

The potential well shape determines the beam shape

We can iteratively find the solution for any (reasonable) $D(r_a)$ – oscillation amplitude distribution of beam particles

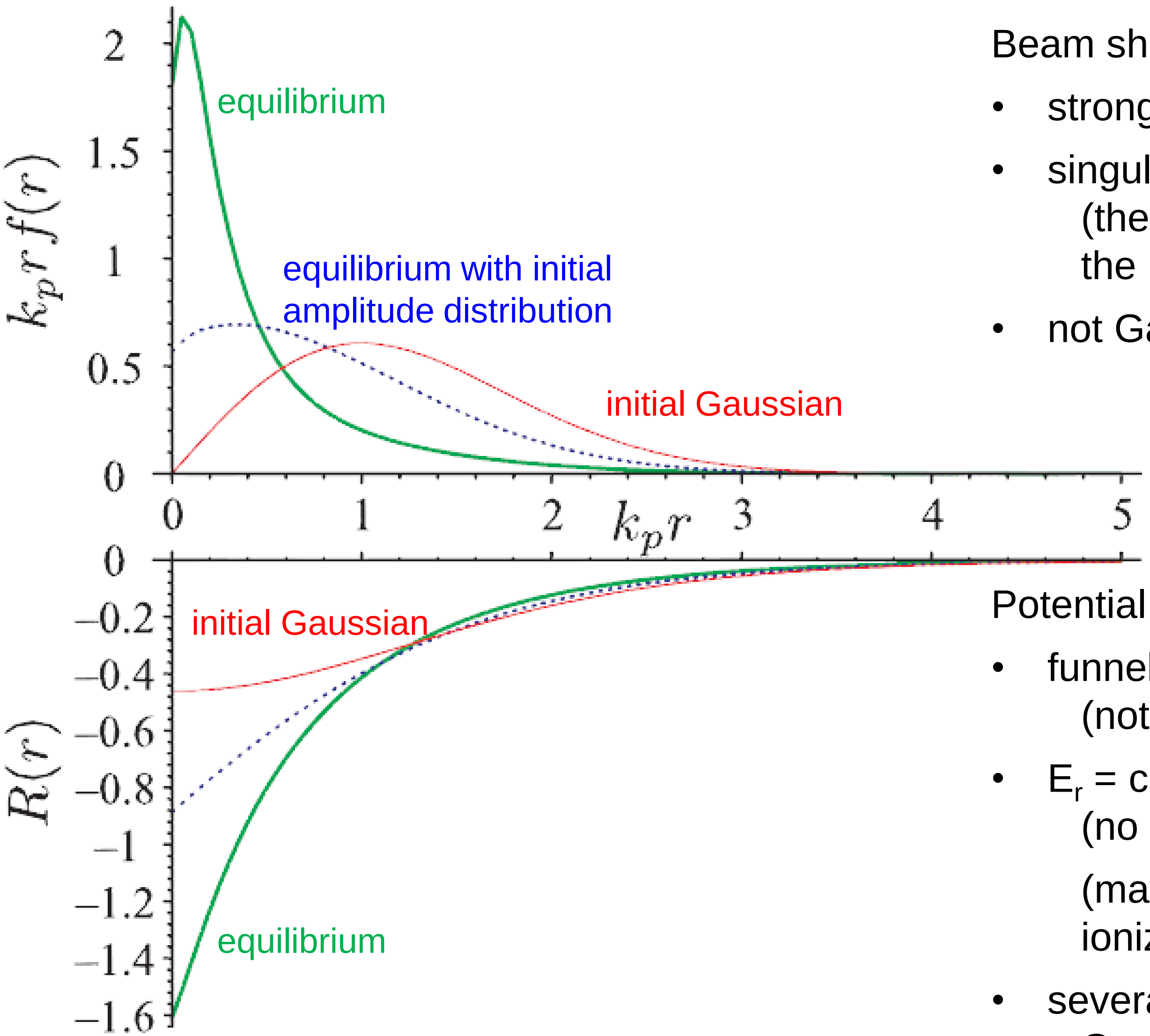
This theory is good for the radial equilibrium of drive bunches in a linearly responding plasma

Results for witnesses will probably be even worse (as follows from derivation)

Results will be quantitatively different, but probably qualitatively the same

Here we discuss witness beams in nonlinear waves

For drive bunches there is a universal solution (difference is in scales only)



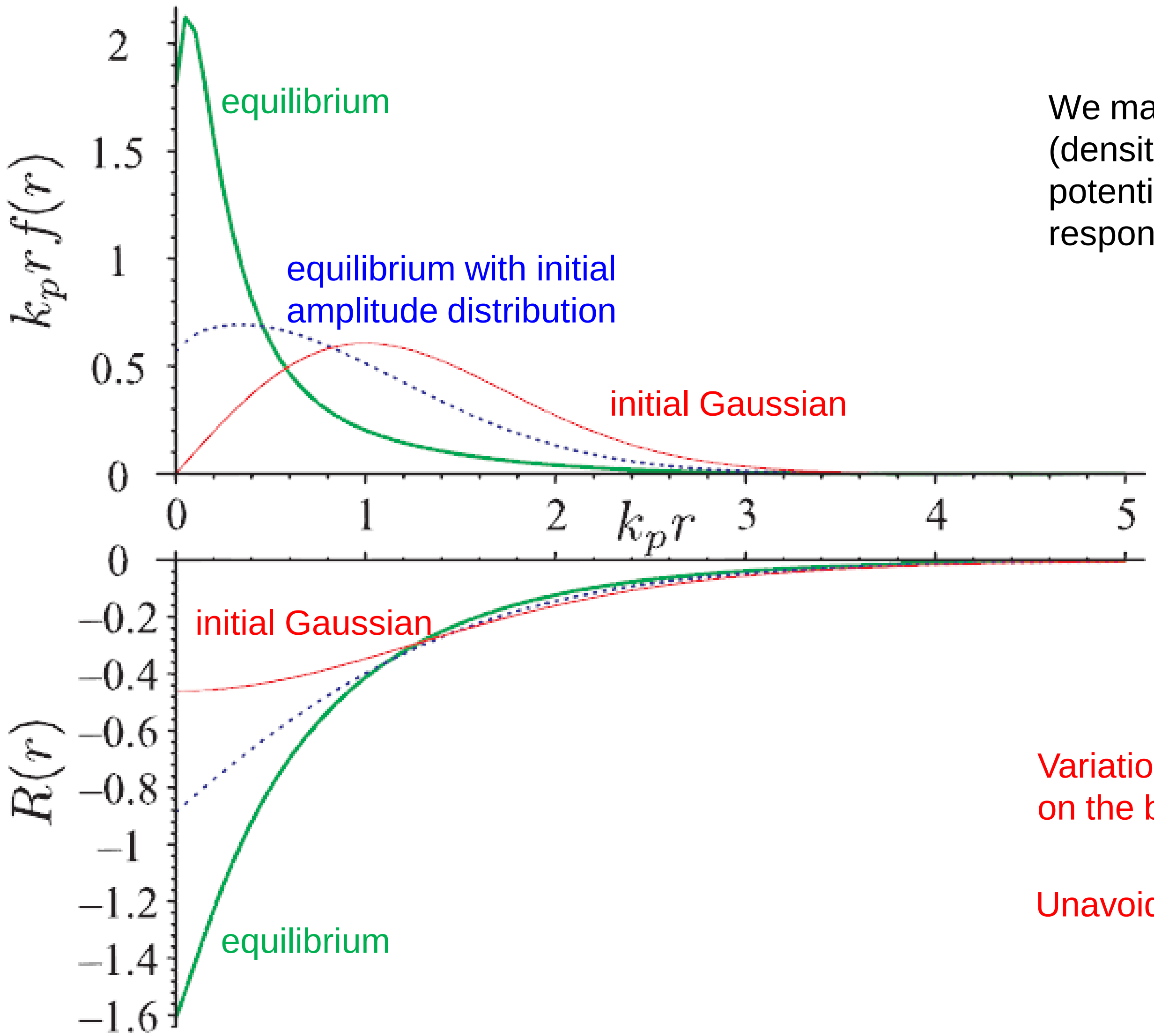
Beam shape:

- strongly peaked near the axis
- singular behaviour (1/r)
  (the smaller the initial emittance, the higher on-axis density)
- not Gaussian

Potential well:

- funnel-shaped
  (not usual parabolic)
- E_r = const up to the axis
  (no usual linear decrease)
  (may be important for ionization by the beam field)
- several times deeper than for a Gaussian beam

For drive bunches there is a universal solution (difference is in scales only)



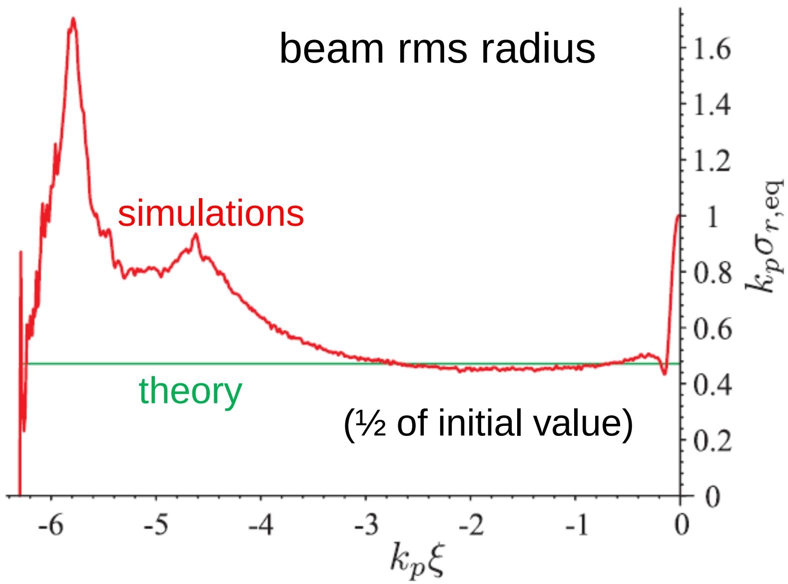
We may expect similar features (density peaking near the axis, deep potential well) for nonlinearly responding plasma as well.

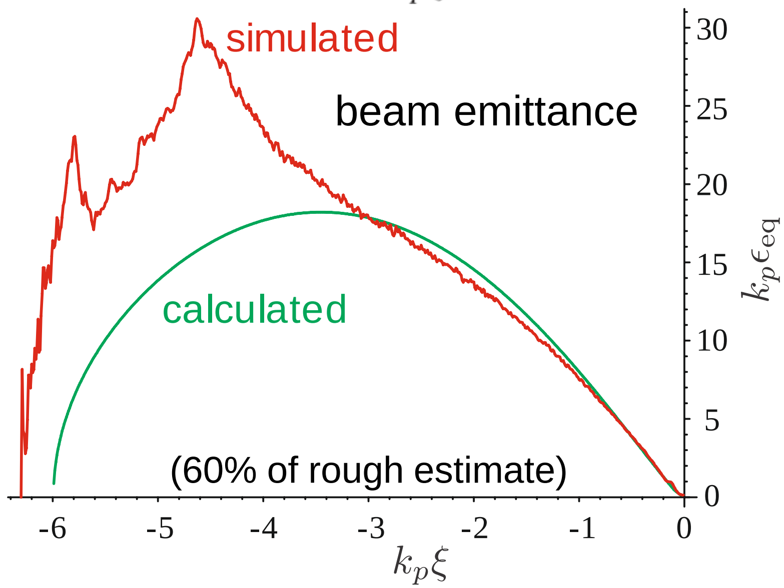
Variation of the potential well depth on the beam radius scale

⇩

Unavoidable energy spread, $E_z \propto R(r)$

Why the theory is good for drivers only?

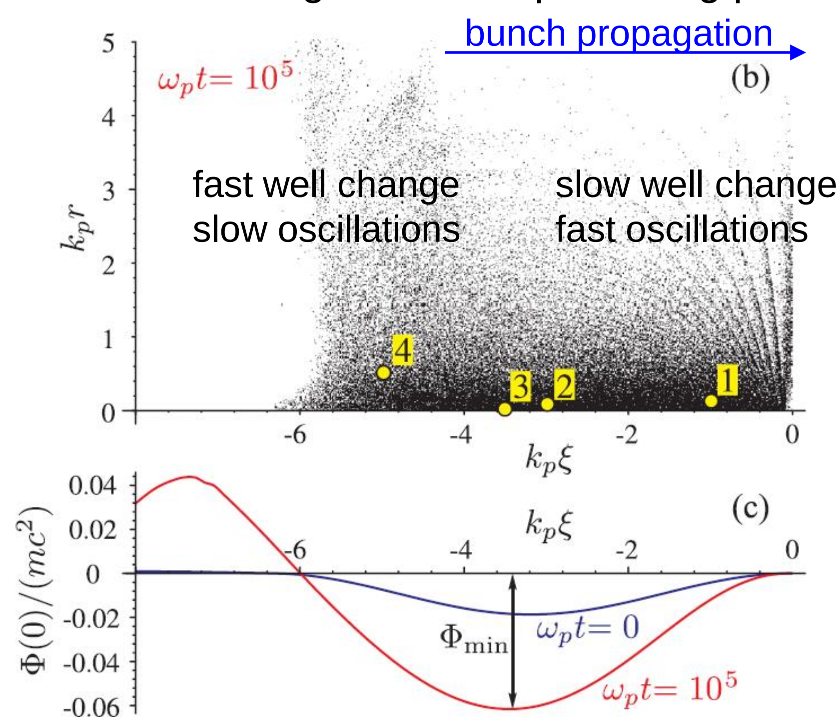




We learned this from simulations: excellent agreement only for the leading half of the bunch

What is wrong with the trailing (accelerated) part? It approaches to equilibrium in a different way.

Times: well deepening VS particle oscillation (the deeper the well, the faster the oscillations; time of well change is that of preceding particles)



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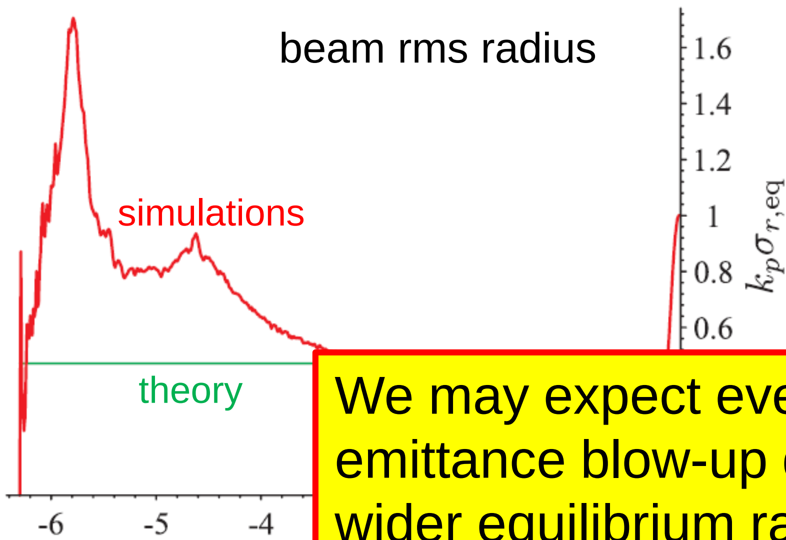

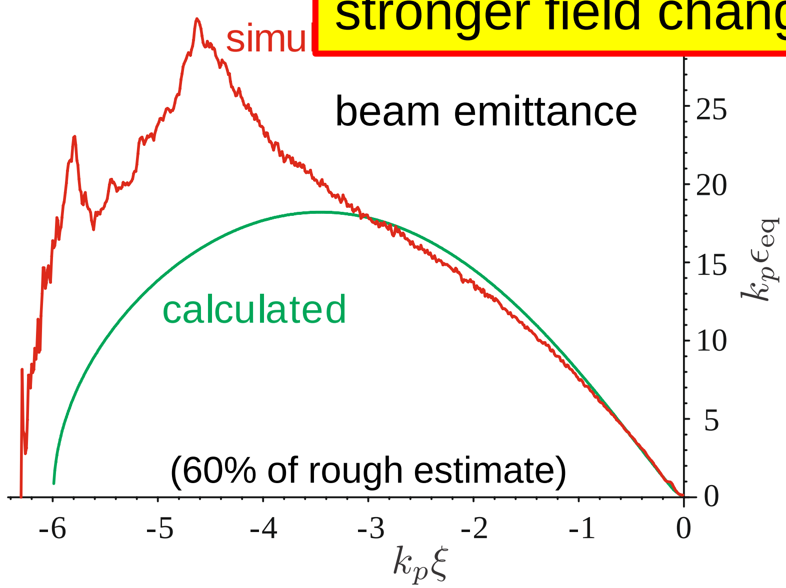

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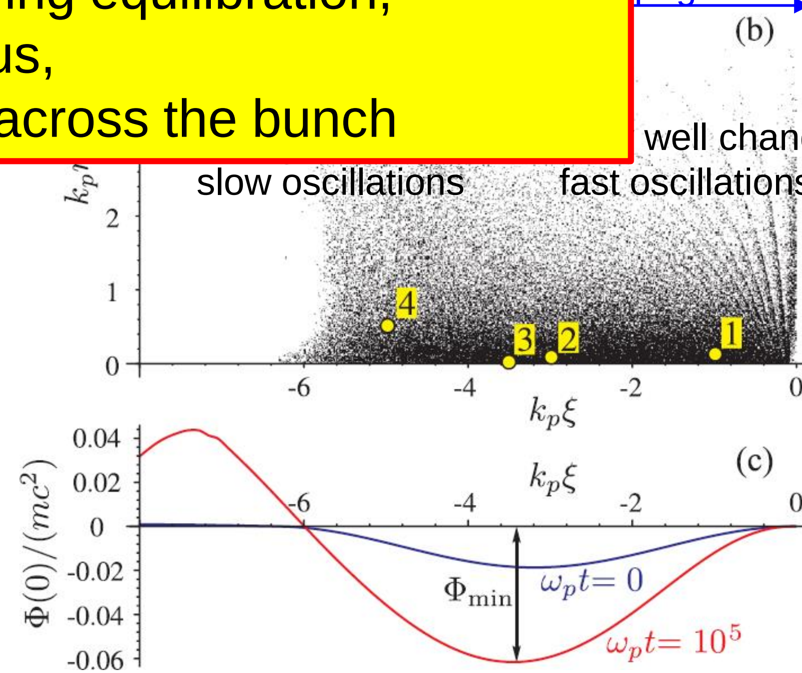
oscillations;

eding particles)

We may expect even worse case for witnesses:
emittance blow-up during equilibration,
wider equilibrium radius,
stronger field change across the bunch



Summary: all methods have problems

Linear wave: Low field amplitudes and efficiencies,
Large energy spread (narrow focusing does not reduce the spread)

Quasi-nonlinear wave: Low field amplitudes and efficiencies,
Large energy spread (narrow focusing does not reduce the spread)
Weird bunch shape

Blowout regime: Weird bunch shape, strict requirements for tolerances

Positron driver (nonlinear regime):
Large energy spread (narrow focusing does not reduce the spread)
(Maybe) weird bunch shape

Hollow channel with electron driver:
Large energy spread (wrong slope of Ez)
Stability issue
Channel production

Hollow channel with positive-charge driver:
Stability issue
Channel production