L'OASIS Program:

Laser Accelerator Theory and Computation

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DoE Review, March 17, 2005

Outline & Accomplishments

- Particle trapping and thermal effects in LWFAs
  - PIC simulations of LWFA experiments
    - Geddes et al., Nature (2004)
  - Thermal trapping and dark current
    - Schroeder et al., Advanced Accel Concepts (2004)
  - Warm fluid model
    - Shadwick et al., Phys. Rev. Lett. (2004)
  - Warm wavebreaking limit
    - Schroeder et al., Phys. Rev. Lett. (submitted)
  - Relativistic Vlasov model
    - Shadwick et al., Phys. Plasmas (2005)
- Fluid modeling of a 1 GeV LWFA
  - Pump depletion and electron dephasing
    - Esarey et al., Advanced Accel Concepts (2004)

Other Accomplishments (2004-2005)

- Beat wave injection using two laser pulses
  - Fubiani et al., Phys. Rev. E (2004)
- Pulse shape and spectrum of coherent transition radiation
  - van Tilborg et al., Laser Particle Beams (2004)
  - Schroeder et al.. Phys. Rev. E (2004)
- Thomson scattering and betatron radiation from LWFAs
  - Leemans et al., IEEE Plasma Sci (2005)
  - Michel et al., Advanced Accel Concepts (2004)
- Propagation of dense electron bunches with large energy spread
  - Fubiani et al., in preparation
- E-beam conditioning by Thomson scattering for FELs
  - Schroeder et al., Phys. Rev. Lett. (2004)

Simulations using VORPAL PIC Code: Wake Evolution & Dephasing Yield Low Energy Spread

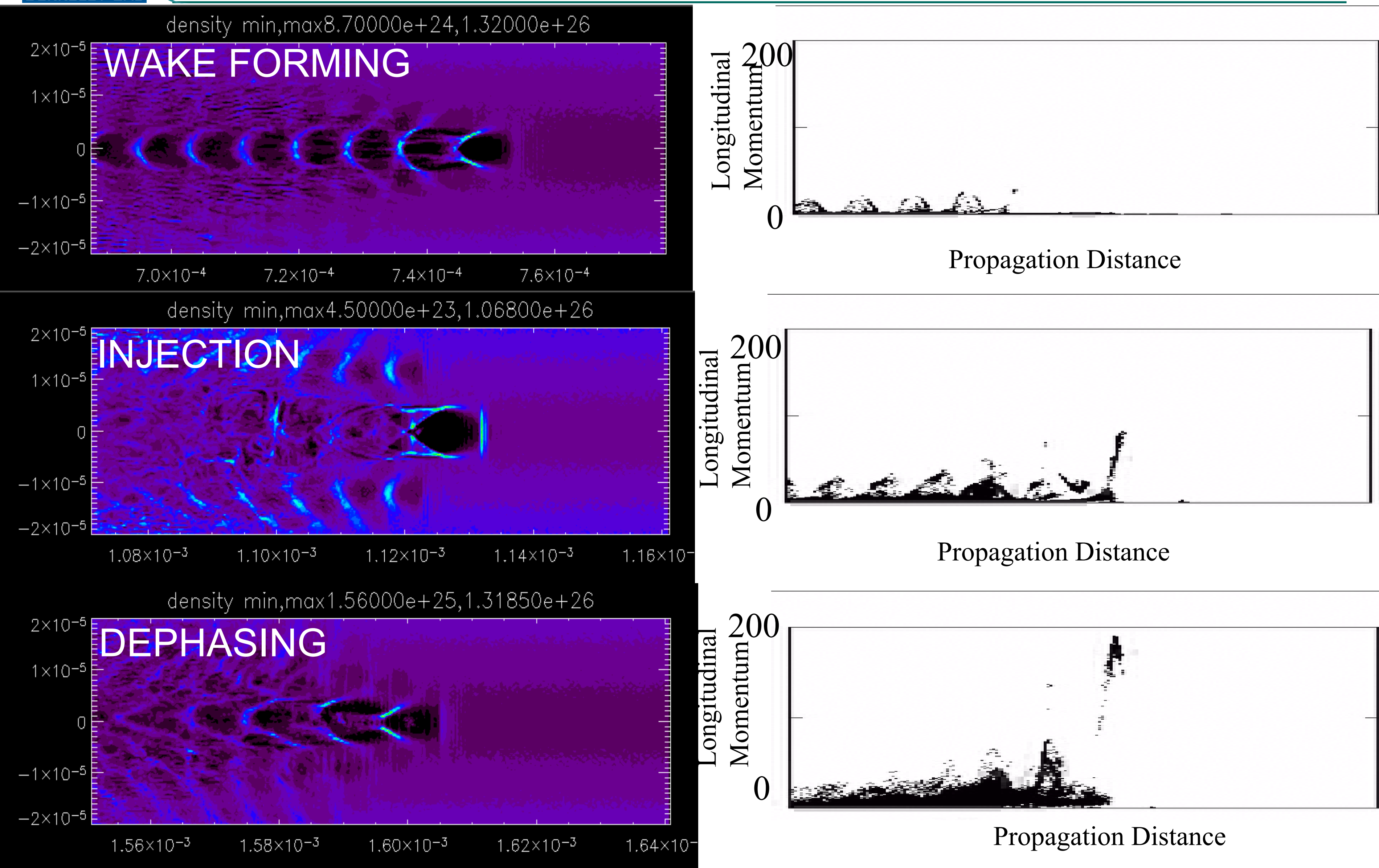
Laser Envelope

Axial Electric Field

Electron Phase Space

VORPAL: Cary, Nieter, Bruhwiler et al., CU & Tech-X

Wake Evolution and Dephasing Yield Low Energy Spread Beams in PIC Simulations



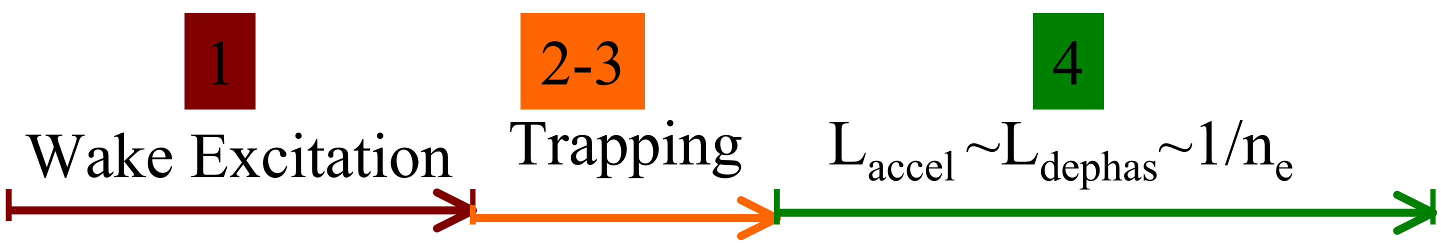
Geddes et al., Nature (2004) & Phys. Plasmas (2005)

LWFA: Production of a Monoenergetic Beam

1. Excitation of wake (e.g., self-modulation of laser)
2. Onset of self-trapping (e.g., wavebreaking)
3. Termination of trapping (e.g., beam loading)
4. Acceleration

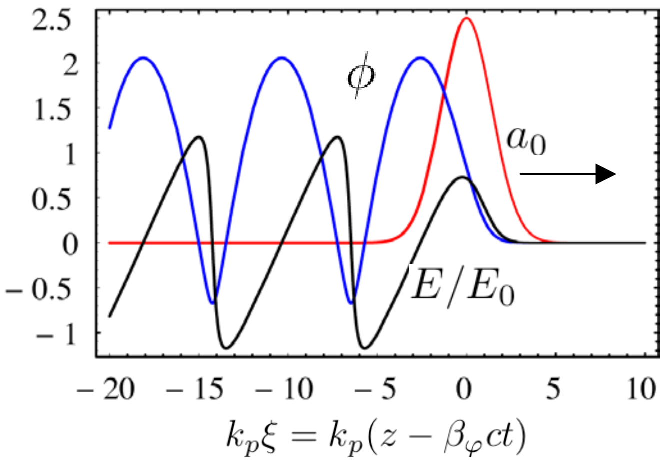
   If > dephasing length: large energy spread

   If ≈ dephasing length: monoenergetic

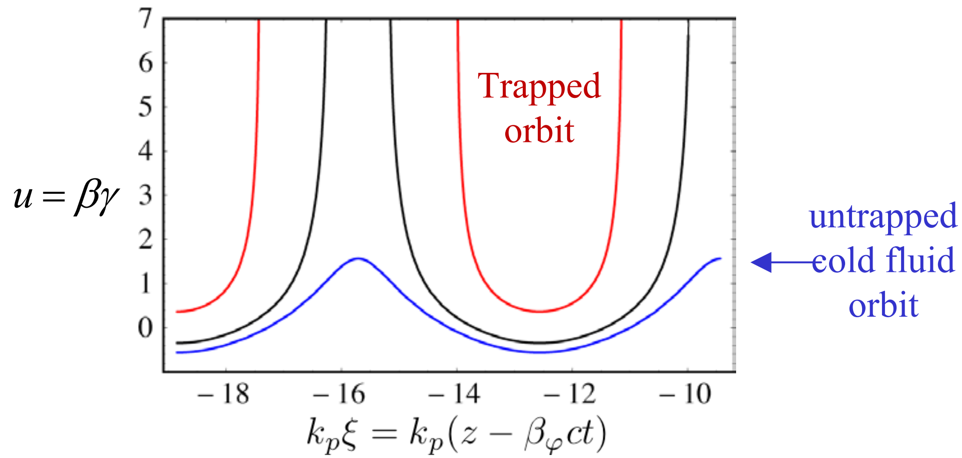


Electron Trapping in Nonlinear Plasma Waves

Plasma wave excitation:



Electron orbits:



Threshold condition for trapping:

$$u_t = \gamma_\varphi\beta_\varphi\left(\gamma_\perp - \gamma_\varphi\phi_{\min}\right) - \gamma_\varphi\left[\left(\gamma_\perp - \gamma_\varphi\phi_{\min}\right)^2 - 1\right]^{1/2}$$

$u_t = p_t/mc$ = electron momentum

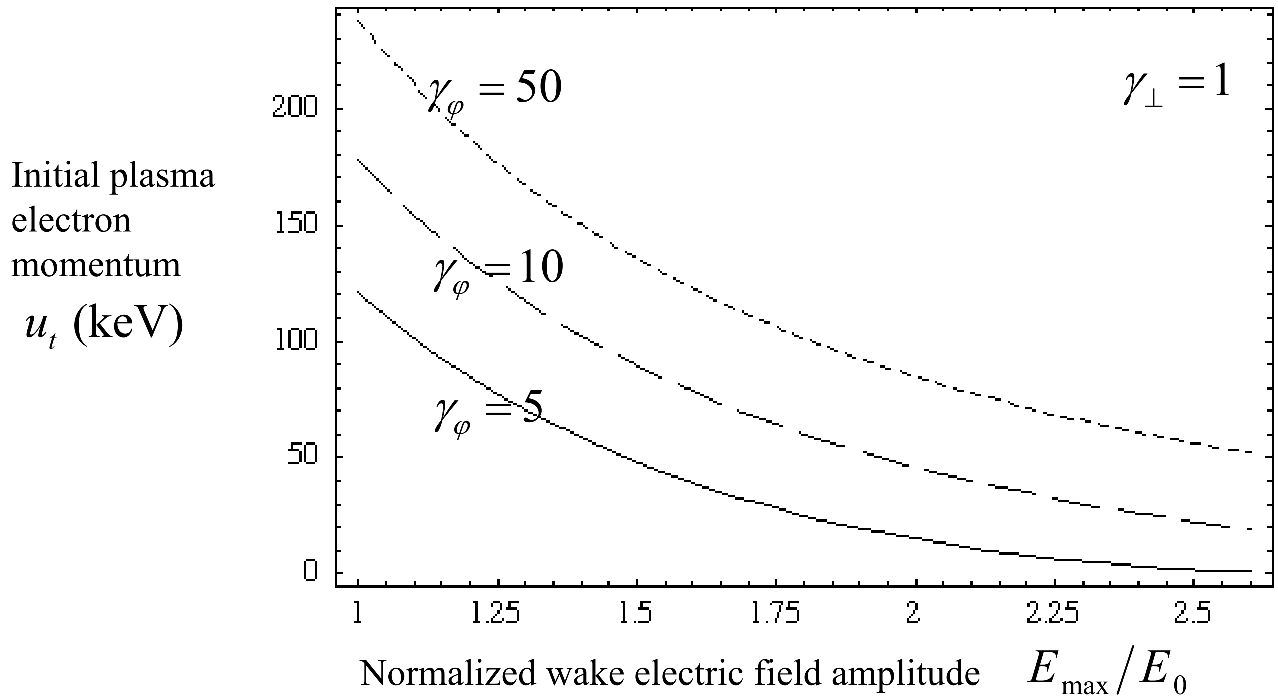
$\gamma_\varphi = (1 - \beta_\varphi{}^2)^{-1/2}$, $\beta_\varphi = v_\varphi/c$ = wake phase velocity

ϕ = wake potential

Lorentz factor of quiver motion: $\gamma_\perp^2 = 1 + a^2/2$

Trapping Threshold

Threshold plasma wave electric field amplitude before the onset of trapping:



Relativistic factor: plasma wave phase velocity

$$\text{Laser}: \ \gamma_\varphi \cong \omega/\omega_p \ \cong 10-100$$

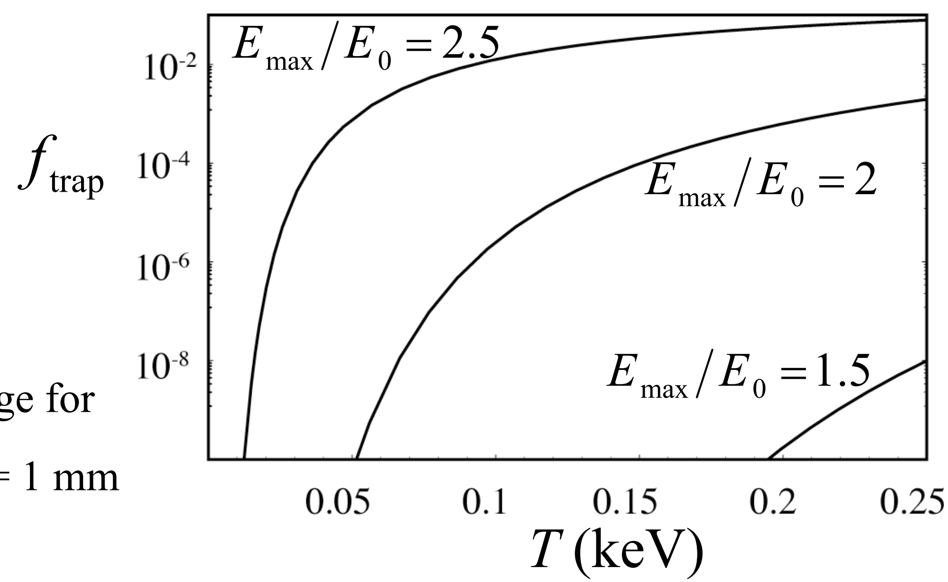
Schroeder et al., Advanced Accel Concepts (2004)

Dark Current (Trapping Fraction)

Fraction of background plasma electrons trapped (for an initial *Gaussian momentum distribution*):

$$f_{\mathrm{trap}} = \frac{1}{2}\left[1 - \mathrm{Erf}(u_t/\sqrt{2}\beta_{\mathrm{th}})\right]$$

where the threshold for trapping is $u_t = u_t(\gamma_\varphi, \gamma_\perp, \phi)$



$\gamma_\perp = 1$

$\gamma_\varphi = 10$

Example:

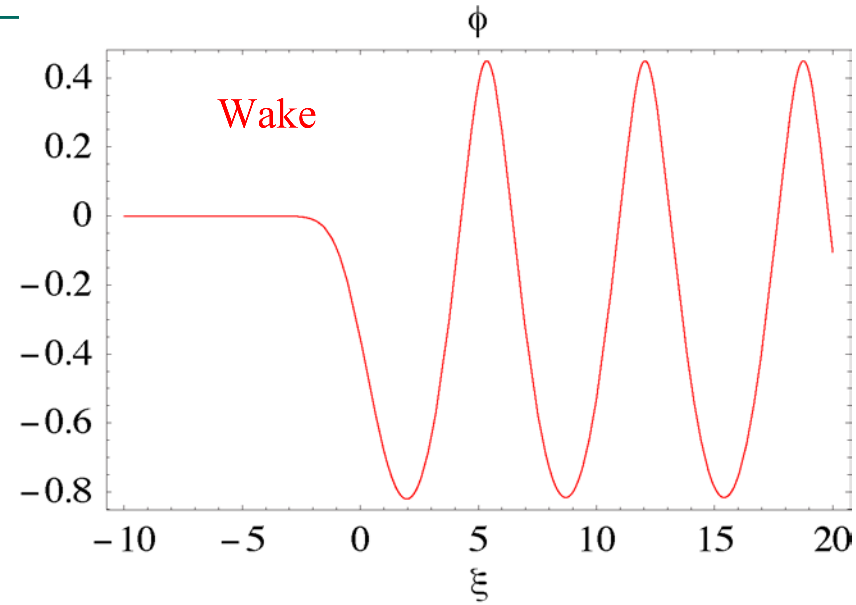
f_{trap}=10^{-2} implies 1 nC of trapped charge for

n=10^{19} cm^{-3}, $r_\perp$=10 μm, and L_{plasma}= 1 mm

- Temperature of plasmas in laser-plasma accelerator experiments T <100 eV

Warm Fluid Model (Low Temperature Kinetic Theory)

B.A. Shadwick *et al*., PRL (2004)



Asymptotic solution of Vlasov-Maxwell

- Valid for small momentum spread (<< *mc)*
- Average momentum fully relativistic
- No closure assumption
- Anisotropic pressure and distribution

Example

- Quasi-static plasma
- a_0 = 1.5, k_0/k_p = 10, $k_p L$ =2
- Initially 10 eV thermal plasma

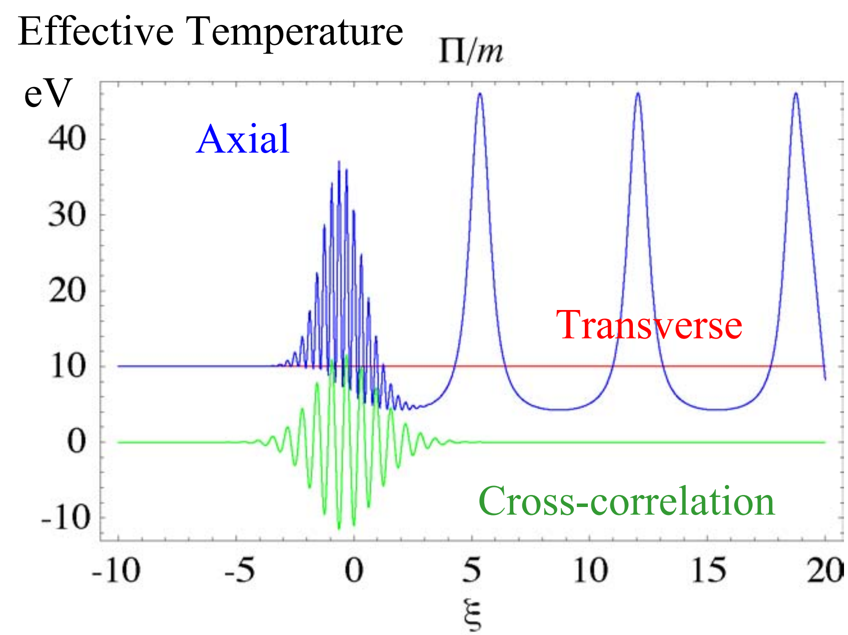
Results

- Thermal forces small and do not affect wake
- No significant heating
- Effective temperature (width of distribution)

$$\Pi_{xx} = m T_0$$

$$\Pi_{xz} = m T_0 \frac{n}{n_0} \beta_x$$

$$\Pi_{zz} = m T_0 \left(\frac{n}{n_0}\right)^2 (1 + \beta_x^2)$$



Maximum Plasma Wave Amplitude: Wavebreaking

Previous work:

- Cold Wavebreaking: Akhiezer and Polovin (1956)

$$E_{\mathrm{AP}} = \sqrt{2}(\gamma_\varphi - 1)^{1/2} E_0$$

$$E_0[\mathrm{V/m}] \cong 96\, n^{1/2}[\mathrm{cm}^{-3}] \;\cong 100\ \mathrm{GV/m}\ \text{for}\ n \cong 10^{18}\,\mathrm{cm}^{-3}$$

$$\text{E-beam}: \; \gamma_\varphi \cong \gamma_{beam} \;\cong 10^4 \;\text{for}\ SLAC$$

$$\text{Laser}: \; \gamma_\varphi \cong \omega/\omega_p \;\cong 10-100$$

- Warm Wavebreaking: Katsouleas and Mori (1988) and Rosenzweig (1988):

$$E_{\mathrm{th}} = (mc^2/T)^{1/4} f_{\mathrm{th}}(\gamma_\varphi, T) E_0 \quad \text{with} \quad f_{\mathrm{th}}(\gamma_\varphi, T) \sim 1$$

Limitations:

- Valid only in the high phase velocity limit (e.g., beam-driven case)

$$\gamma_\varphi (T/mc^2)^{1/2} \ll 1$$

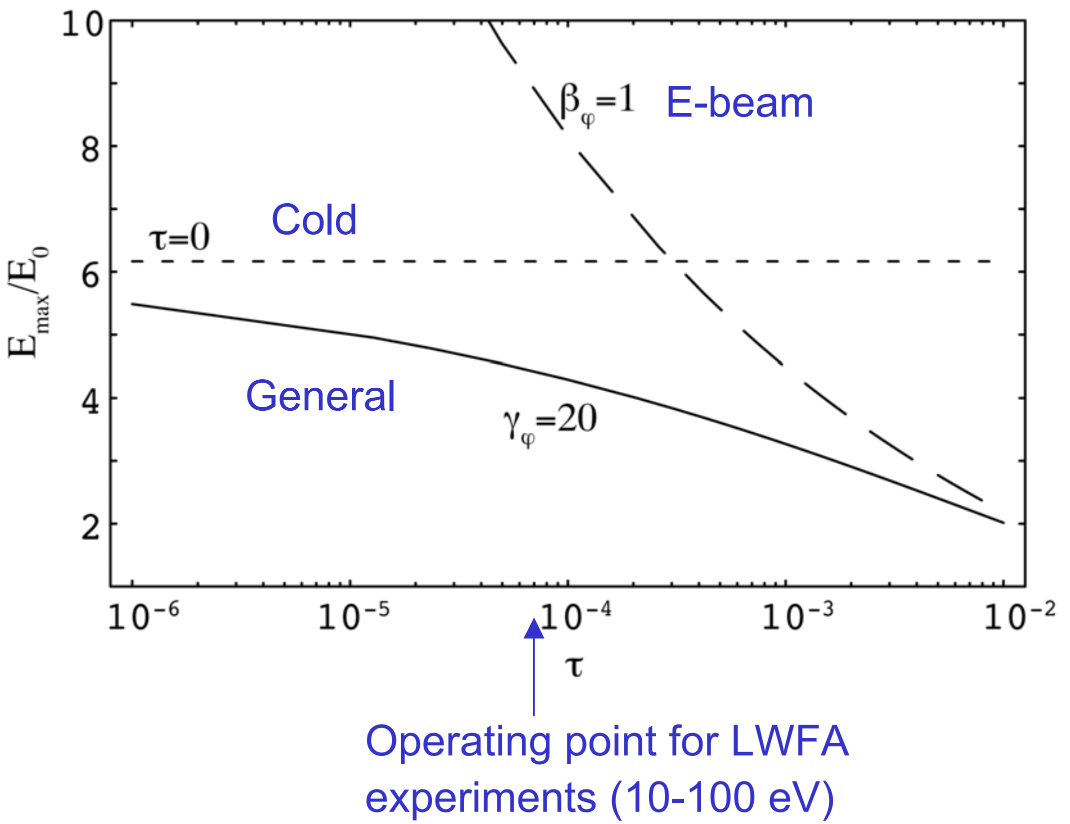
- Not valid for typical laser-driven plasma accelerator parameters: (T ~ 10 eV, γ_p~10-100)

$$\gamma_\varphi (T/mc^2)^{1/2} \gg 1$$

- Does not reduce to the cold wavebreaking result *($T \to 0$)*

Maximum Accelerating Field: General Case

Analytic theory based on relativistic warm fluid model: Schroeder et al., Phys. Rev. Lett. (submitted)



Normalized plasma temperature: $\tau = 3T/2mc^2$

Characteristic accelerating field: $E_0 = mc\omega_p/e \cong (0.96\ \text{V/cm})\ n^{1/2}[\text{cm}^{-3}]$

Momentum-Centered Vlasov Model

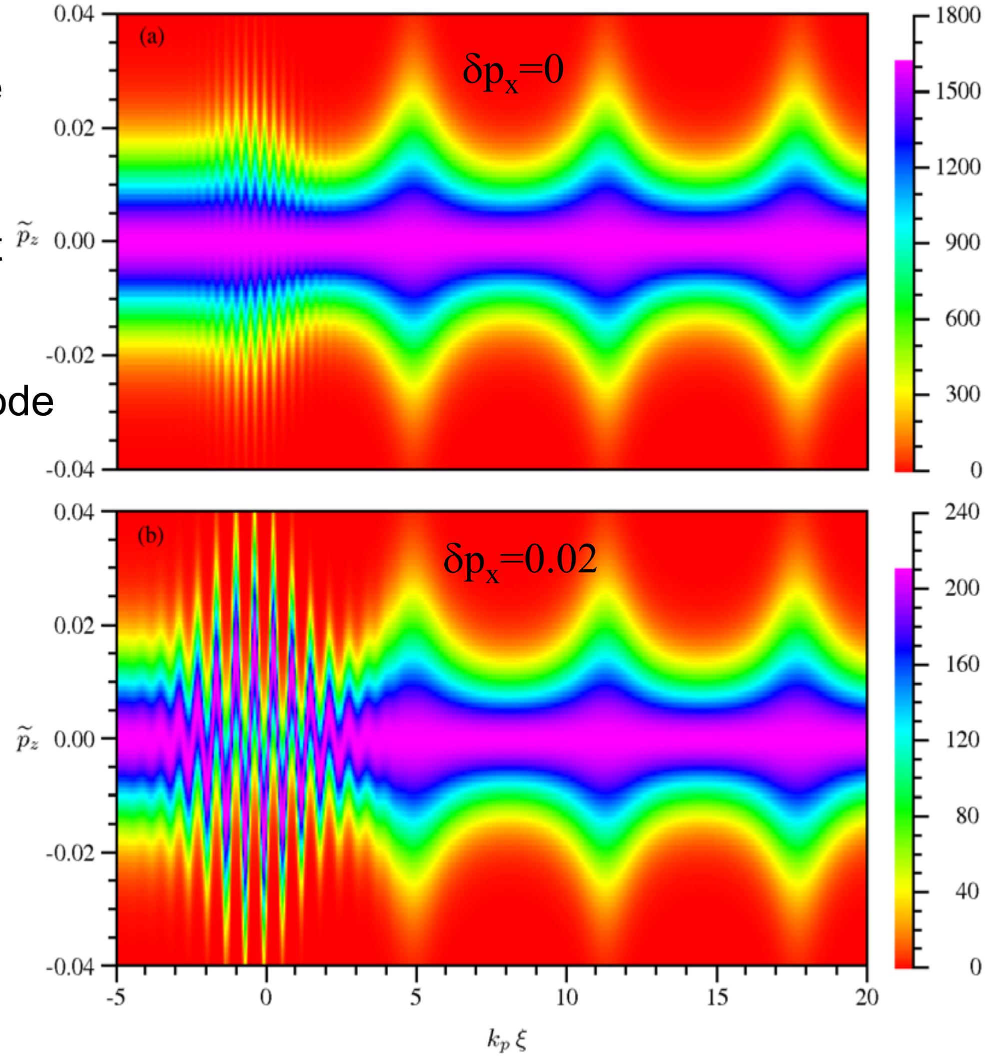
B.A. Shadwick *et al.*, Phys. Plasmas (2005)

Standard Vlasov code: particle distribution f(r,p,t)
- Must resolve momentum space
- Highly relativistic quiver momentum
- Large momentum space area - slow code

Momentum-centered Vlasov code:
- Momentum spread small about fluid orbit
- Extract transformation about fluid orbit
- Solve for momentum spread: f(r,δp,t)
- Small δp momentum space area - fast code
- Speed up: Orders of magnitude

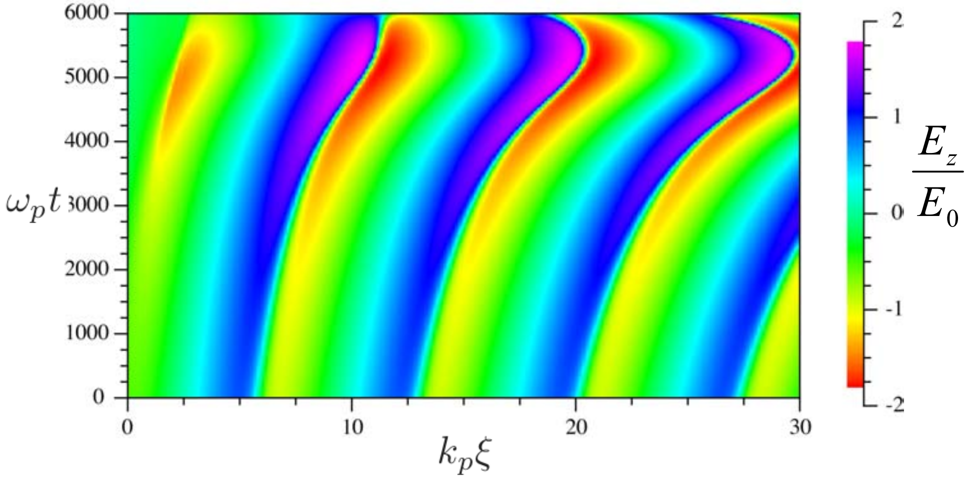
Example
- Quasi-static plasma
- Standard LWFA regime
- a_0 = 1, k_0/k_p = 10, $k_p L$ =2
- Initially 50 eV thermal plasma
- No significant heating
- Agrees with warm fluid results

Distribution function f(δp_z, δp_x, ξ)



Numerical Studies: GeV-class Example

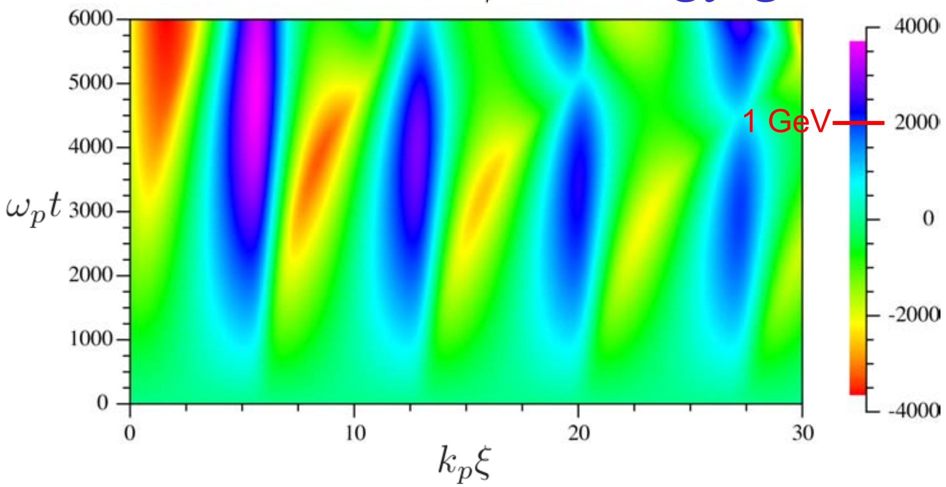
E_z Axial wakefield



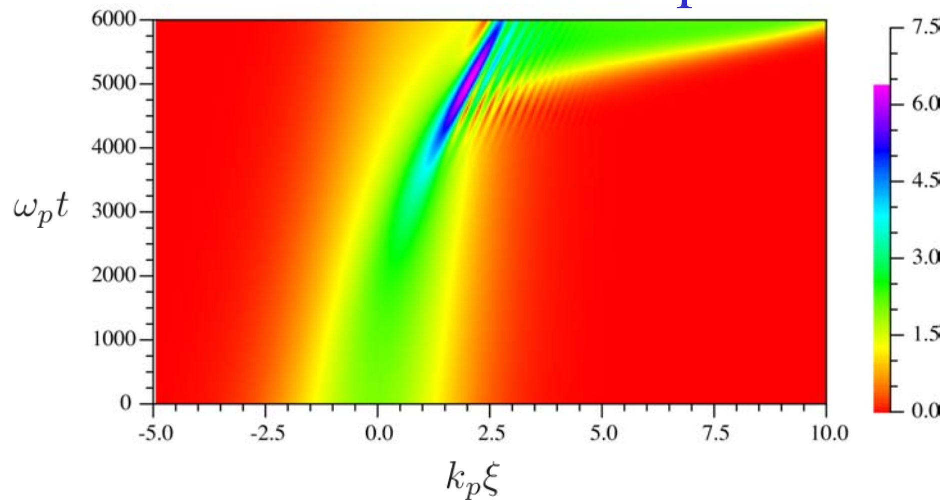
Fluid code

- Standard LWFA regime
- a_0 = 1.5, k_0/k_p = 40, k_p L =2
- Laser: 0.8 μm, 5x10^{18} W/cm^2, 30 fs
- Plasma: 10^{18} cm^{-3}, 3 cm

$\Delta\gamma$ Energy gain



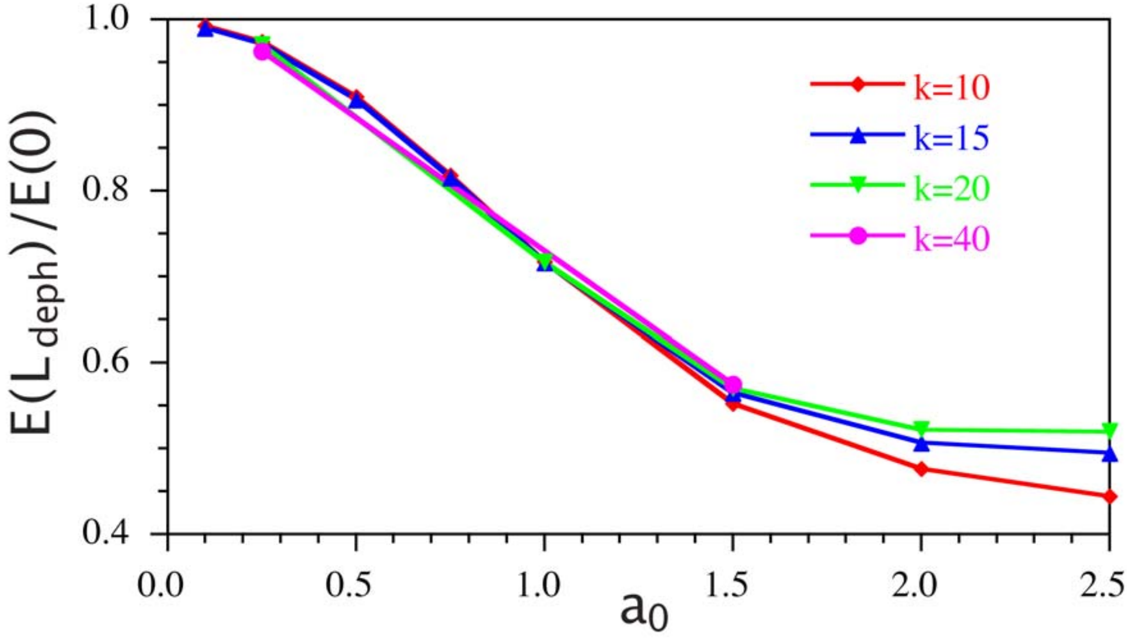
$|a|$ Laser pulse



Pump Depletion versus Electron Dephasing

Optimized acceleration stage: dephasing length ~ depletion length

Fraction of remaining laser pulse energy after propagating the dephasing length



Summary

- Simulation of LWFA experiments: 2D, 3D PIC
  - Identified process for mono-energetic bunch production
- Self-trapping of thermal electrons
  - Dark current small for experimental temperatures (10-100 eV)
- Warm fluid model (relativistic, nonlinear, small thermal spread)
  - Calculation of plasma temperature in wake - no heating
- Maximum plasma wave amplitude
  - Warm wavebreaking limit - valid in LWFA regime
- Momentum-centered Vlasov model
  - Exact transformation about fluid momentum
  - Orders of magnitude increase in computational speed
- Modeling of 1 GeV channel-guided stage (few cm)
  - Fluid modeling in 1D, 2D ongoing; PIC simulation in 2D ongoing
  - Optimization including nonlinear pump depletion and dephasing
- Other topics: Space charge effects, colliding pulse injection, THz and x-rays, etc.
- Close connection between theory, computation, and experiment
  - Model, design, and interpret L'OASIS experiments
  - SciDAC Collaboration