Ultrashort Electron Bunches Generated by Laser Plasma Accelerators

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Outline

- Self-Modulated Laser Wakefield Accelerator (LWFA)
  - Observations

    Self-Trapping ($\sim$ 100 MeV, $\delta\gamma/\gamma \sim 100\%$)

    Wake Amplitudes $E_z < E_0$
    (Below Wavebreaking)
  - Coupling to Raman Backscatter

    Slow Beat Wave $\Rightarrow$ Trapping

    Fast Wakefield $\Rightarrow$ Acceleration
  - Trapping Threshold: $E_z < E_0$

    Lower Threshold for Linear Polarization

- Standard Laser Wakefield Accelerator (LWFA)
  - Injection by Colliding Pulses

    Forward and Backward Laser Pulses

    Slow Ponderomotive Beat Wave
  - Relativistic Electron Bunches

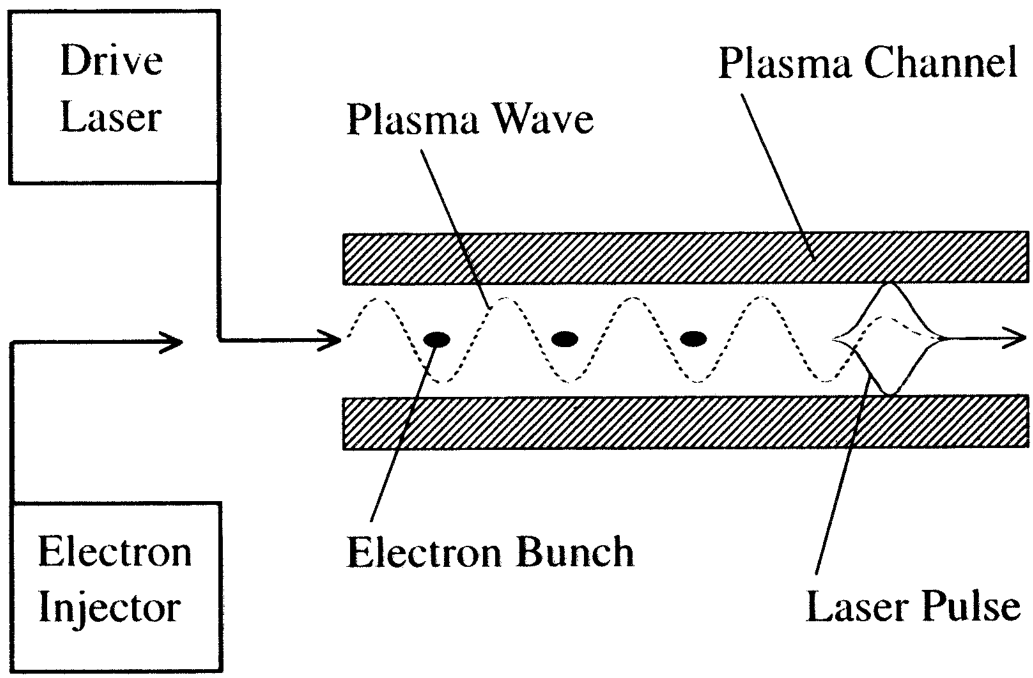
    Ultrashort ~ 1 fs

    Small Energy Spread $\sim 1\%$
  - 3D Test Particle Simulations

Laser Wakefield Accelerator

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

Review: E. Esarey et al., IEEE Plasma Sci. **24**, 252 (1996)



$\frac{\lambda_p}{c} \sim 100$ fs $\qquad L \simeq \lambda_p$

$\tau_b \ll 100$ fs $\qquad \lambda_p = \frac{2\pi c}{\omega_p} \sim n^{-1/2}$

Density Channel $\Delta n = \frac{1}{\pi r_e r_L^2}$

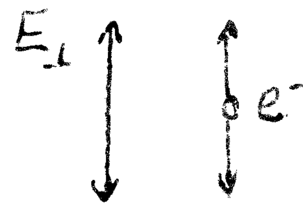
Ultrahigh Power Lasers

- Laser power: P_0

$$P_0\,[\mathrm{GW}] = 21.5\,(a_0 r_L/\lambda)^2$$

r_L = laser spot size

- Laser strength parameter: a_0



➡ $a_0 = eA_\perp/m_e c^2 = \gamma v_\perp/c$

- Laser intensity: I_0

$$a_0 \simeq 10^{-9}\lambda[\mu\mathrm{m}]\left(I_0[\mathrm{W/cm^2}]\right)^{1/2}$$

- For $\lambda \simeq 1$ μm

$$\boxed{I_0 \gtrsim 10^{18}\ \mathrm{W/cm^2} \Rightarrow a_0 \gtrsim 1}$$

⇒ highly relativistic quiver motion

- Compact lasers technology*

$\gtrsim 10^{18}$ W/cm^2, $\gtrsim 10$ TW, $\gtrsim 10$ J, $\lesssim 1$ ps

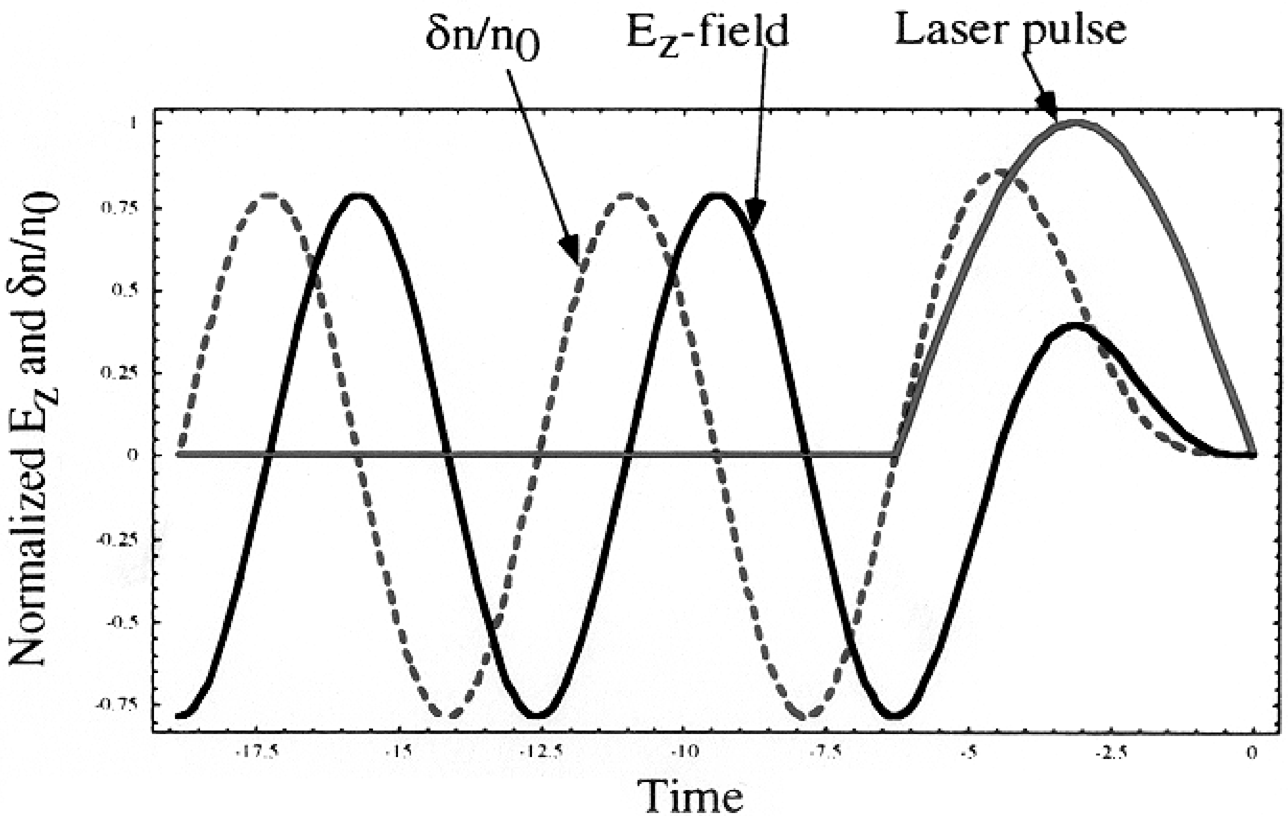
*Chirped Pulse Amplification, G. Mourou et al. (1985)

Laser wakefield excitation

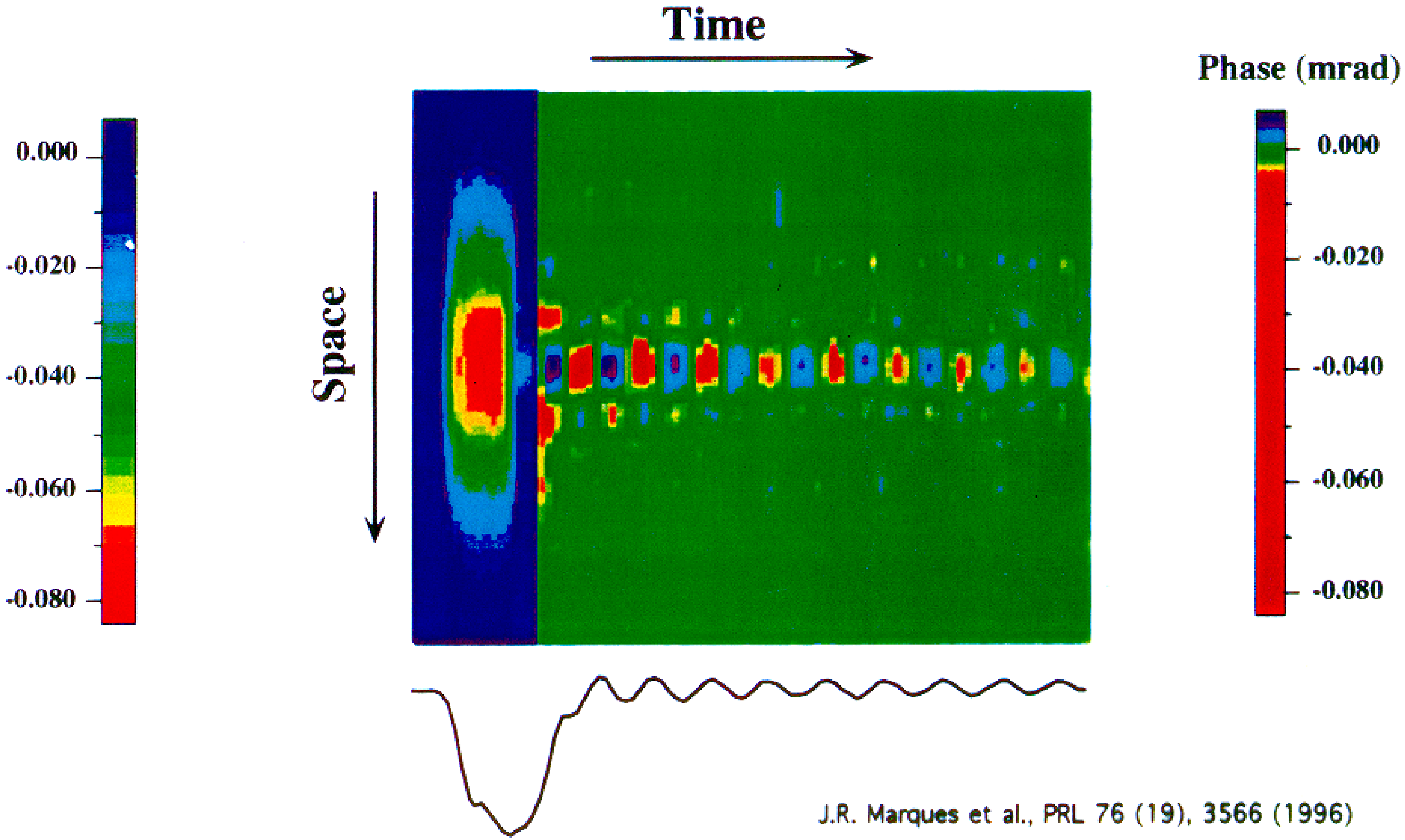
- Laser pulse excites a plasma wave via the ponderomotive force

Density perturbation — Ponderomotive force

$$\left(\frac{\partial^2}{\partial t^2}+\omega_p^2\right)\frac{\delta n}{n_0}=c^2\nabla^2\frac{a^2}{2}$$

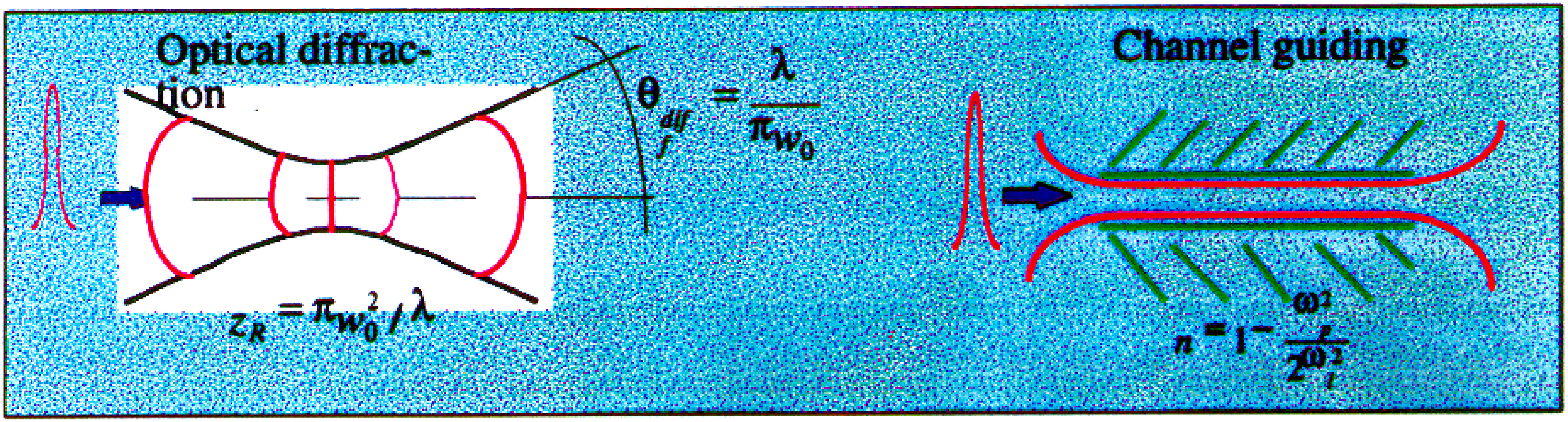


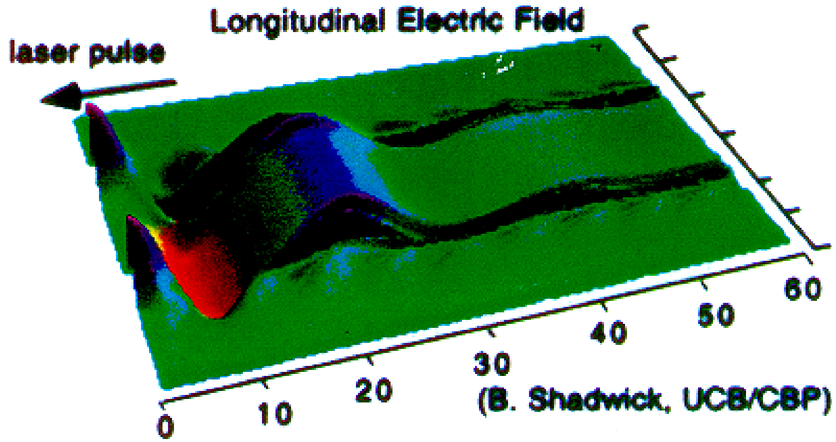
Electron density oscillation



J.R. Marques et al., PRL 76 (19), 3566 (1996)

Plasma channel: structure for guiding laser and supporting wake





Goal:

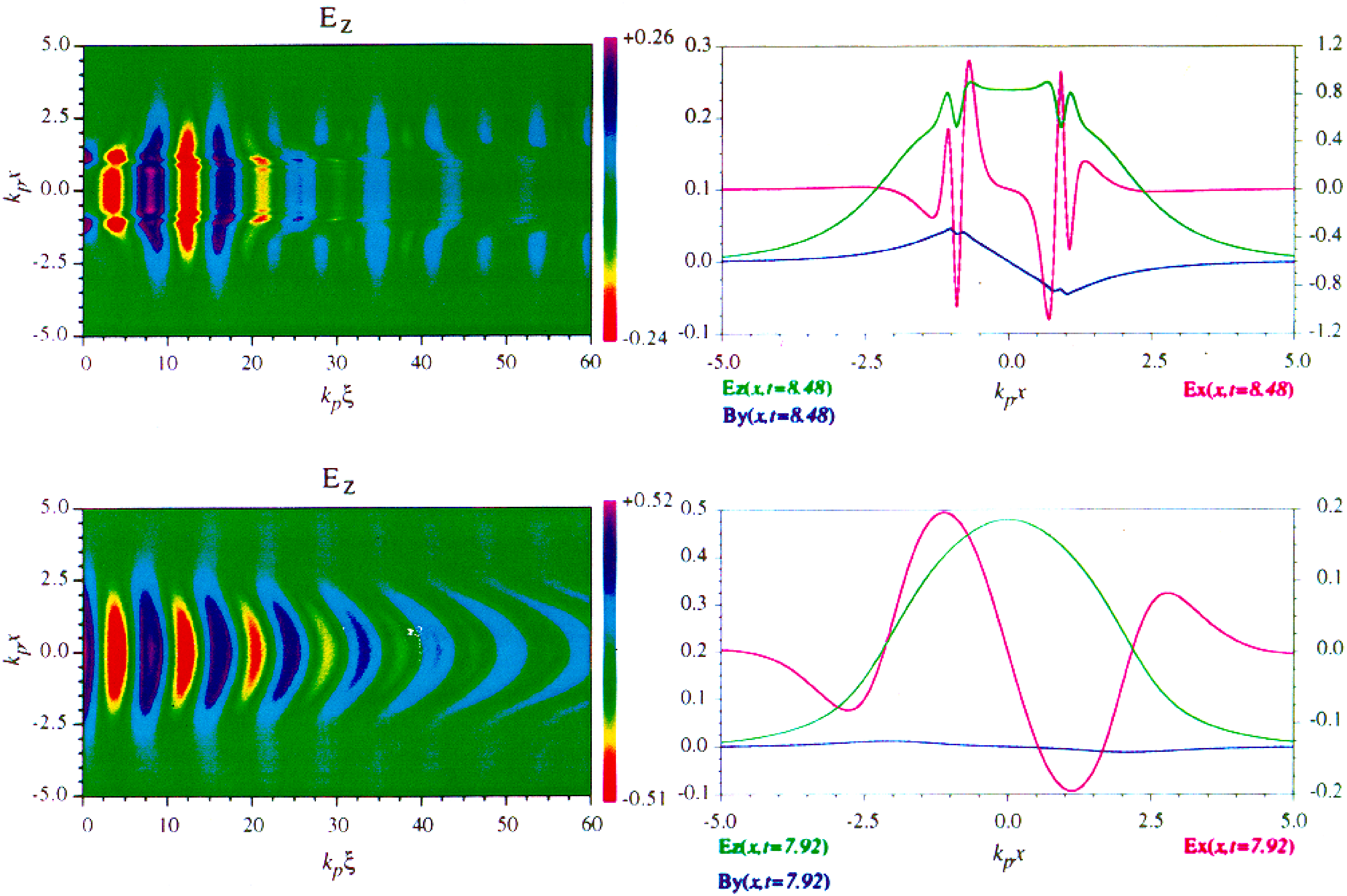
Guide 10^{18} W/cm^2 pulses over many diffraction lengths

Approach:

Preformed channels production through hydrodynamic shockwave in plasma

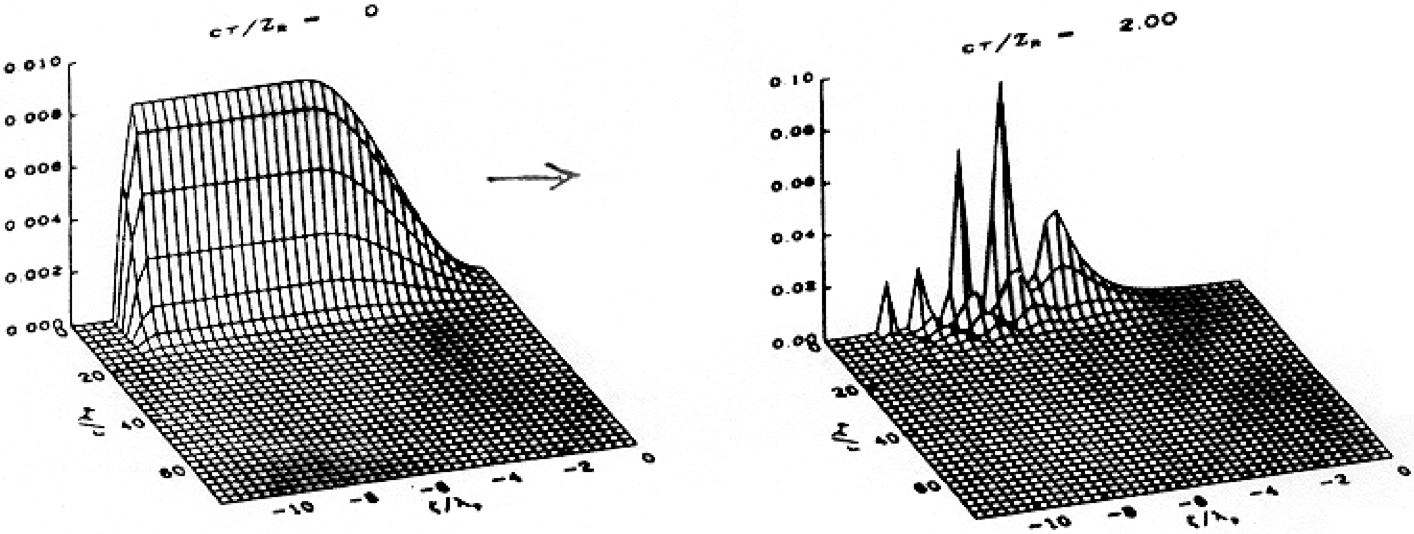
⇒ Dual pulse Ignitor-heater scheme

Wakes in Hollow and Parabolic Channels



B. A. Shadwick J. S. Wurtele 1997

Self-Modulated
Laser Wakefield Accelerator
(SM-LWFA)



$z = 0$ $z = 2Z_R$

- Operation Regime
  - Pulse length: $L > \lambda_p \sim 1/\sqrt{n_0}$
  - Power: $P > P_{crit} \sim 1/n_0$

  For fixed L, P

  $\Rightarrow$ Operate at high n_0

$P = 2$ TW
$n_0 = 10^{19}$ cm^{-3}
$E_z > 100$ GV/m

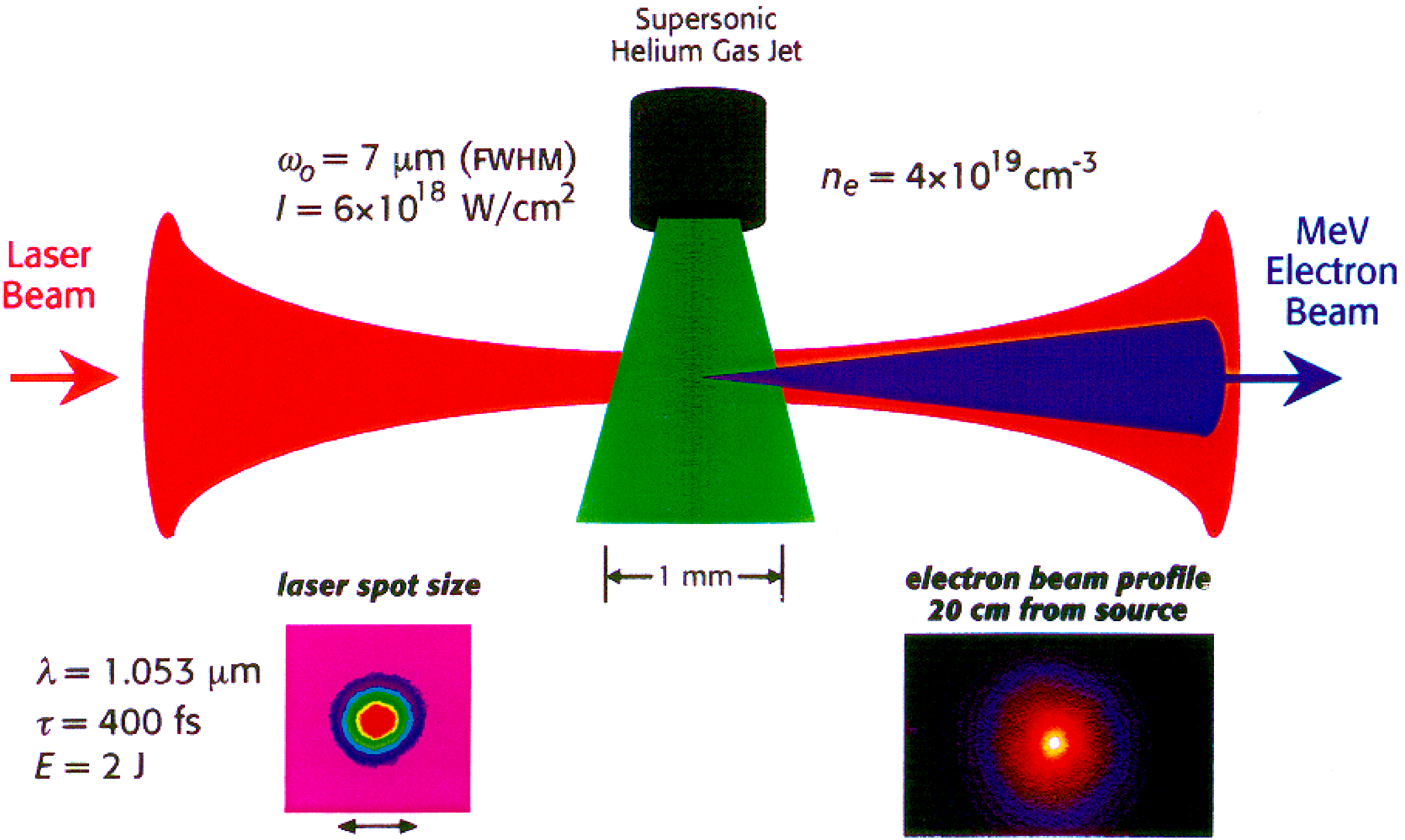
- Enhanced wakefields/acceleration
  - Higher densities: $E_z \sim \sqrt{n_0}$
  - Resonant excitation

→ Self-Trapping

Sprangle, Esarey, Krall, Joyce, Phys. Rev. Lett. 69, 2200 (1992)
Andreev *et al.*, JETP Lett., 55, 571 (1992)
Antonsen and Mora, Phys. Rev. Lett. 69, 2204 (1992)

Table-top accelerator creates energetic, ultrashort, and ultrabright electrons

A relativistic electron beam is created when an ultrashort (400 fs) laser pulse is focused into a jet of Helium gas. Under the right conditions, energetic electrons (1-40 MeV) emerge in a well-collimated beam. The acceleration occurs in less than 1 mm!



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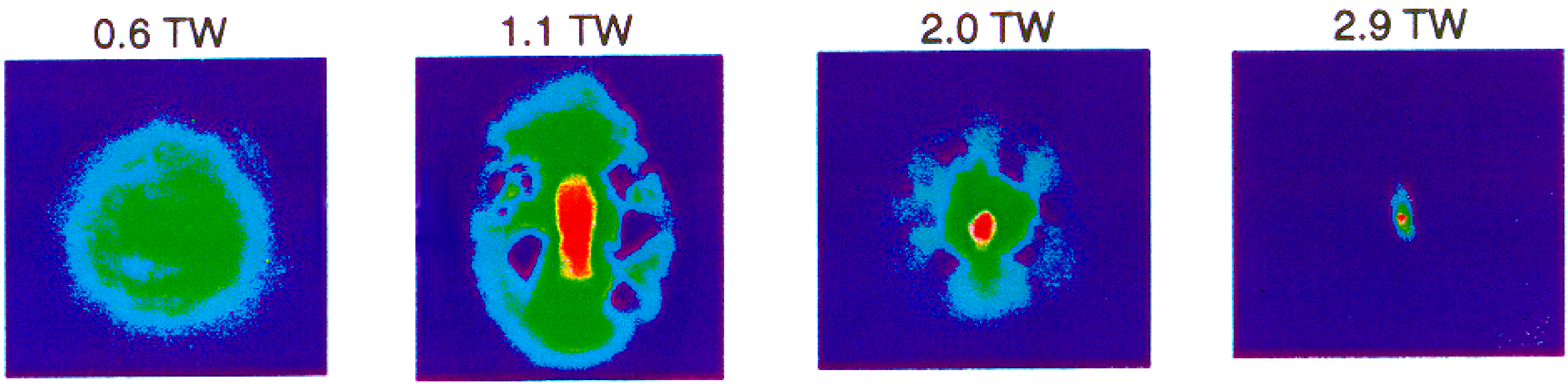
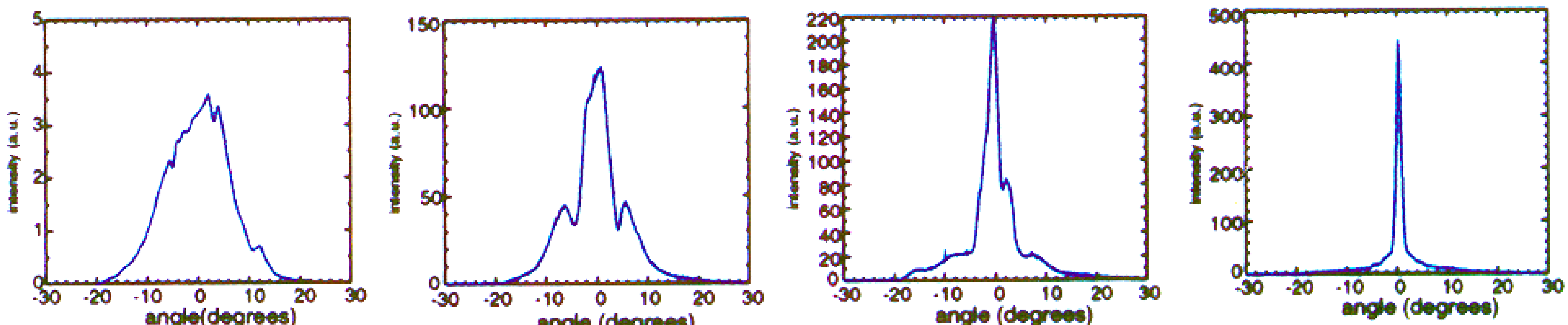
The Profile of the Electron Beam Shows Three Concentric Components

Variation of the electron beam profile with increase of laser power for 2.3×10^{19} cm^{-3} plasma density



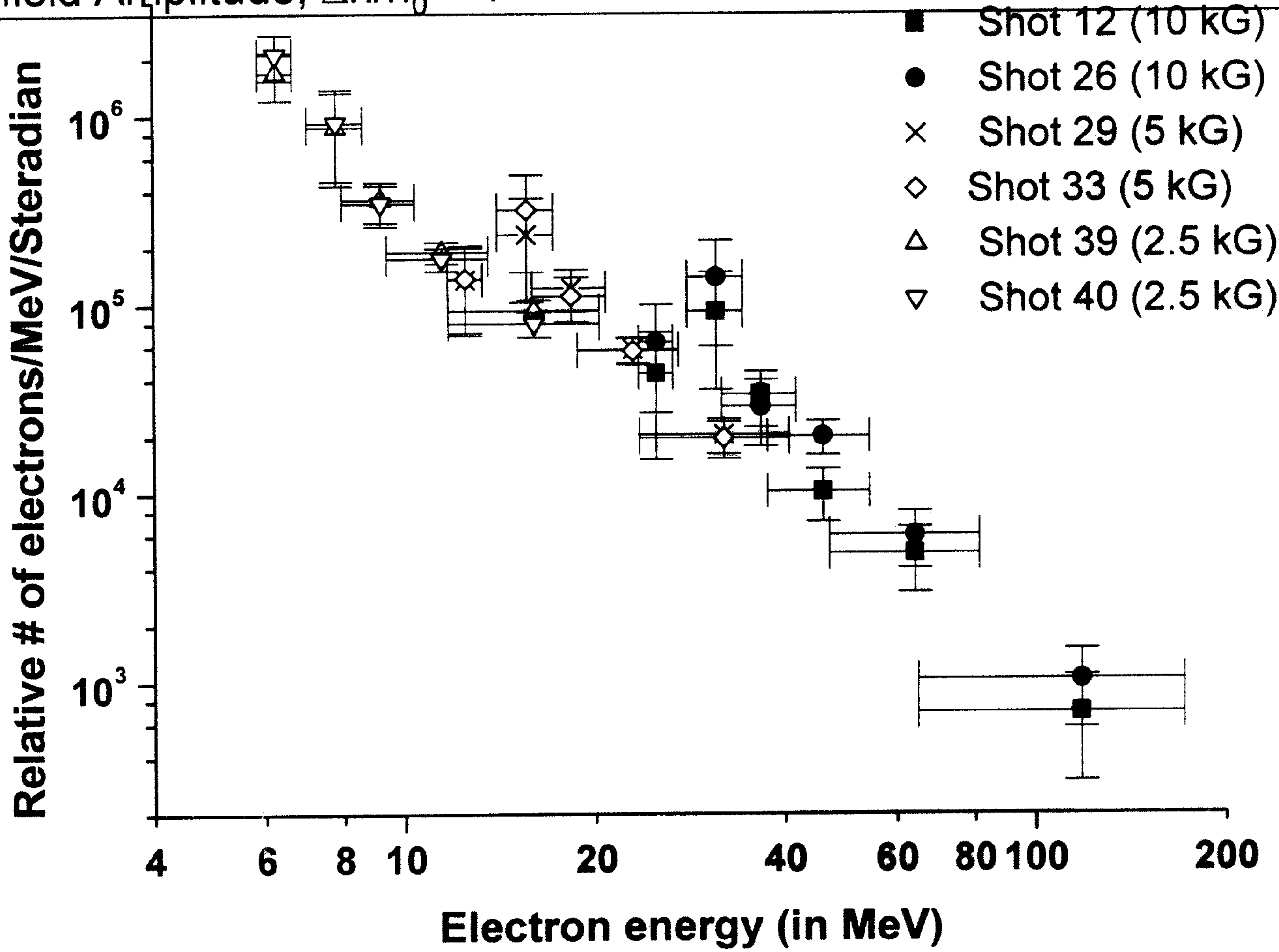
Horizontal lineouts through the center of the beam profiles



* The FWHM divergence angles of the 1st, 2nd, and 3rd components are 20°-25°, 5°-10°, and 1°-3°, respectively.
* Symmetric dark holes appear in the first beam component when the second beam component appears.

Single shot electron energy spectra in the NRL SM-LWFA using a new multi-channel electron spectrometer

- Peak energy ~ 100 MeV
- Peak Acceleration field = 100-500 GV/m
- Wakefield Amplitude, $\Delta n/n_0 \approx 1$
- Electrons trapped in the wakefield by backward Raman scattering[1]



NRL
~100 MeV

Total e⁻
10^8-10^9

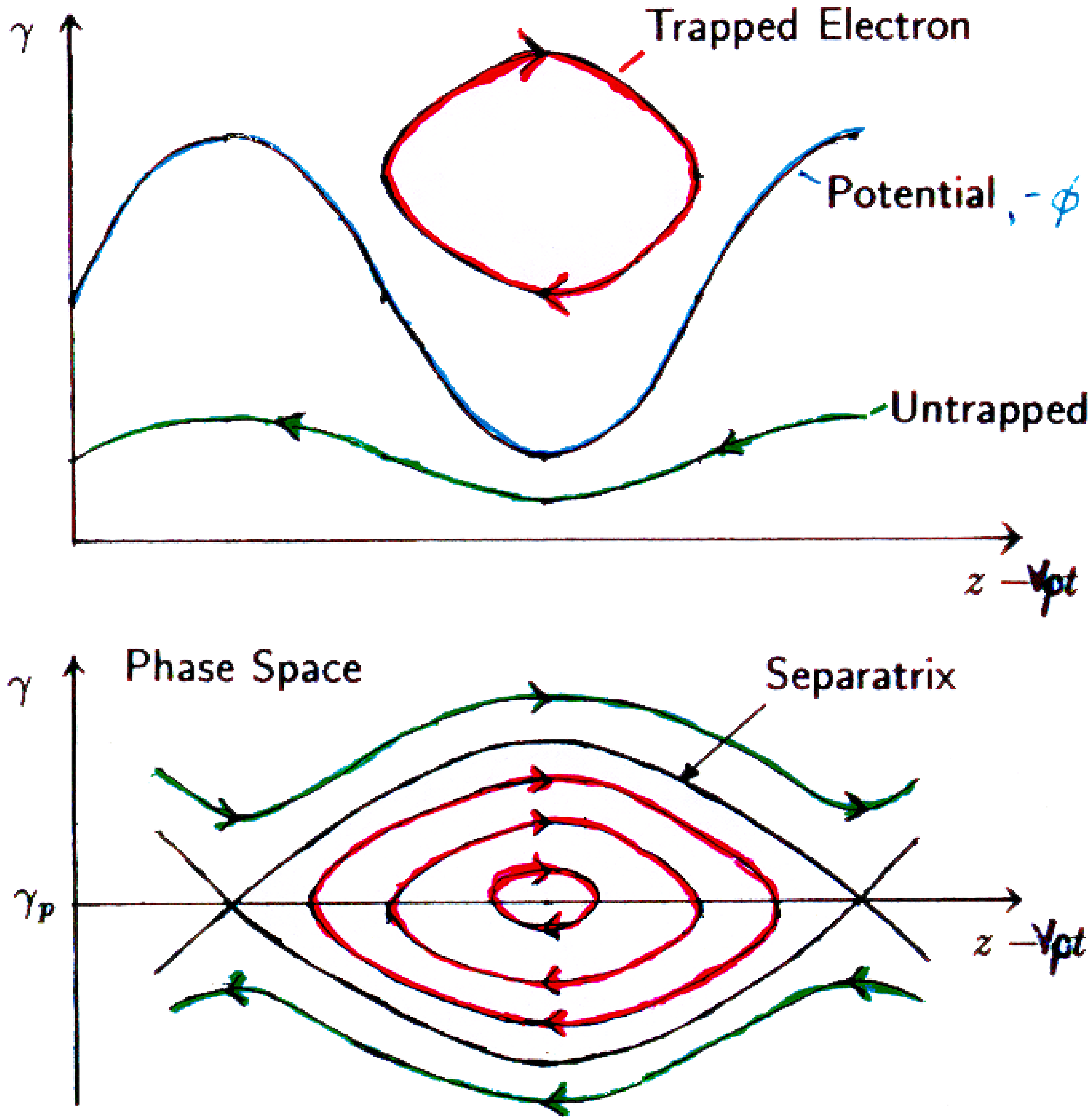
NRL

1 C.I. Moore *et al.*, *Phys. Rev. Lett.* **79**, 3909 (1997)

RAL/IC/UCLA (100 MeV), Michigan (40 MeV), Japan (>100 MeV)

Single Particle Dynamics

- Particle orbits/Phase space



Wavebreaking

- Cold nonrelativistic: [Dawson, Phys. Rev. (59)]

$$\nabla \cdot E = 4\pi e n_e$$

$$(\omega_p/c)E_0 = 4\pi e n_0$$

$n_0 = 10^{19}\ \mathrm{cm}^{-3}$

$$\boxed{E_0 = c m_e \omega_p / e \simeq n_0^{1/2}[\mathrm{cm}^{-3}]\ \mathrm{V/cm}}$$

$E_0 = 300$ GV/m

Ex.: $n_0 = 10^{17}\ \mathrm{cm}^{-3} \Rightarrow \underline{E_0 \simeq 30\ \mathrm{GV/m}}$

RF linacs: 30 MV/m

- Cold relativistic: [Akhiezer, Polovin, JETP (56)]

$$v_{fluid} \rightarrow v_{phase}, \quad \gamma_p = (1 - v_p^2/c^2)^{-1/2}$$

$$\boxed{E_{WB} = \sqrt{2}(\gamma_p - 1)^{1/2} E_0}$$

Ex.: $\gamma_p \simeq \omega/\omega_p \simeq 300 \Rightarrow \underline{E_{WB} \simeq 25 E_0}$

- Warm relativistic: $|v_{fluid} + v_{th}| \rightarrow v_{phase}$

[Katsouleas, Mori, PRL (88); Rosenzweig, PRA (88)]

$$\boxed{E_{th} = (m_e c^2/3T)^{1/2} f(\gamma_p, T) E_0}$$

$E_{th} > E_0$

$$f(\gamma_p, T) \sim 1$$

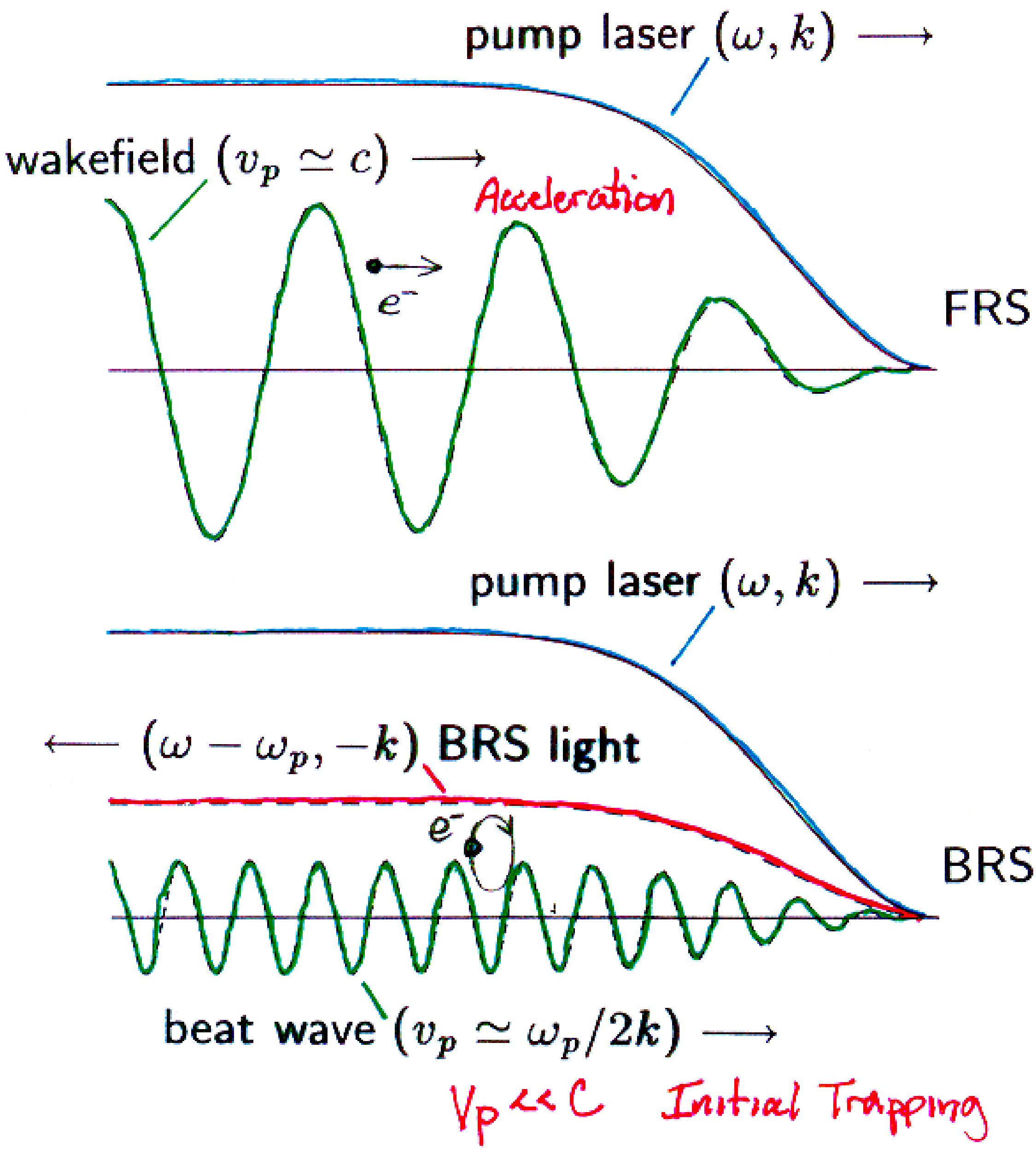
Ex.: $E_{th} < E_{WB} \Rightarrow \underline{T > 290\ \mathrm{eV}}$ for $\gamma_p \simeq 300$

2D Wavebreaking: J.K. Kim (Mich)

Self-Modulated LWFA: Trapping by BRS

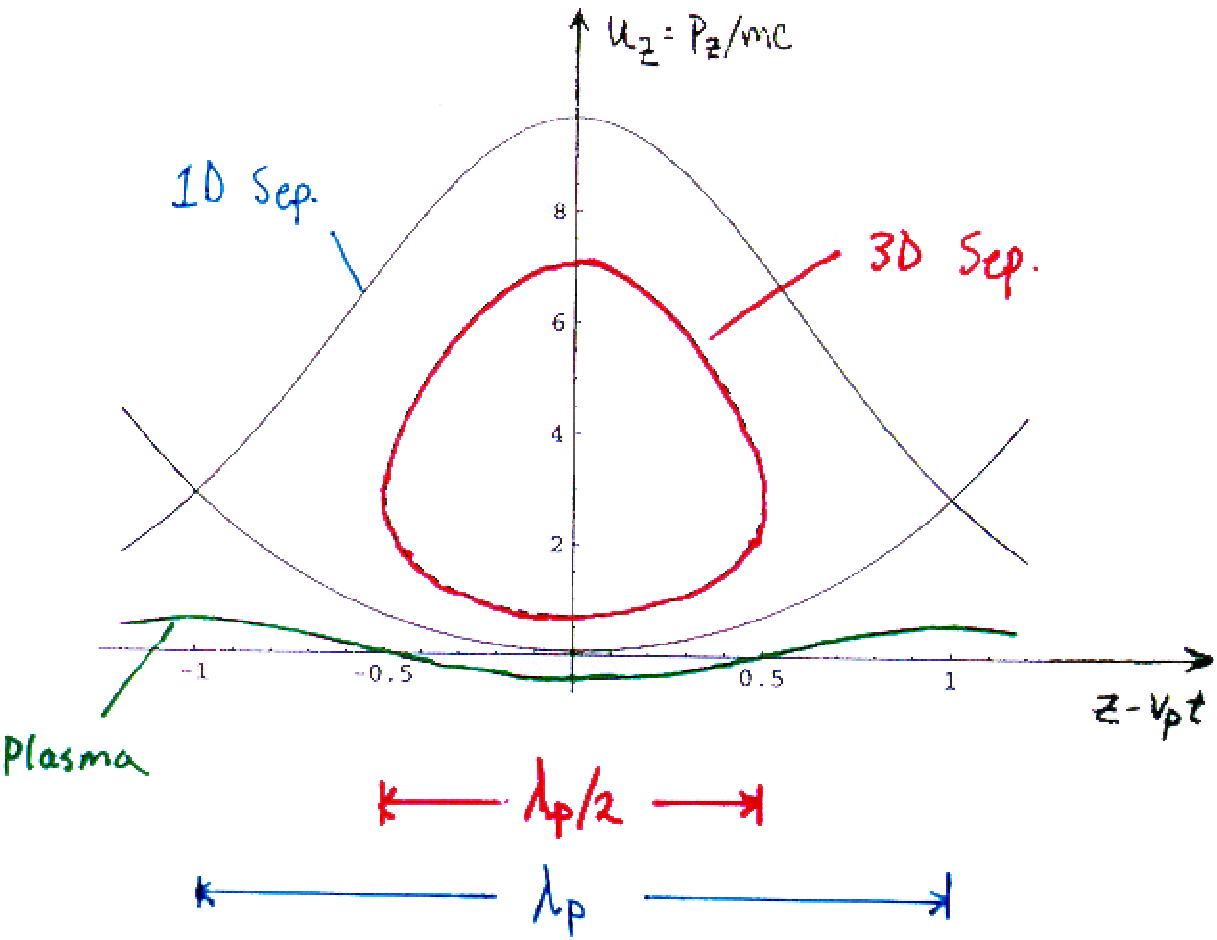
Esarey et al. PRL 98

- Two Stage Acceleration Process
  1. Fast wakefield $v_p \simeq c$ (self-modulation/FRS)
     High energy acceleration
  2. Slow beat wave $v_p \ll c$ (Raman backscatter-BRS)
     Initial trapping and heating



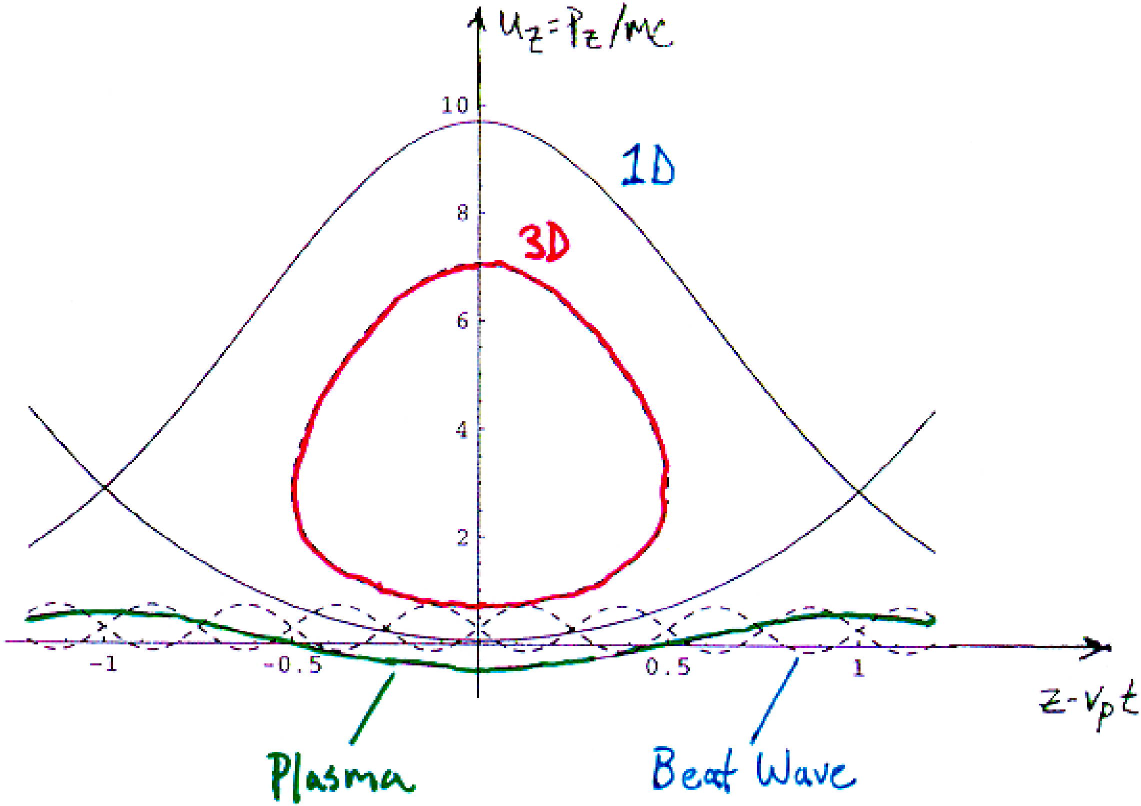
Electron Phase Space

- Separatrices



Electron Phase Space

- Separatrices



Self-Trapping Threshold

- Overlapping Separatrices:

$$u_{max}^{beat} > u_{min}^{wake}$$

$u = \frac{P_z}{mc}$

$$\boxed{\phi_0 > (1-\beta_{pb})\gamma_{\perp 0}/2 - (a_0 a_1)^{1/2}}$$

$\phi_0 = \frac{E_z}{E_0} = \frac{\delta n}{n_0}$

- Example: circular polarization

$$a_0 = 1.4,\ a_1 = 0.033,\ \gamma_p = 8.5,\ \beta_{pb} = 0.056$$

$$u_{max} = 0.53$$

$$\underline{\phi_0 > 0.54}$$

(linear polarization: $\underline{\phi_0 > 0.24}$)

$$(\phi_{0,3D} = 2\phi_{0,1D})$$

- Note: 1D Cold Wavebreaking

$$\phi_{WB} = \sqrt{2}(\gamma_p - 1)^{1/2} \simeq 3.9$$

$a_0^2 \simeq 10^{-18} \lambda^2 [\mu m]\, I\, [W/cm^2]$

Test Particle Simulations

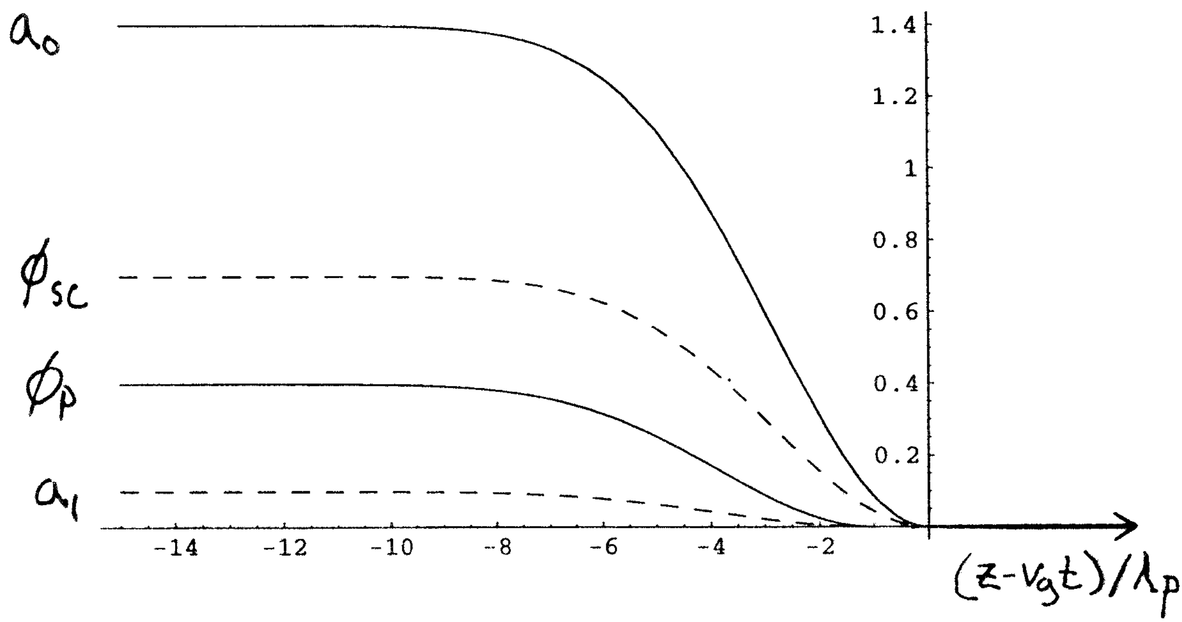
- Push electrons in specified 3D fields

1. Pump laser: $a_L = \hat{a}_0 e^{i(k_0 z - \omega_0 t)}$
2. Raman backscatter: $a_B = \hat{a}_1 e^{i(k_1 z - \omega_1 t)}$
3. Wakefield: $\phi_p = \hat{\phi}_0 e^{i(k_p z - \omega_p t)}$
4. DC space charge: $\phi_{sc} = (1 + \hat{a}_0^2)^{1/2} - 1$

   Envelopes: $\hat{a}_0 = a_0 \exp(-r^2/r_0^2 - \zeta^2/L^2)$

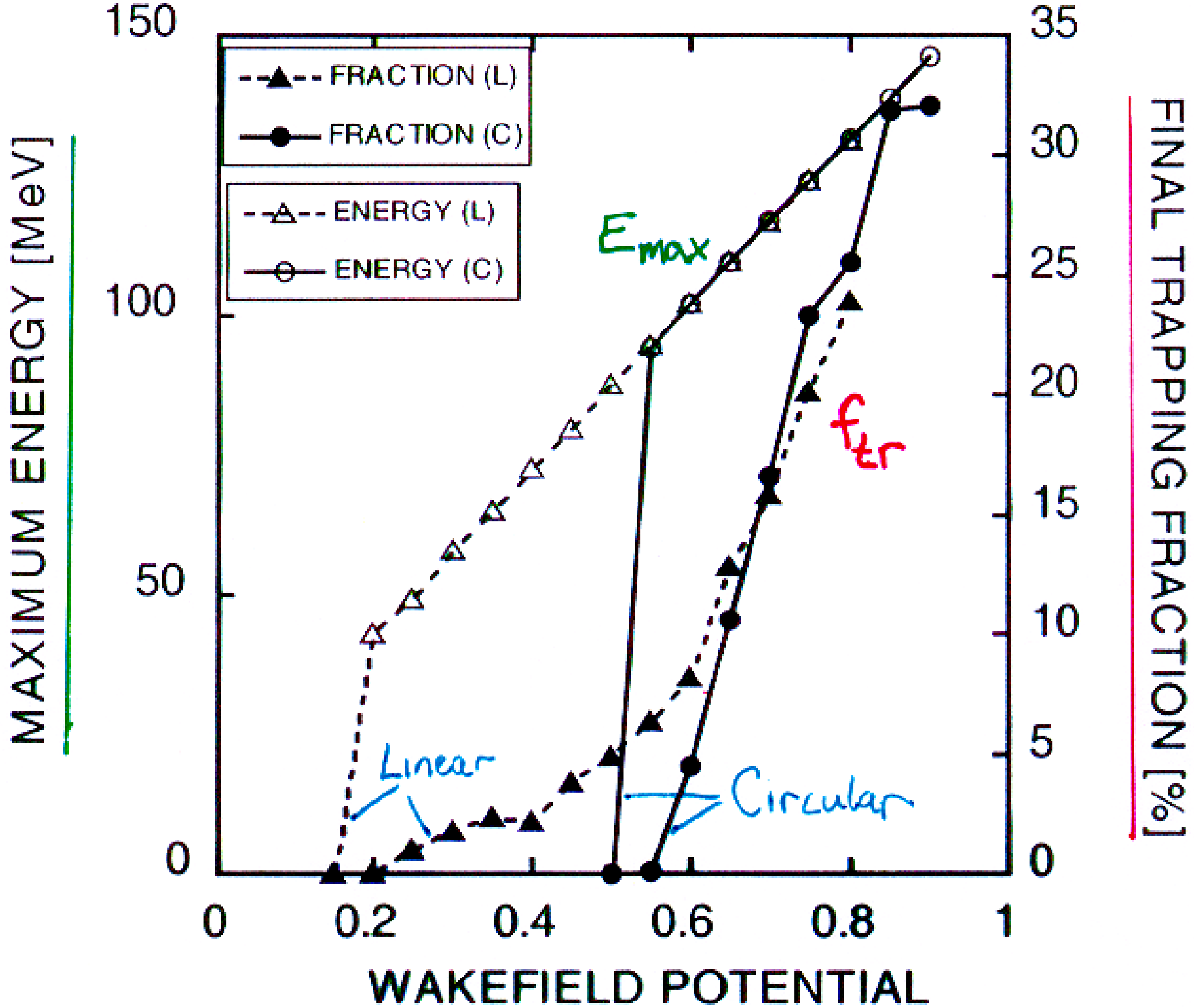
   Dispersion: $\omega_1 \simeq \omega_0 - \omega_p$, $k_1 \simeq -2k_0$

Ex: $a_0 = 1.4$, $a_1 = 0.03$, $\phi_0 = 0.3$, $\lambda_0 = 1$ μm, $r_0 = 4$ μm, $\omega_0/\omega_p = 8.5$, $n_0 = 10^{19}$ cm^{-3}, $P \simeq P_c = 1.3$ TW



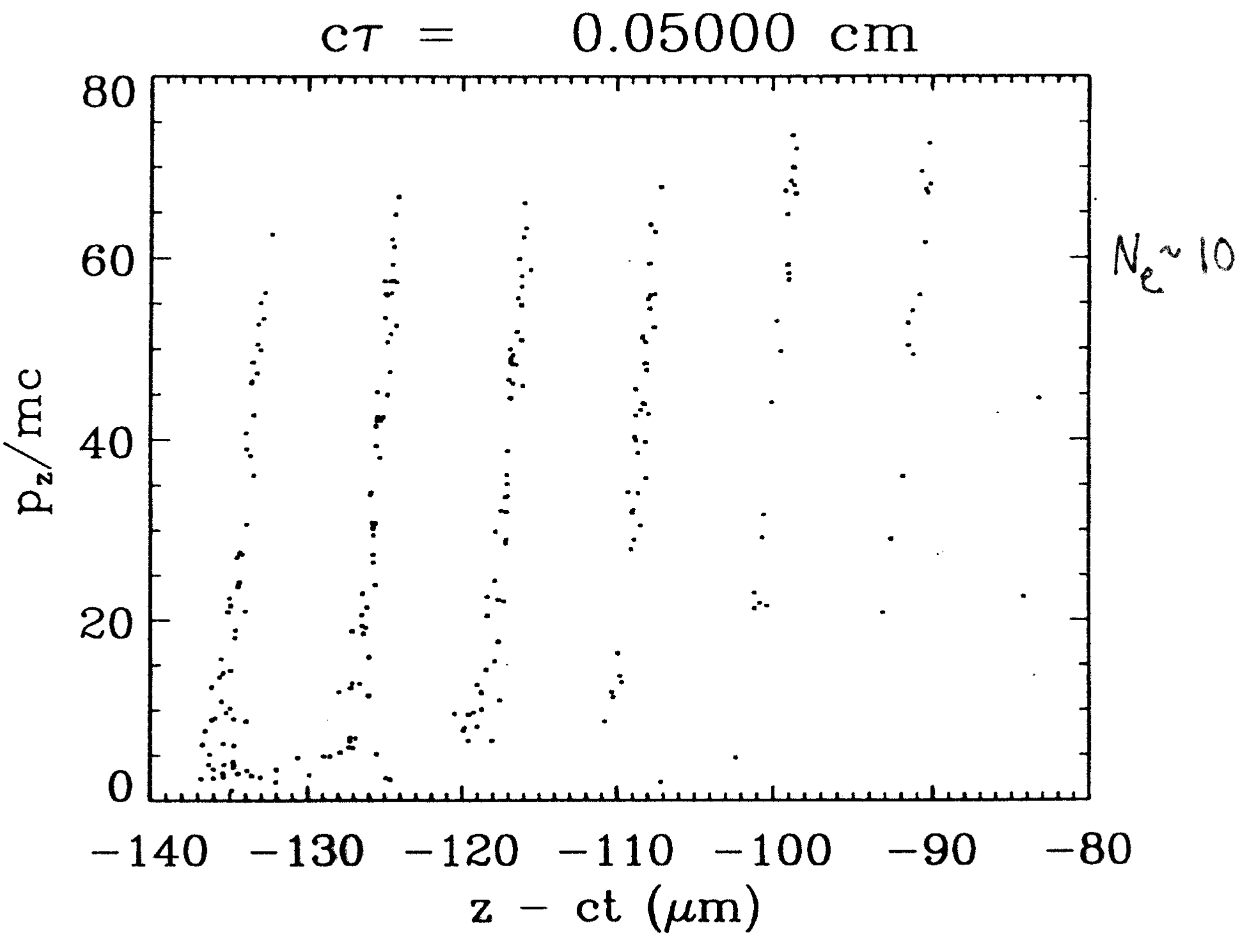
1D Linear/Circular Polarization

$$a_0 = 2, \quad a_1 = 0.046, \quad \omega_0/\omega_p = 8.5$$



Longitudinal Phase Space

3D Linear Polarization



$a_0 = 2$, $a_1 = 0.046$, $\phi_0 = 0.3$, $\omega_0/\omega_p = 8.5$

$\lambda_0 = 1\ \mu m$, $r_0 = 4\ \mu m$, $P_0 = 1.4$ TW, $n_0 \approx 10^{19}\ cm^{-3}$

Total No. of Trapped Electrons

- Self-Trapped Electrons

$$N_b \simeq f_{tr} n_0 \pi r_f^2 L_p$$

$$f_{tr} = 1\%,\ r_f = 2\ \mu\text{m},\ L_p = 1\ \text{mm},\ n_0 = 10^{19}\ \text{cm}^{-3}$$

$$\underline{N_b \sim 10^9}$$

- Beam Loading Limit

$$N_0 \simeq 5 \times 10^5 (E_z/E_0) n_0^{1/2} [\text{cm}^{-3}] A[\text{cm}^2]$$

$$\underline{N_0 \sim 10^9}$$

Maximum Energy Gain

- Conventional Result (3D Separatrix Theory)

$$\gamma_{max} = 2\gamma_p^2 E_z / E_0$$

$$\gamma_p^2 \simeq \omega_0^2 / \omega_p^2$$

- Self-Channeling Forces (1D Separatrix Theory)

$$\gamma_{max} = 4\gamma_p^2 E_z / E_0$$

- Nonlinear Effects

  Relativistic effects: $\omega_p^2 \rightarrow \omega_p^2 / \gamma_\perp$

  Self-Channeling: $n < n_0$

$$\gamma_p^2 \rightarrow \gamma_\perp (n_0/n) \omega_0^2 / \omega_p^2$$

$$\boxed{\gamma_{max} = \underline{2[\gamma_\perp (n_0/n)]^{3/2}} \cdot \underline{[2(\omega_0^2/\omega_p^2) E_z / E_0]}}$$

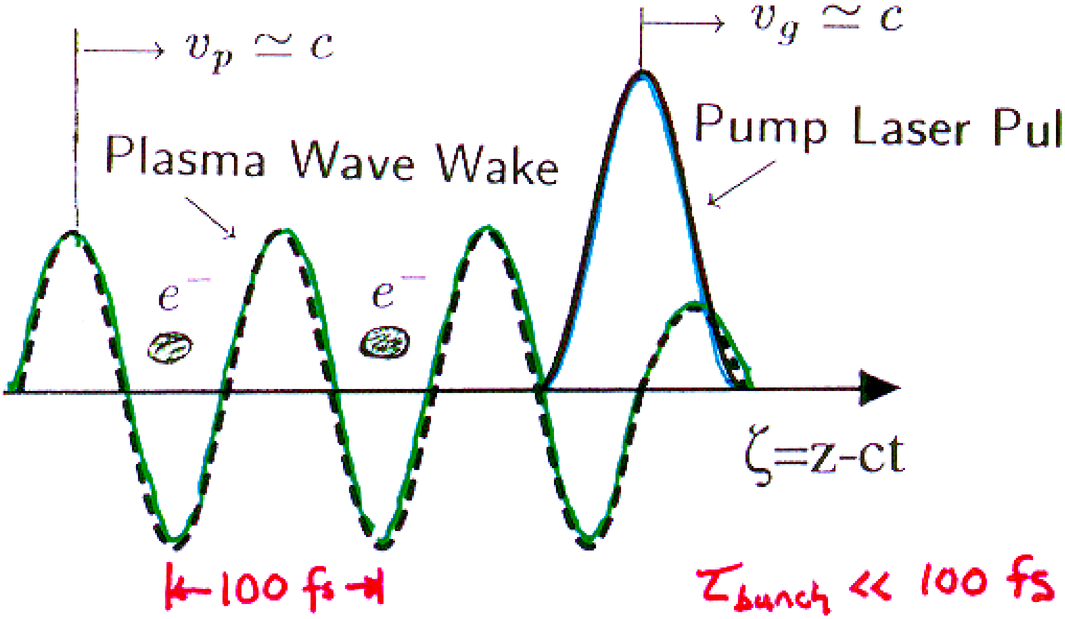
$$\gamma_\perp = (1 + a_0^2)^{1/2}$$

Correction ~5-10

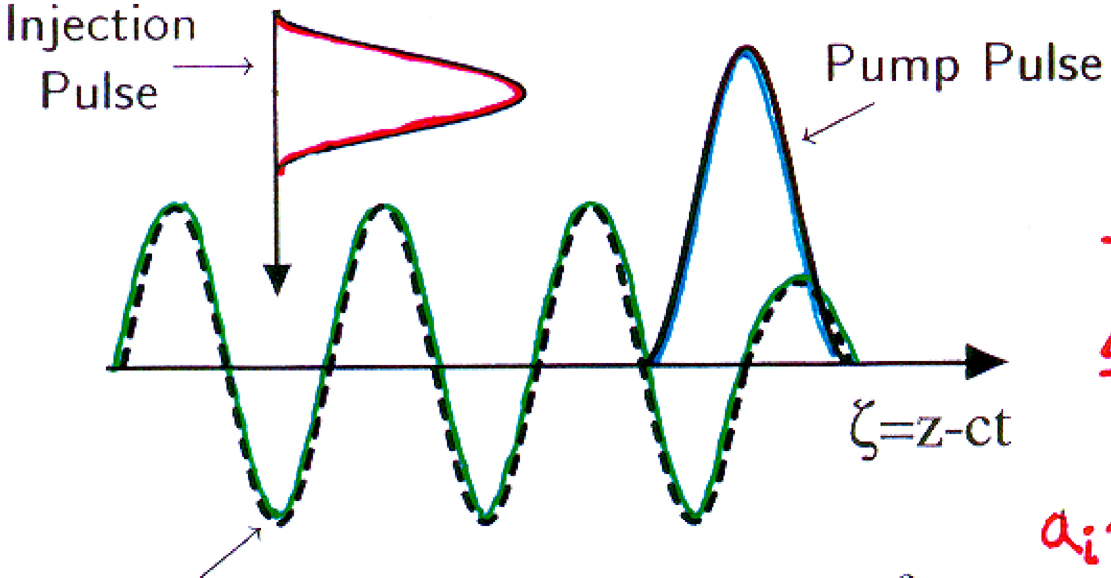
Conventional

Electron Injection in LWFAs

- External Injection (e.g., RF Gun)



- Laser Injection [Umstadter et al, PRL (1996)]



$\tau_b = 10$ fs

$\frac{\Delta\gamma}{\gamma} = 20\%$

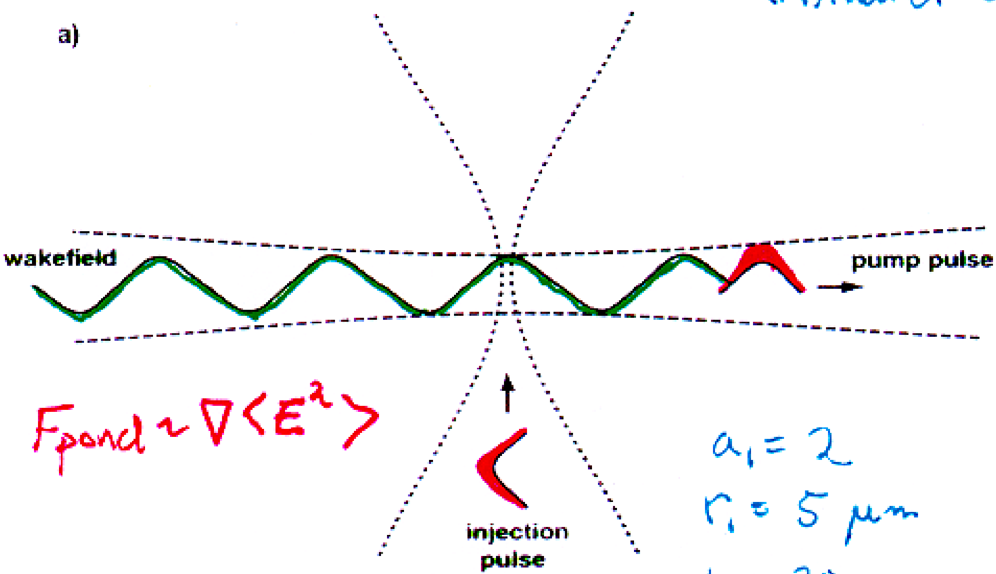
$a_i \sim a_0 \sim 2$

Ponderomotive Force $F_p \sim \nabla I \sim a_0^2/r_0$

Injects Electrons into Wakefield

LASER INJECTION

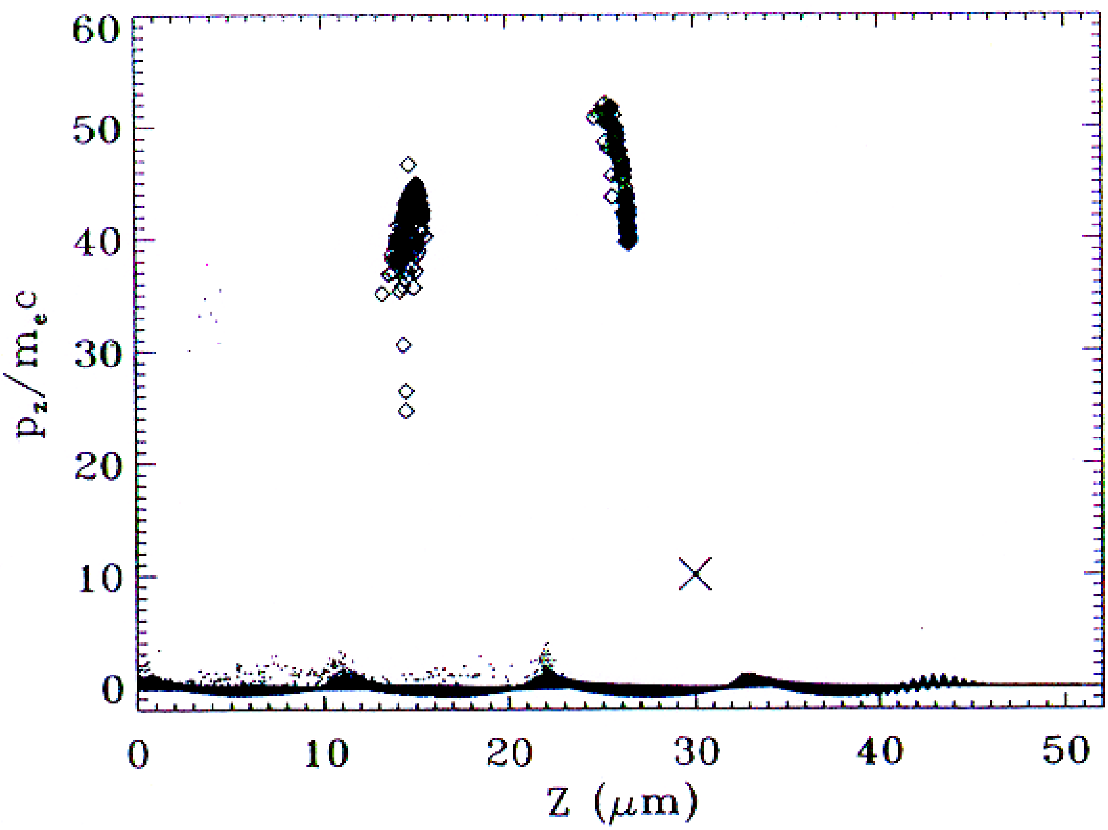
Umstadter et al PRL 96



$a_0 = 1.6$
$r_0 = 8\ \mu m$
$L_0 = 10\ \mu m$

$a_1 = 2$
$r_1 = 5\ \mu m$
$L_1 = 20\ \mu m$

$z = 100\ \mu m$, 2.3 GV/cm, $10^{19}\ cm^{-3}$

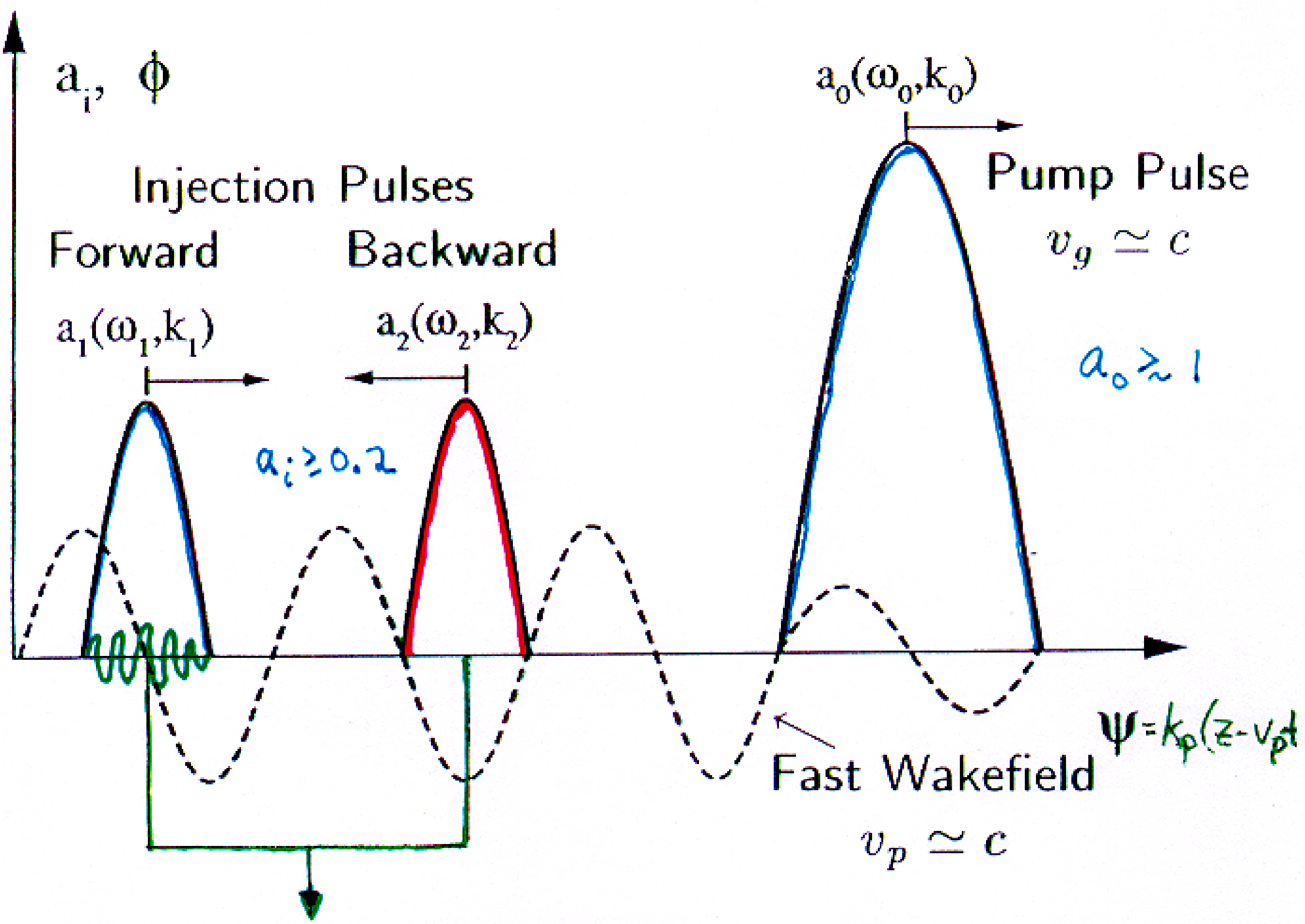


10 fs
23 MeV ±20%
2π mm-mrad
$3 \times 10^7\ e^-$

Laser Injection: Colliding Pulses

LBNL NRL

Esarey et al PRL (1997)



Slow Ponderomotive Beat Wave: $F_p \sim \partial(a_1 a_2)/\partial z$

$$F_p \sim (k_1 + k_2)\hat{a}_1\hat{a}_2 \cos[(k_1 + k_2)z - (\omega_1 - \omega_2)t]$$

$$v_p = \frac{\omega_1 - \omega_2}{k_1 + k_2} \simeq \frac{\Delta\omega}{2k_0} \simeq \frac{\Delta\omega}{2\omega_0}c \ll c \quad \left(\lambda_{beat} = \frac{\lambda_0}{2} \ll \lambda_p\right.$$

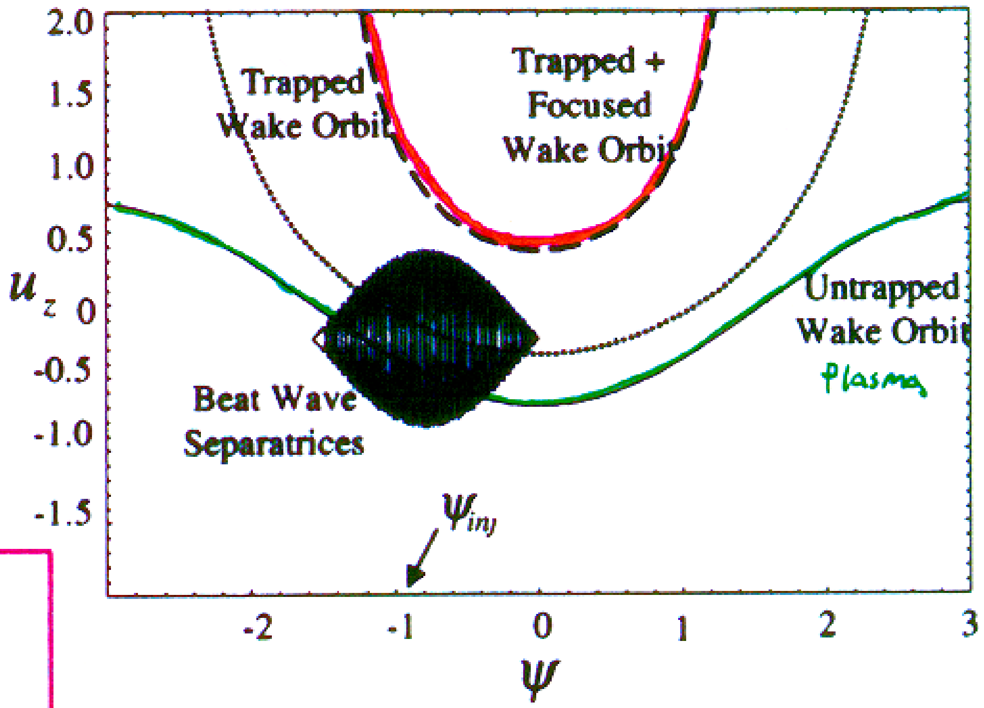
① Slow Beat Wave ($v_p \ll c$) → Initial Trapping + Heating

② Fast Wakefield ($v_p \simeq c$) → Acceleration

Resonance Overlap: Conditions for Trapping

$$[(\gamma\beta)_{beat}]_{\min} \le (\gamma\beta)_{untrapped}$$

$$[(\gamma\beta)_{beat}]_{\max} \ge (\gamma\beta)_{trapped}$$



Solutions: $$\sqrt{\hat{a}_1\hat{a}_2} = \frac{1-H}{4\gamma_b(\beta_\varphi - \beta_b)}$$

$$\cos\psi_{opt} = \phi_o^{-1}\left[\gamma_b(1-\beta_b\beta_\varphi)\gamma_\perp(0) - \frac{1}{2}(1+H)\right]$$

for trapped orbit: $H_t < \gamma_\varphi^{-1} + \phi_o$

for trapped and focusing orbit: $H_{tf} \le \gamma_\varphi^{-1}$

Threshold: Trapped + Focused

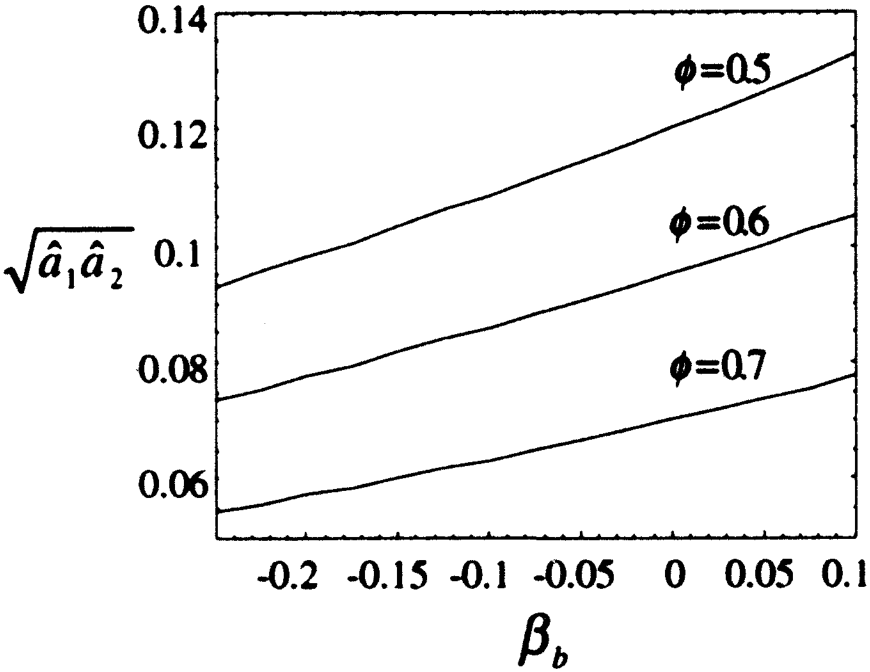
$a_i > 0.25$

$I_i > 10^{17}$ W/cm^2

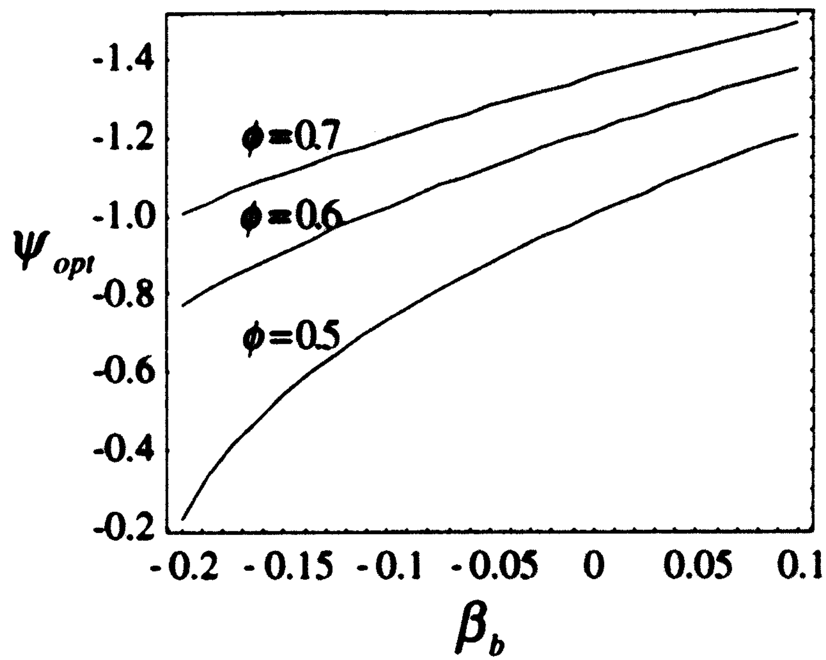
C. B. Schroeder *et al.*

Analytic Estimations:

Threshold injection pulse amplitude for trapping:



Optimal wake phase for trapping:

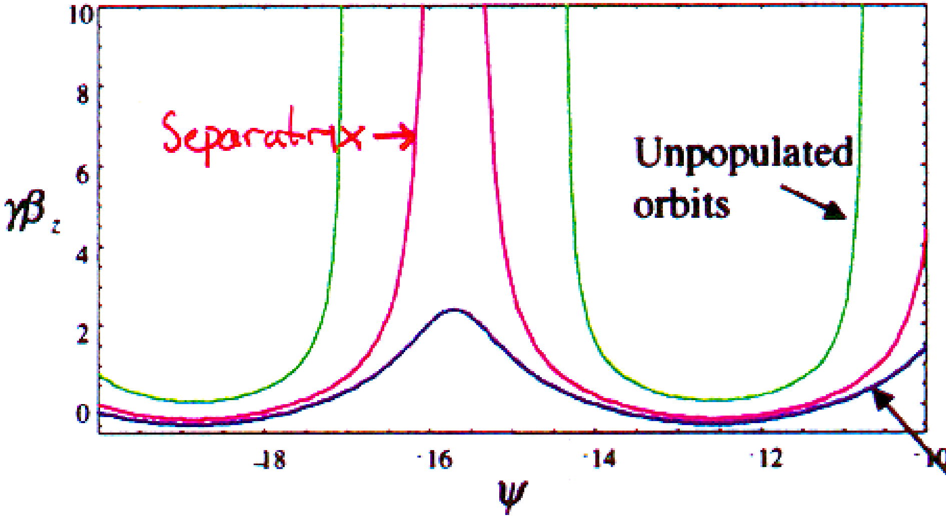


Minimizing injection pulse amplitude will reduce required laser power,

$$P_i[\mathrm{GW}] \cong 43\left(\hat{a}_i r_i / \lambda_i\right)^2$$

C. B. Schroeder *et al.*

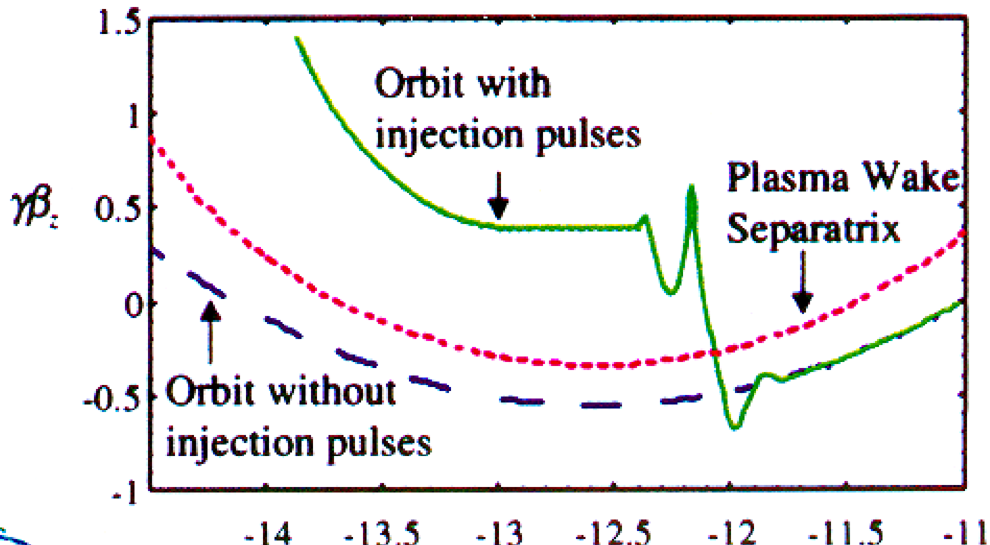
Particle Motion in Plasma Wake:



Phase space orbits of electrons in the plasma wake (without injection):

Trapped orbits
Untrapped orbits
Separatrix

Plasma electrons (fluid oscillations)



Example of trapped electron orbit

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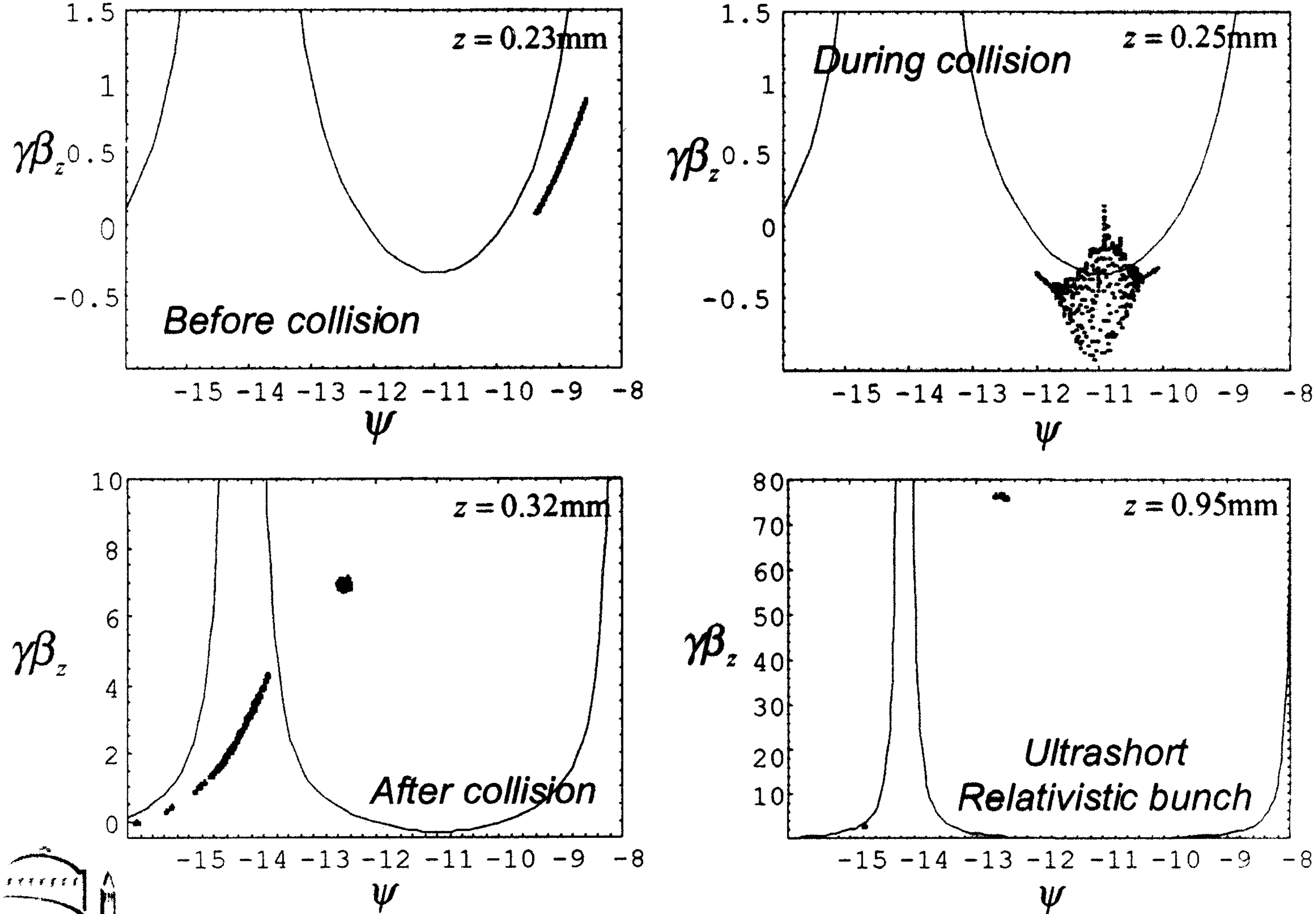
Simulation Parameters 3D Fields

Relevant to Proposed Experiments at LBNL

Plasma wavelength	λ_p	40 μm	(n_o=7x10^{17}cm^{-3})
Pump pulse wavelength	λ_0	0.8μm	($\gamma_\phi = \frac{\omega_0}{\omega_p} = 50$)
Pump pulse length	L_o	40 μm	
Pump pulse amplitude	a_o	~ 0.9	(wake amplitude $\approx \phi_0$ ~ 0.7)
Pump pulse power	P_o	5 TW	(spot size r_s ~ 15μm)
Colliding pulse amplitude	$a_1 = a_2$	~ 0.4	
Colliding pulse length	$L_1 = L_2$	10 μm	(30 fs)
Colliding pulse power	$P_1 = P_2$	1 TW	
Beat wave phase velocity	β_b	-0.2	

Electron Orbits:

Longitudinal phase space evolution of distribution of plasma electrons



Mean energy = 39 MeV

Bunch duration = 1 fs

Energy spread = 0.08 MeV

C. B. Schroeder *et al.*

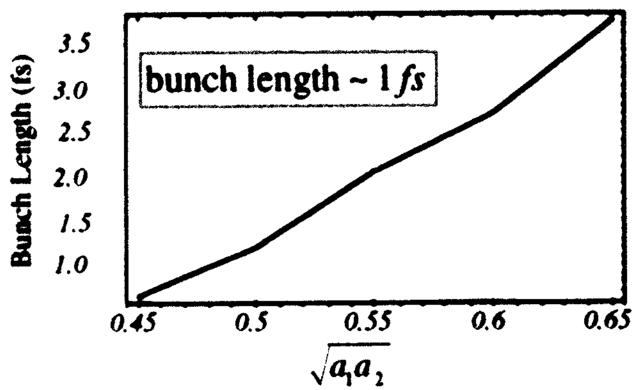
3-D tracking simulations indicate colliding pulse scheme produces high brightness beams*

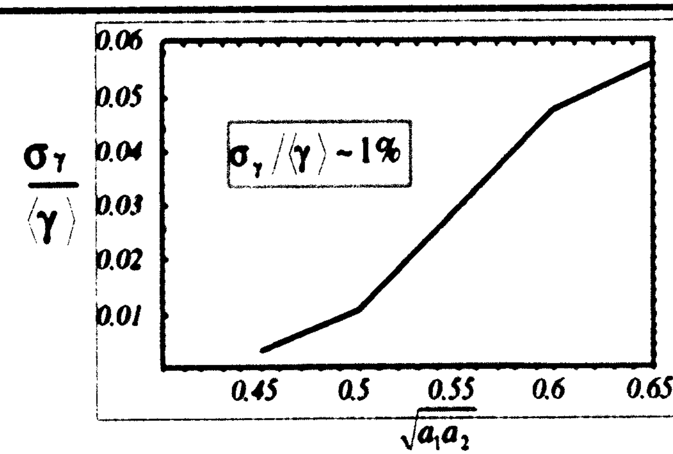
Plasma wavelength = 40 μm ($n_0 = 7\times10^{17}\,cm^{-3}$) ← Optimization for minimum injection pulse power

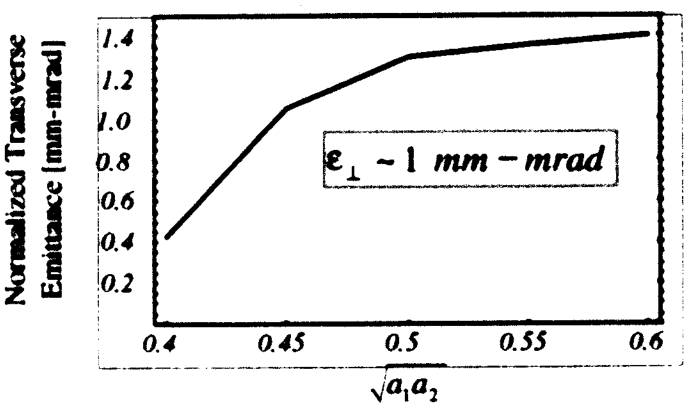
Laser wavelength = 0.8μm,

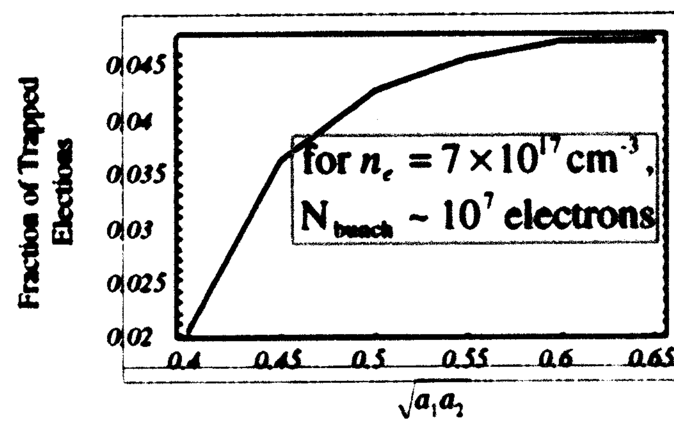
drive pulse power = 5 TW in 120 fs, colliding pulse power = 1 TW in 30 fs

Pump pulse amplitude = a_0 = 0.9, colliding pulse amplitde = $a_{1,2}$ = 0.4 (spot size = 20 μm)



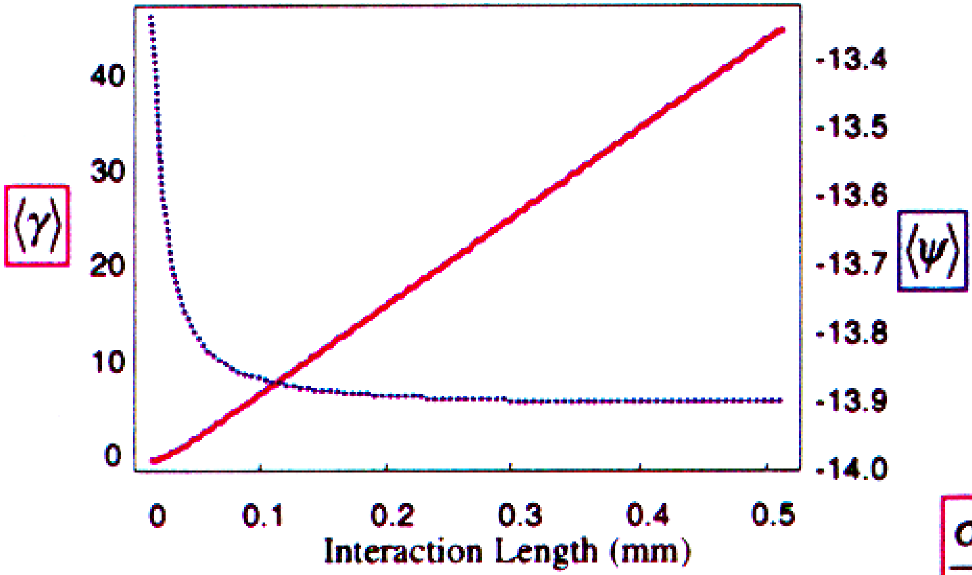


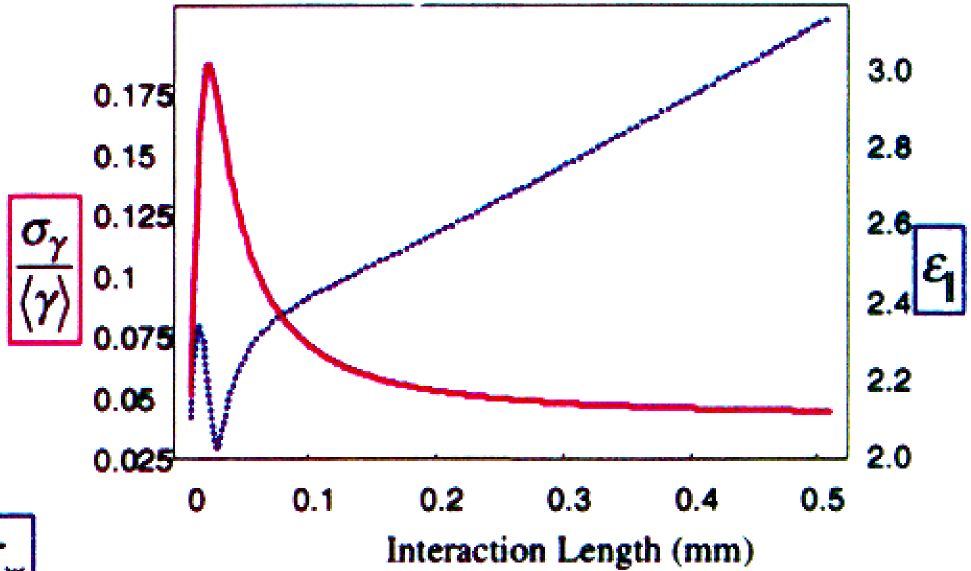


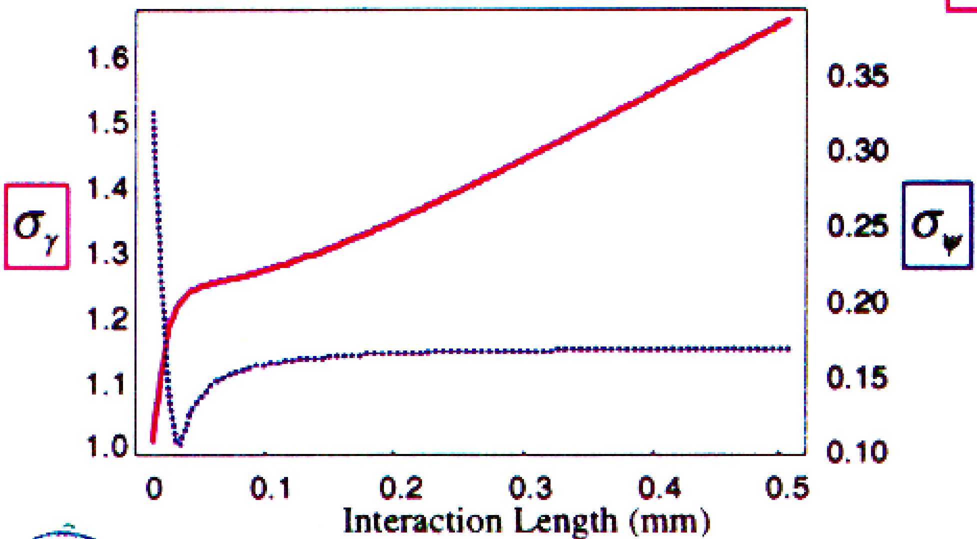


* C.B. Schroeder et al., Phys. Rev. E., in preparation

Trapped Electron Bunch Dynamics:







Relativistic Electron Bunch:

- Constant bunch length, σ_ψ
- Asymptotic fractional energy spread

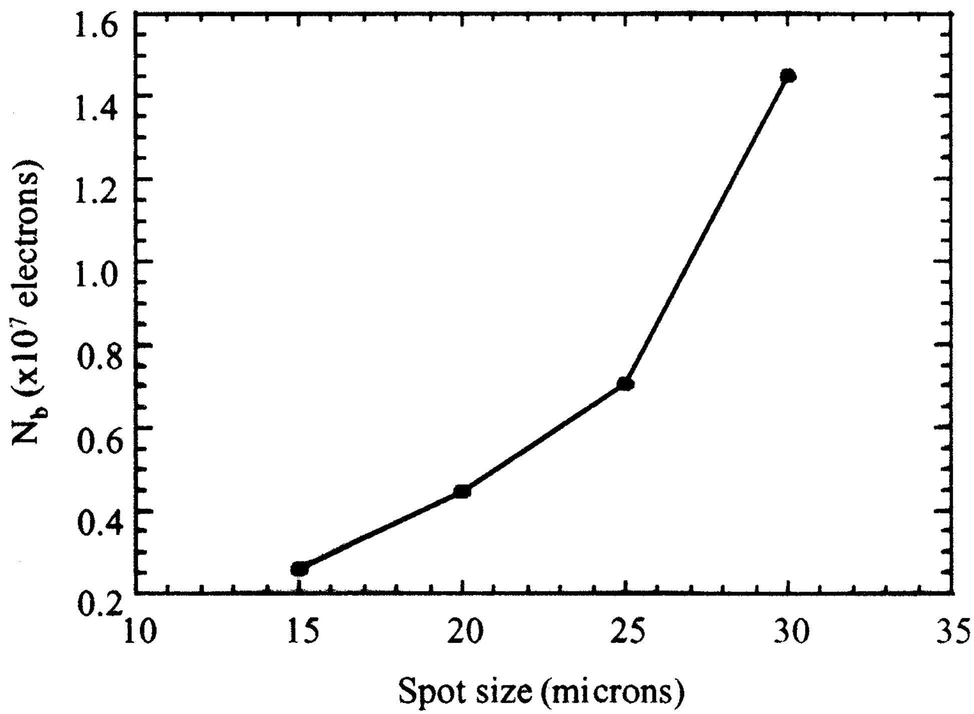
$$\sigma_\gamma / \langle\gamma\rangle \rightarrow \sigma_\psi \cot\langle\psi\rangle$$

C. B. Schroeder *et al.*

Number of Trapped Electrons:

The number of trapped electrons can be increased by increasing the injection laser spot size (i.e., increasing the injection laser pulse power).

Number of trapped electrons vs spot size of laser pulses.



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Space Charge:

Envelope Equation: $$\sigma_r'' + (\gamma'/\gamma)\sigma_r' + k^2\sigma_r = \frac{2(I/I_o)}{\gamma^3\sigma_r} + \frac{\varepsilon_\perp^{\;2}}{\gamma^2\sigma_r^3}$$

Ratio of emittance and space charge terms: $$\frac{2I}{\gamma I_o}\frac{\sigma_r^2}{\varepsilon_\perp^2} \sim 10^{-3}$$

Beam is emittance dominated.

E(space charge) << E(wake) if $$\frac{n_b}{n_o} \ll \frac{a_0^2}{k_p\sigma_z}$$

This condition is satisfied → Space charge effects are small while bunch remains in the plasma.

Conclusions

- Self-Modulated LWFA ($L > \lambda_p$)

  "Wavebreaking" not required for self-trapping

- Two-Stage Acceleration Requires:

  Slow RBS beat wave $v_p \ll c$: Initial trapping

  Fast wakefield $v_p \simeq c$: Acceleration

- Trapping Threshold: $E_z \gtrsim 0.2E_0$

  Overlapping separatrices

  Lower threshold for linear polarization

- Maximum Energy

  Focusing via self-channeling

  $\gamma_{max} = 4\gamma_p^2(E_z/E_0)f_{NL}$

- Trapped Electrons

  Inherently large energy spread (100%)

  $W_{max} \sim 50$ MeV in 1 mm

  $\epsilon_n \sim 1$ mm-mrad

  $N_b \sim 10^9\ e^-$

Conclusions

- Standard LWFA ($L \simeq \lambda_p$)
- Injection by Colliding Pulses

  Forward Pulse (ω, k)

  Backward Pulse $(\omega - \Delta\omega, -k)$

  Collide: Beat Wave $(v_{pb} \simeq \Delta\omega/2k)$
- Two-Stage Acceleration:

  Slow beat wave $v_p \ll c$: Initial trapping

  Fast wakefield $v_p \simeq c$: Acceleration
- Control of Injection Process: $v_{pb}(\Delta\omega)$, a_i, τ_i
- Trapping Regime: $E_z/E_0 > 0.5$

  $\omega_i/\omega_p \sim 100$, $\Delta\omega/\omega_p \sim 10$, $n_0 \sim 10^{17}$ cm^{-3}

  Injection Pulse: $\tau_i < 100$ fs

  $a_i > 0.3 \rightarrow I_i > 10^{17}$ W/cm^2

  Electron Bunch: $\tau_b \sim 3$ fs

  27 MeV $\pm 0.32\%$ (0.14 cm)

  $n_b \sim 10^{18}$ cm^{-3}

3D

~ 1 fs

$\Delta E/E \sim 1\%$

$\sim 1\ \pi$ mm mrad

$\sim 10^7\ e^-$

Summary of Experiments on Self-modulated LWFA (AAC98)*

	RAL/UCLA	NRL	Univ. of Michigan
Laser			
Wavelength λ [μm]	1.05	1.05	1.05
Pulse length [fs]	800	400	400
Peak power P [TW]	20	2	4
Intensity at Focus [W/cm^2]	4×10^{18}	2.5×10^{18}	3×10^{18}
Rayleigh length [μm]	300	75	135
Rep. Rate	single shot	one/3 min	one/7 min
Plasma			
Source	gas jet	gas jet	gas jet
Plasma species	H, He	He	He
Plasma density n_p [cm^{-3}]	5×10^{18} - 2×10^{19}	3×10^{19}	3×10^{19}
Plasma length [mm]	4	1	1
Laser guiding	self-guided	self-guided	self-guided
P/P_{crit}	6-20	3	6
Wakefield			
Plasma wavelength λ_p, [μm]	7-8	6	6
Wakefield amplitude, $\Delta n/n$	0.5	≈ 1	0.3
Detuning length, λ_p^3/λ^2 [μm]	500	200	200
Acc. field, $\Delta n/n\,(n_e)^{1/2}$ [GV/m]	160	500	160
Wakefield duration [ps]	not measured	5	2
Trapping Mechanism	self-trapped	2 stage acc. by RBS	self-trapped
Accelerated electrons			
Max. energy gain [MeV]	96	120±50	70±20
Total # of el. acc.	10^{10}	10^{9} (> 1 MeV)	10^{10}
El. flux at ΔE_{max} [/MeV/sr]	10^{7}	10^{9}	3×10^{6}
S/N at ΔE_{max}	2	2	3
Divergence of acc. el.		less than laser divergence	1.5 degrees
Diagnostics			
Plasma	Stokes/Anti-Stokes Thomson scatt. of Probe Thomson scatt. of self-gen 2 ω	0° forward Raman scatt. 90° Thomson scatt.	collective Thomson scatt.
Electrons	electromagnetic spectrometer	8 ch. electromagnetic spectrometer/scintillating fiber/PMT	one channel electromagnetic spectrometer/wire chamber detector

Summary of Experiments on ~~Self-modulated~~ Standard LWFA (AAC98)*

	KEK/JAERI	Ecole Polytechnique
Laser		
Wavelength λ [μm]	0.79	1.057
Pulse length [fs]	90	400
Peak power P [TW]	1.8	3.5
Intensity at Focus [W/cm²]	7x10¹⁷	4x10¹⁷
Rayleigh length [μm]	670	2000
Rep. Rate	10 Hz	one/5 min
Plasma		
Source	backfilled	backfilled
Plasma species	He	He
Plasma density n_e [cm^{-3}]	1.4x10^{18}	2.2x10^{16}
Plasma length [mm]	20	25
Laser guiding	self-guided	no
P/P_{crit}	0.14	~0
Wakefield		
Plasma wavelength λ_{pe} [μm]	29	226
Wakefield amplitude, Δn/n	0.11 (calculated)	0.1 (calculated)
Detuning length, λ_p^3/λ^2 [mm]	40	>>
Acc. field, _n/n (np)1/2 [GV/m]	15 (calculated)	1.5
Wakefield duration	~1 ps	~1 ps
Injection		
Injector	3 GHz RF linac	VandeGraaff (CW)
Injection energy [MeV]	17	3
El./bunch	1 nC	300 _A (CW)
Phase occupied	360	360
Accelerated electrons		
Max. energy gain [MeV]	300	1.5
Total # of el. acc.	2x10⁴ (>10 MeV)	200
El. flux at _emax [/MeV/sr]	250	6
S/N at _Emax	1	1
Divergence of acc. el.	not reported	not reported
Diagnostics		
Plasma	Thomson scatt. FDI-wakefield	0° forward Raman scatt. 90° Thomson scatt
Electrons	Desmarques screen-spot size Cerenkov light-pulse length, timing 32 ch. scintillator and magnet-energy	high acceptance double focusing spectrometer/17 ch. scintillating fiber/PMT at 0.15 MeV binning

Summary of Experiments on Laser Guiding (AAC98)*

	Univ. Mich.	NRL	NRL	LBNL	Maryland	UT-Austin	Hebrew/NRL
1. Length [cm]	0.1	0.3	0.3	0.1	1. 5	1 2	1,2,3,6
2. Diameter [μm]	10 (30)	5	10-20	variable	variable	30	300
3. n_e(r=0) [cm^{-3}]	$3x10^{19}$ ($3x10^{19}$)	$1\text{-}3x10^{19}$	$1.5x10^{19}$	$7x10^{18}$	$2x10^{18}$-$6x10^{18}$	$5x10^{18}$	$5\text{-}10x10^{18}$
4. Method	Relativistic	Relativistic	Relativistic	Hydro	Hydro	Hydro	Hydro
5. I_{max} [W/cm²]	$2x10^{17}$	$5x10^{18}$	$3x10^{16}$	$2x10^{17}$	10^{17}	-	10^{14}-10^{17}
6. Gas/material	He	H_2/He	He	N_2/H_2	Ar+N_2O	He	CH_2
7. Rep. rate	7 min/shot	3 min/shot	3 min/shot	10 Hz	10 Hz	20 Hz	min/shot (few 100 shots/capill)
8. gasjet/backfill	jet	jet	jet	jet	jet	backfill	
9. Transmission	60%	?	70%	25%	52%	-	15% (1cm) 50% (3 cm) 10% (6 cm)
10. Cost	$$	$$	$$	$$	$$	$$	$

*: W.P. Leemans and E. Esarey, AAC98 Proceedings