Electrons Trapping in the Plasma Wakefield Accelerator

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Work supported by US Department of Energy

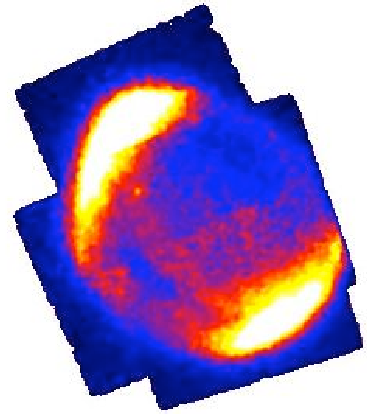
OUTLINE

- Introduction to particle trapping
- Trapping in the SLAC PWFA experiment
- Trapped particles characteristics
- Conclusions

PARTICLE TRAPPING

- Ultra-high energy cosmic rays: plasma shock waves and frozen magnetic field

  Supernova SN 1006. The images reveal high energy synchrotron radiation from the rims of the supernova remnant. This suggests that electrons are accelerated in the shock waves at the boundary of the remnant.
  http://www.tp1.ruhr-uni-bochum.de/~hs/forschung/shockaccel.html



- Plasma accelerators:
  - + Injection mechanism for LWFA, PWFA
  - \- Limit plasma wave amplitude: wavebreaking

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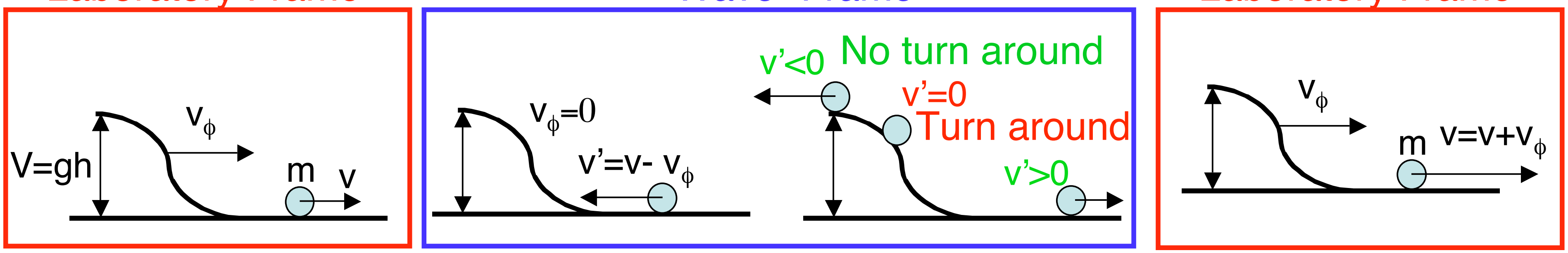
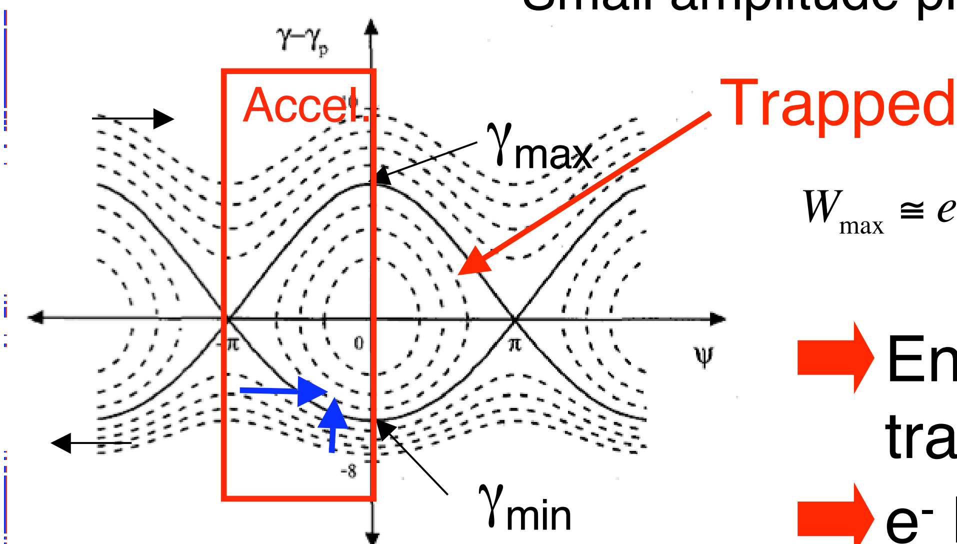
PARTICLE TRAPPING



Turn around if: $v_\phi - \sqrt{2gh} < v < v_\phi$ ➡ $\frac{1}{2}mv_\phi^2 - mgh \le E \le \frac{1}{2}m\left(v + v_\phi\right)^2$

Small amplitude plasma wave:



$$W_{\max} \cong eE_0 L_d \cong 2\pi\gamma_\phi^2 \frac{E_0}{E_{WB}} mc^2$$ Esarey, IEEE TPS 24,2 (1996)

Injection/trapping

- Energy, and phase condition for trapping
- e^- born at rest (lab frame)
- need injection mechanism

WAVE AMPLITUDE LIMIT WAVEBREAKING

	Non Relativistic	Relativistic
Cold	Dawson, Phys. Rev. 113, 2 (1959) $E_{WB} = \frac{mv_\phi \omega_p}{e}$	Akhiezer, Polovin, JETP 3, 5 (1956) $E_{\max} = \frac{mc\omega_p}{e}\sqrt{2}(\gamma_\phi - 1)^{1/2}$
Warm	Coffey, PoF 14, 7 (1971) $E_{\max} = \frac{mv_\phi \omega_p}{e}\left(1 - \frac{1}{3}\beta - \frac{8}{3}\beta^{1/4} + 2\beta^{1/2}\right)^{1/2}$	Katsouleas, Mori, PRL 61, 1 (1988) $E_{\max} = \frac{mc\omega_p}{e}\beta^{-1/4}\left(\ln \gamma_\phi^{1/2}\beta^{1/4}\right)^{1/2}$

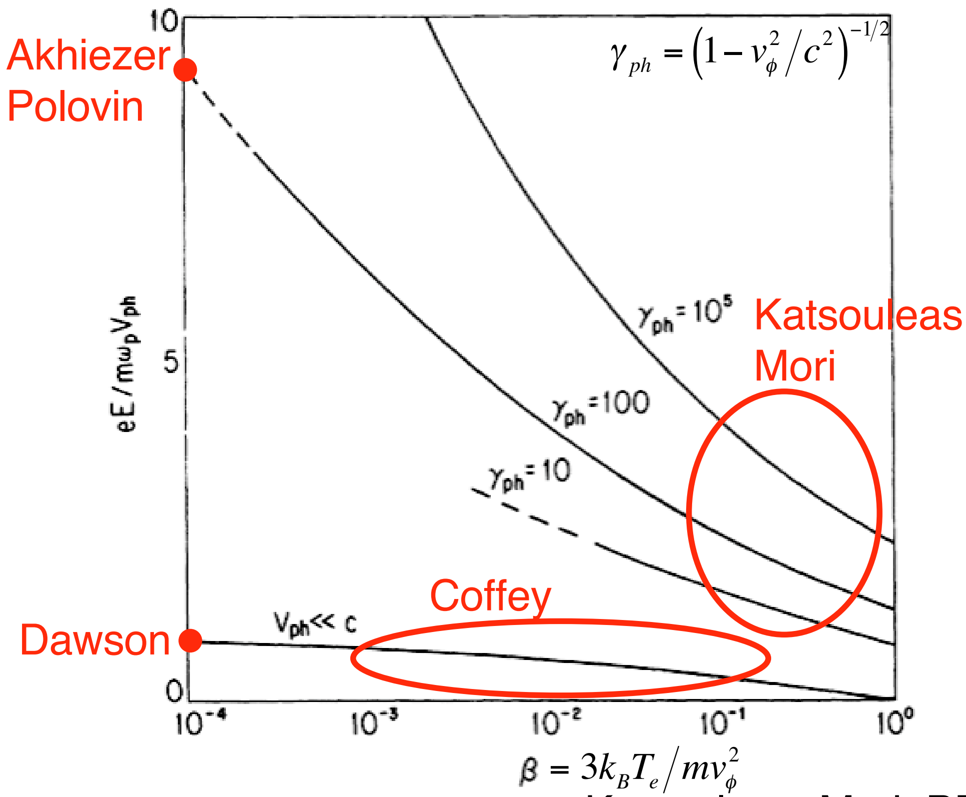
$\omega_p = \left(n_e e^2 / \varepsilon_0 m\right)^{1/2}$ Plasma frequency

$v_\phi, \gamma_\phi = \left(1 - v_\phi^2 / c^2\right)^{-1/2}$ Wave phase velocity and relativistic factor

$\beta = 3k_B T_e / m v_\phi^2$ Thermal energy to wave kinetic energy ratio

Rosenzweig, PRA 38, 7, 3634 (1988)
Mori, Katsouleas, Phys. Scripta T30, 127 (1990)

WAVE AMPLITUDE LIMIT



Katsouleas, Mori, PRL 61, 1 (1988)
Mori, Katsouleas, Phys. Scripta T30, 127 (1990)

- Relativistic effects increase E_{max}
- Thermal effects decrease E_{max}

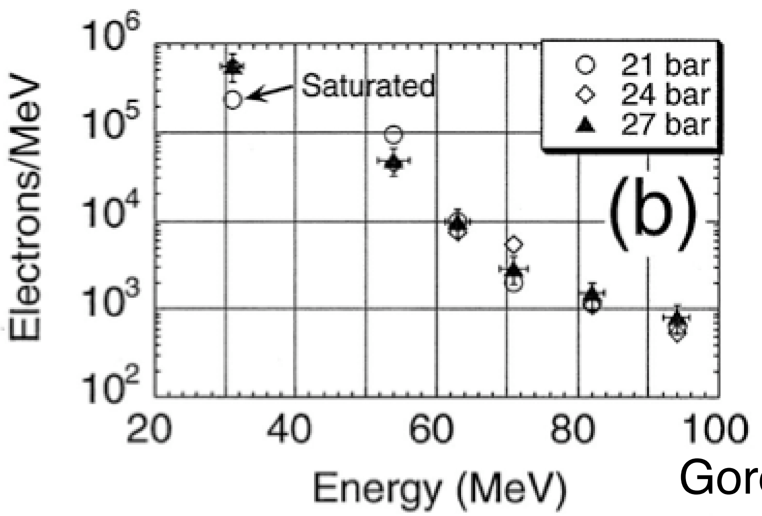
WAVE BREAKING - TRAPPING

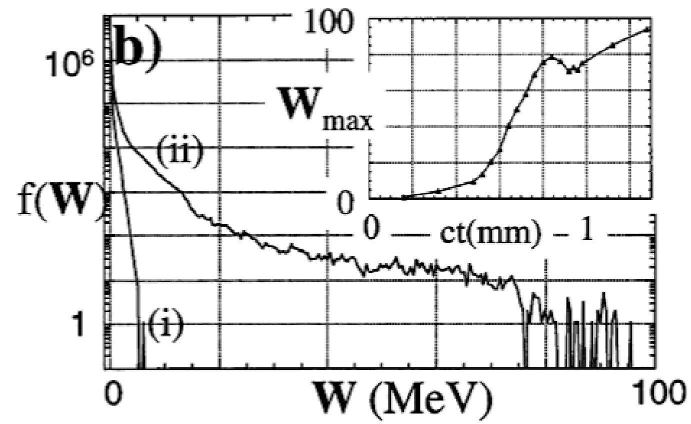
Katsouleas,
Nature 431,515 (2004).

- Harmonics of ω_p, sine to "sawtooth" wave
- Wave-particles dephasing
- Wave breaking → Injection and trapping

LWFA INJECTION MECHANISM

- Wavebreaking = injection mechanism for (SM-)LWFA





Gordon, PRL 80(10), 1998

- SM-LWFA: self-injection, no control, large energy spread …
- … but well described by simulations!

INJECTION

- Transverse injection, Umstadter, PRL 76, 2073 (1996).
- Co-linear injection, Esarey, PRL 79, 2682 (1997). ← LOA, this workshop

news and views Katsouleas, Nature 431,515 (2004).

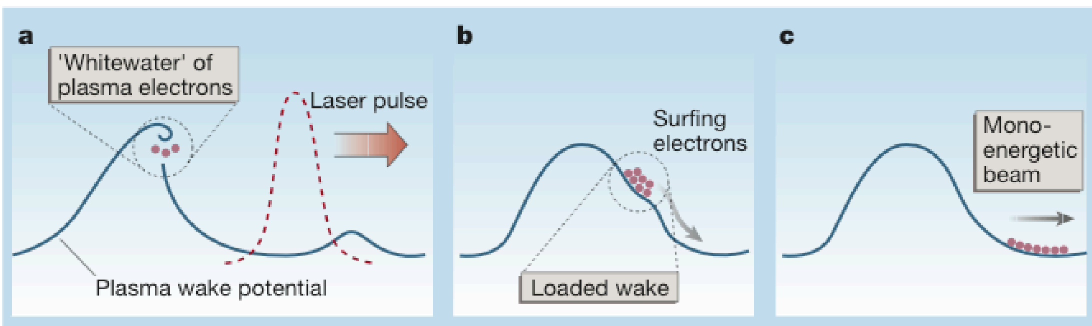
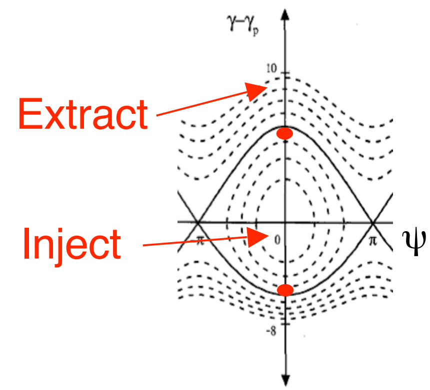


Figure 1 **Wakefield acceleration.** a, In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the 'whitewater' and surf the wave. b, The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma. c, As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy.

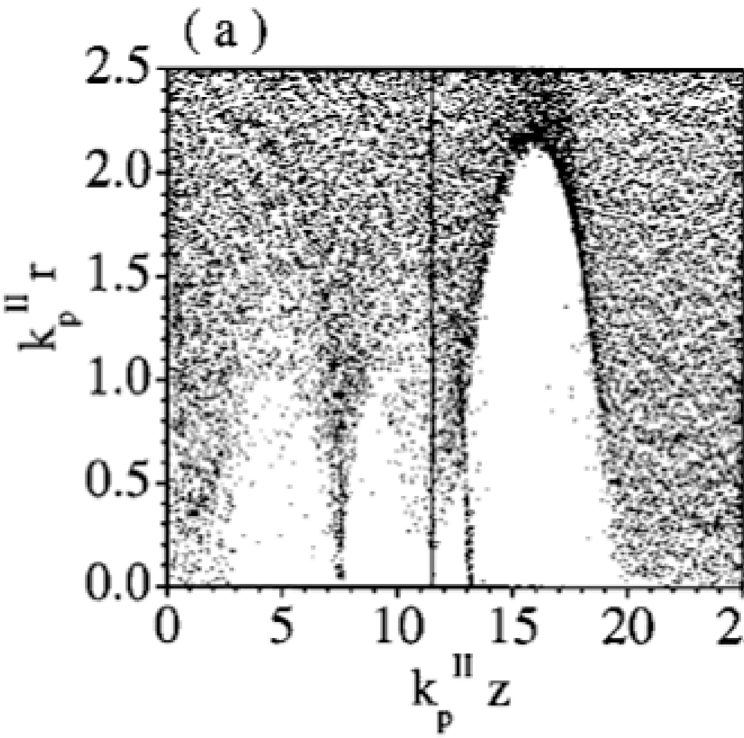


Geddes,C.G.R.et al.Nature 431, 538 (2004).
Mangles,S.P.D.et al.Nature 431, 535 (2004).
Faure,J.et al.Nature 431, 541 (2004).

- Self-injection → ΔE/E<<1

Plasma Density Transition Trapping

Plasma Density Transition Trapping is a self-trapping scenario that uses the rapid change in the wake field wavelength at a steep drop in the plasma density to dephase plasma elec into an accelerating phase of the wake.



- Automatic injection of substantial charge into the accelerating phase.
- Operates in the PWFA "Blow Out" regime where $n_{beam} > n_{plasma}$ or in strongly driven LWFAs.
- The length of the plasma density transition must be shorter than the plasma skin depth $k_p^{-1} = c/\omega_p$ for significant trapping to occur.
- Brightness of the trapped beam scales linearly with plasma density and surpasses state-of-the-art photoinjectors at densities higher than about 10^{17} cm^{-3}.

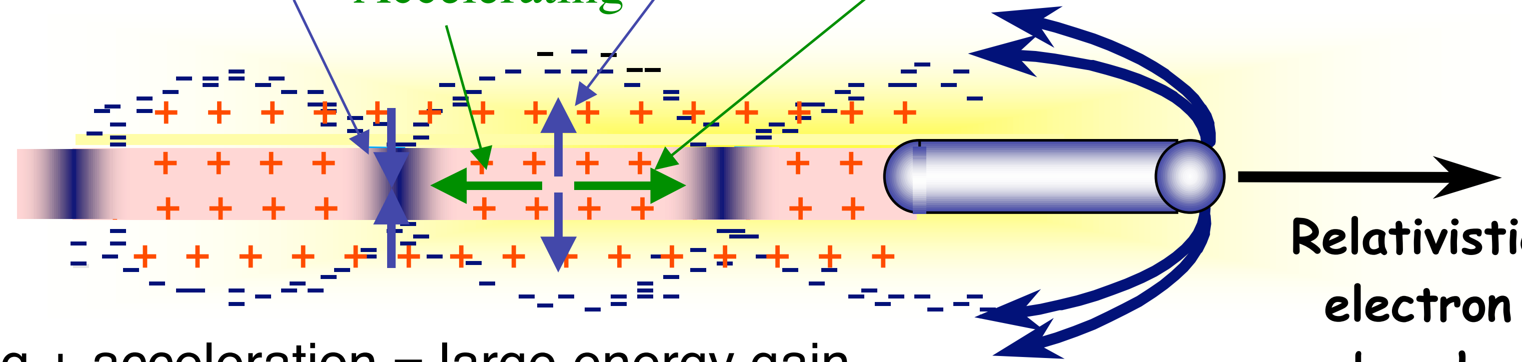
Major Transition Trapping Papers:

Concept Proposed - H. Suk, *et al.*, Phys. Rev. Lett. **86**, 1011 (2001)
Analysis of Trapped Beam Brightness and Scaling - M.C. Thompson, *et al.*, Phys. Rev. STAB **7**, 011301 (2004)
Demonstration of sub-skin depth plasma density transitions - M.C. Thompson, *et al.*, Rev. Sci. Instrum. **76**, 013303 (2005).

Courtesy of M. Thompson

PLASMA WAKEFIELD ACCELERTAOR (e^-)

PWFA = beam-driven plasma accelerator



- Focusing + acceleration = large energy gain
- Single bunch => particles at all phases => ΔE/E≈200%
- Wavebreaking limit: cold-relativistic

SLAC PWFA:

γ_p=55686 (28.5 GeV)
N=1.8×10^{10}
σ_z=30 μm
n_e=2.6×10^{17} cm^{-3}

Akhiezer, Polovin, JETP 3, 5 (1956)
$\gamma_\phi=\gamma_b$

$$E_{\max} = \frac{mc\omega_p}{e}\sqrt{2}\left(\gamma_\phi - 1\right)^{1/2} \quad ? \longleftrightarrow \quad E_{acc} \cong 110(MeV/m)\frac{N/2\times10^{10}}{\left(\sigma_z(\mu m)/600\right)^2}$$

$k_p\sigma_z\approx\sqrt{2}$, $k_p\sigma_r$<<1

1.7 TV/m >> 39 GV/m → No trapping?

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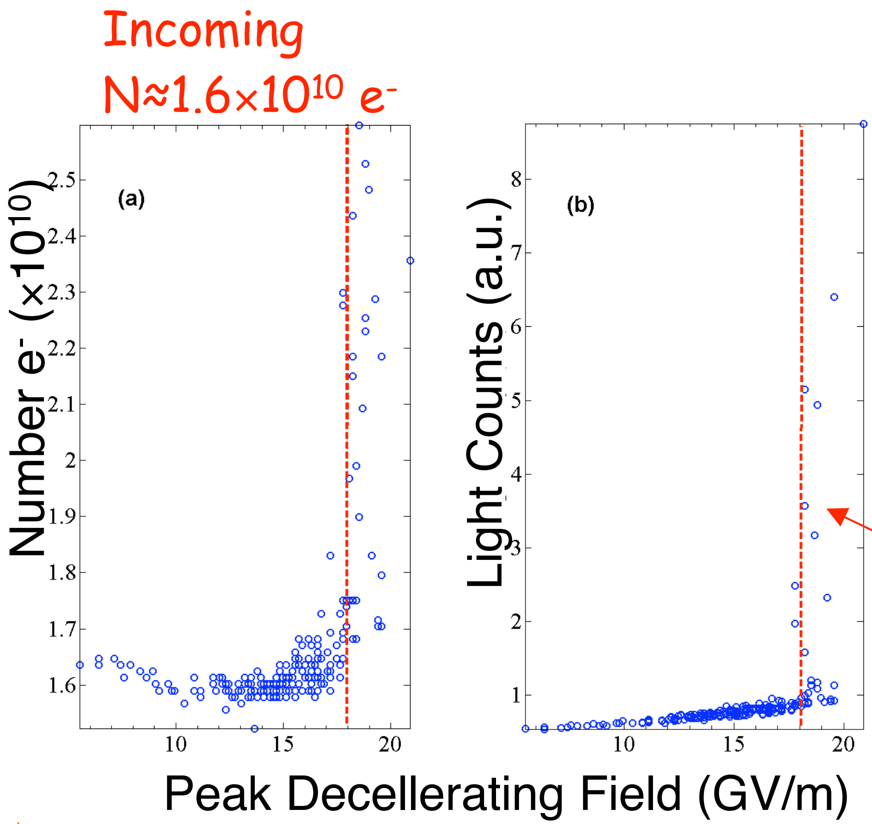
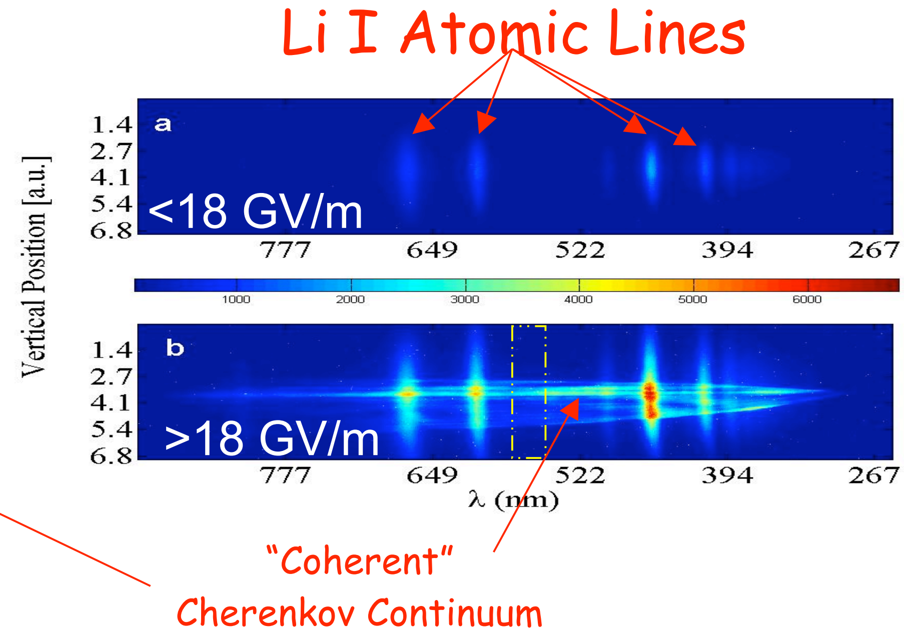
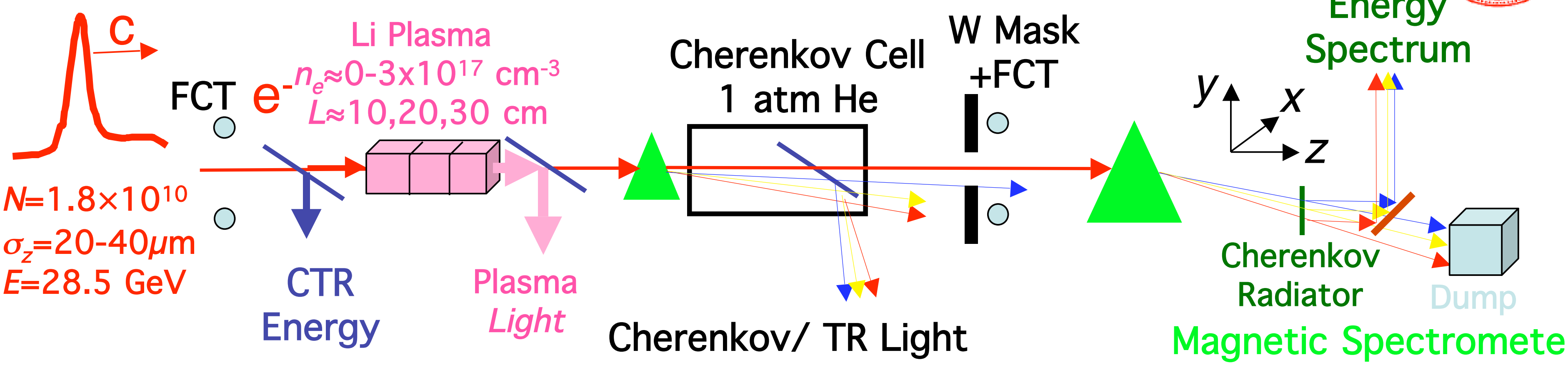
Evidence For Trapped Particles





- Excess charge/light appear at ≈18 GV/m
- Excess charge of the order of incoming charge, 1.6-1.8×10^{10} e^-
- Excess visible light >> excess charge
  Excess visible light<< (excess charge)^2 → Partially Coherent

TRAPPED PARTICLES DIAGNOSTICS



- Transition radiation (TR) and Cherenkov light
- Cherenkov cell gives low energy trapped particles spectrum
- Magnetic spectrometer gives high energy trapped particles spectrum

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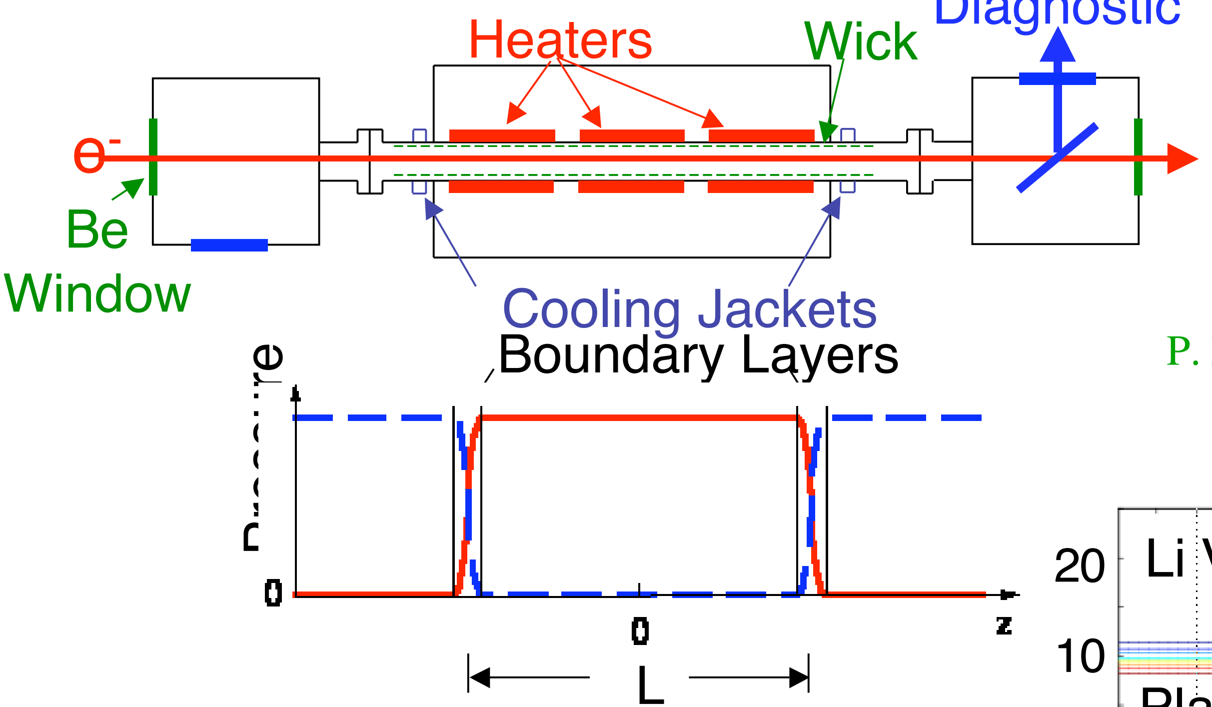
"PLASMA SOURCE"

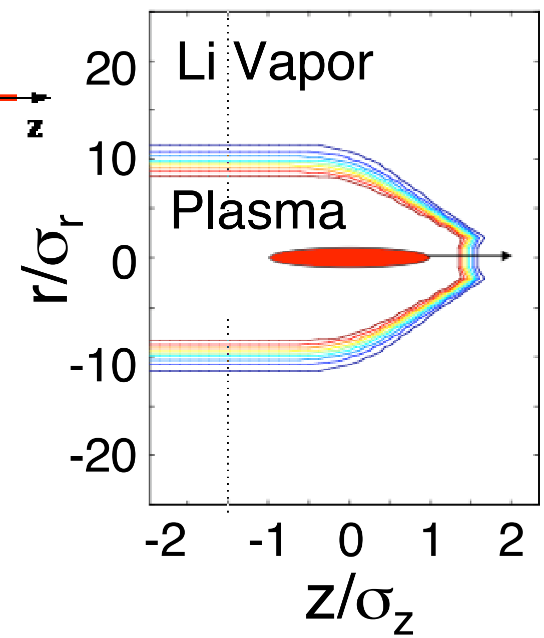
- Lithium vapor in a heat-pipe oven



n_0=0.5-3.5×10^{17} cm^{-3}
T=700-1050°C
L=13-22-31-90 cm
P_{He}≈1-40 T

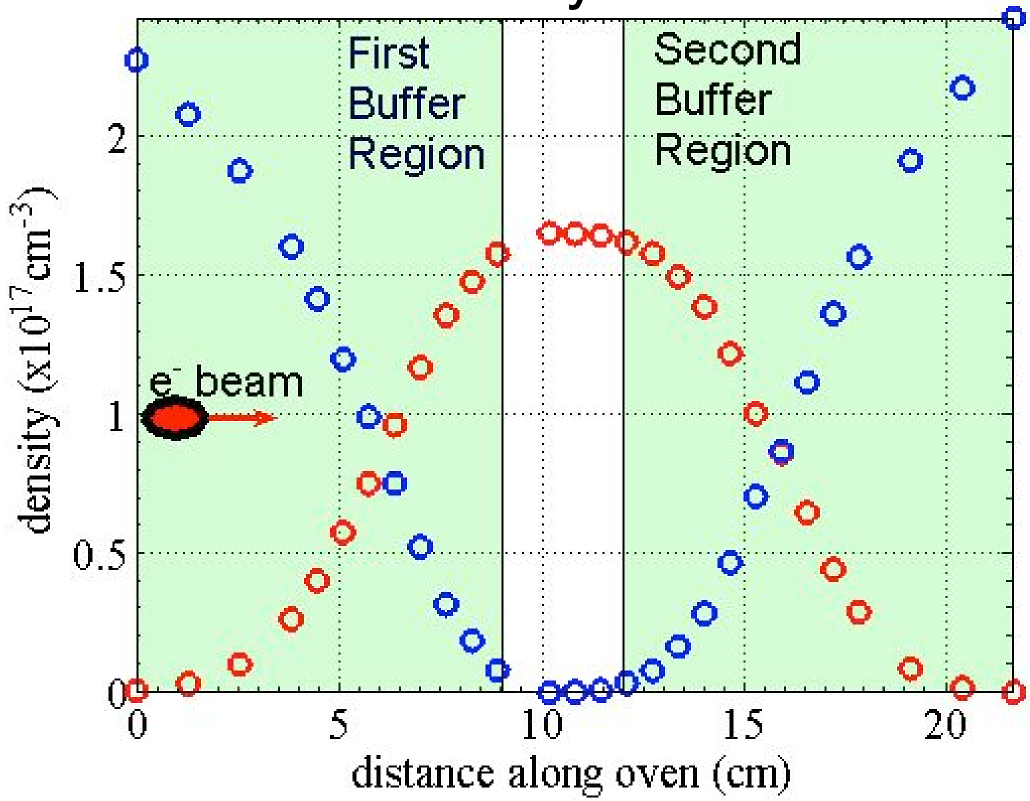
P. Muggli *et al.*, IEEE TPS (1999)

- Field-ionization (ADK theory):
  - Lithium: low Z, low IP (5.4 eV)
  - Ultra-short bunch E_r field > 6GV/m
  - $n_e=n_{o,\ Li}$
  - Plasma very "reproducible"



ORIGIN OF TRAPPED e^-

Measured Li Density Profile: 10 cm FWHM



1) Bunch does not ionize He I (24.5874 eV), but does ionize Li I (5.392 eV)

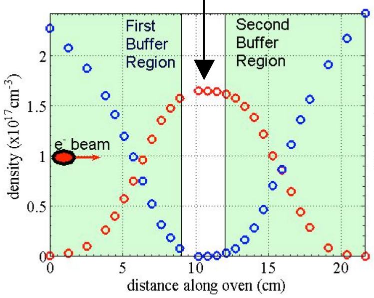
2) Bunch is focused by the wake in the Li I plasma

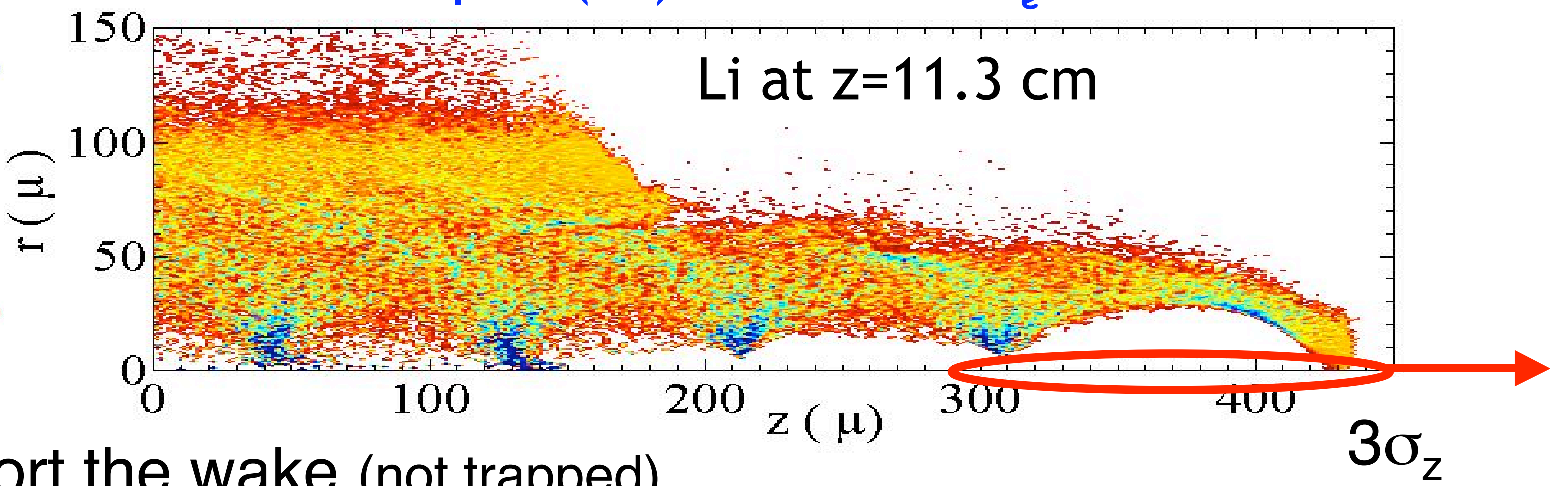
3) Bunch ionizes He I (24.5874 eV), but not Li II (75 eV)

➡ He e^- born in the He-Li transition region, inside the wake

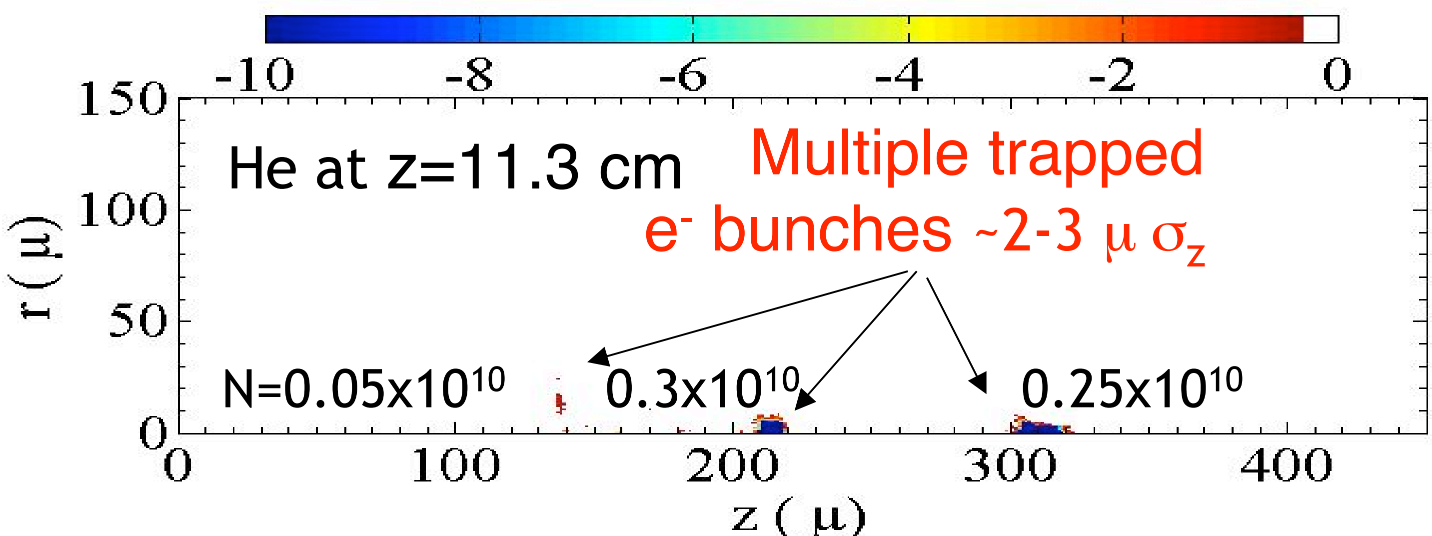
ORIGIN OF TRAPPED PARTICLES

OSIRIS Simulation: Real Space (r-z) of Li & He e^-: $n_e=1.6\times10^{17}$ cm^{-3}



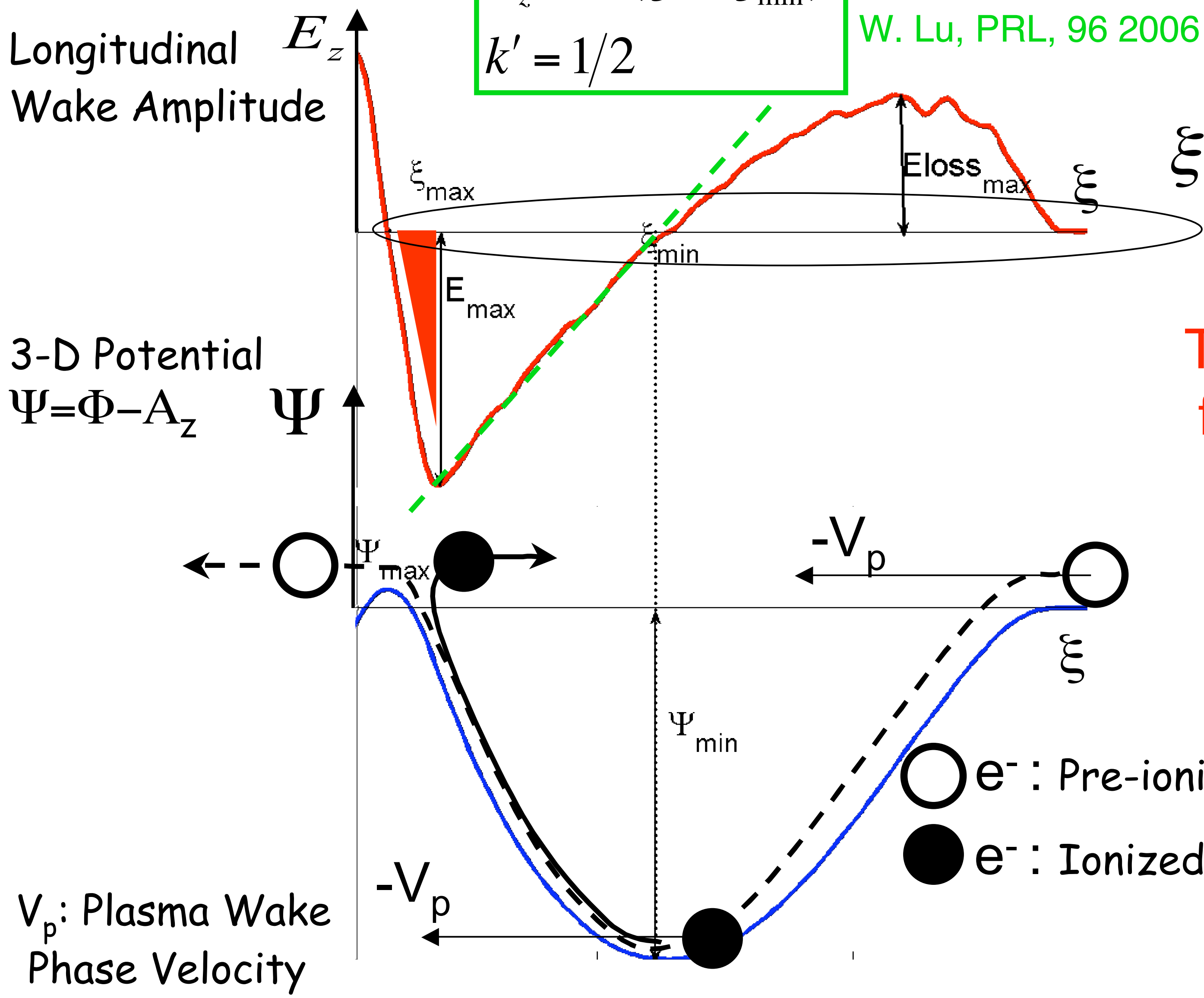


➡ Li e^- support the wake (not trapped)



➡ He e^- born on-axis inside the wake and trapped

TRAPPING IN IONIZING WAKE



Ultra-relativistic blow-out regime
W. Lu, PRL, 96 2006

$$\xi = z - ct$$

Trapping threshold for field-ionized e⁻

$$E'_{max} \geq \sqrt{2k'}$$

E. Oz
to be submitted to PRL

e⁻ : Pre-ionized (Li)

e⁻ : Ionized inside the wake (He)

Patric Muggli,AAC'06 07/17/06

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Trapping in Ionizing Wake

$$E'_z = k'(\xi' - \xi'_{min})$$
$$k' = 1/2$$

+

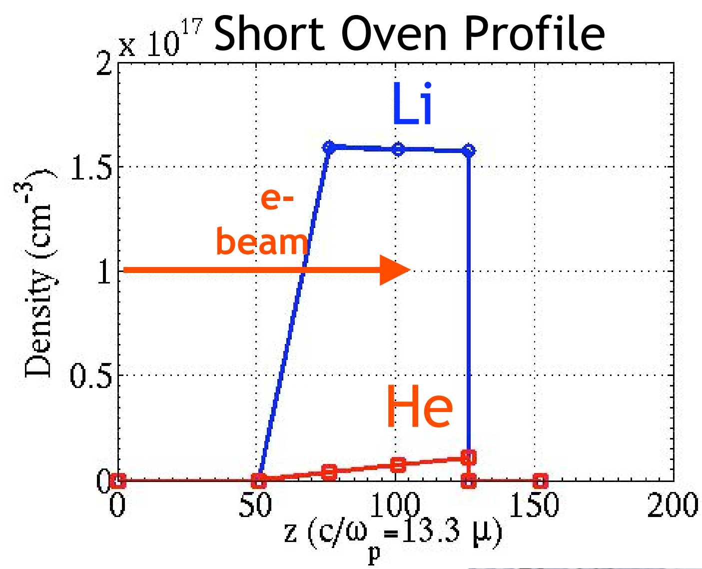
$$E'_{max} \geq \sqrt{2k'}$$

➡ $$\frac{mc\omega_p}{e} \leq E_{max} << \frac{mc\omega_p}{e}\sqrt{2}(\gamma_\phi - 1)^{1/2}$$

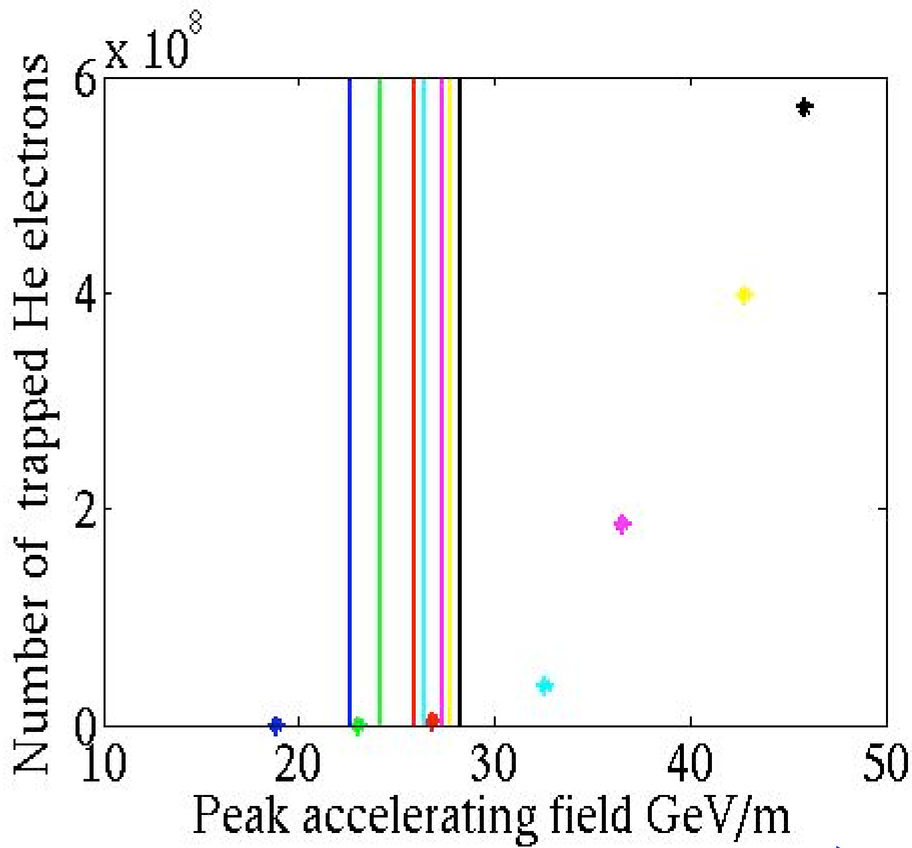
➡ Recover Dawson's E_{WB} for field ionized (He) e^- !

➡ Simulations verification

- Short simulation
- Increase wake by increasing N_{beam}
- "Measure", count $N_{trapped}$
- "Measure" k
- Compare $N_{trapped}$ threshold with $E_{max}(k)$



THRESHOLDS COMPARISON



Beam charge is varied from 0.4 to 1 times 1.8×10^{10} e^-/bunch

$$E'_{max} = \sqrt{2k'}$$

k': calculated from linear fits to E_z from simulations

Peak field: calculated from simulations

Threshold at ~28 GeV/m:

Peak Field $>E_{max}$

<u>and</u>

$N_{trapped} >> 1$

Excellent "analytical model" - simulations agreement!

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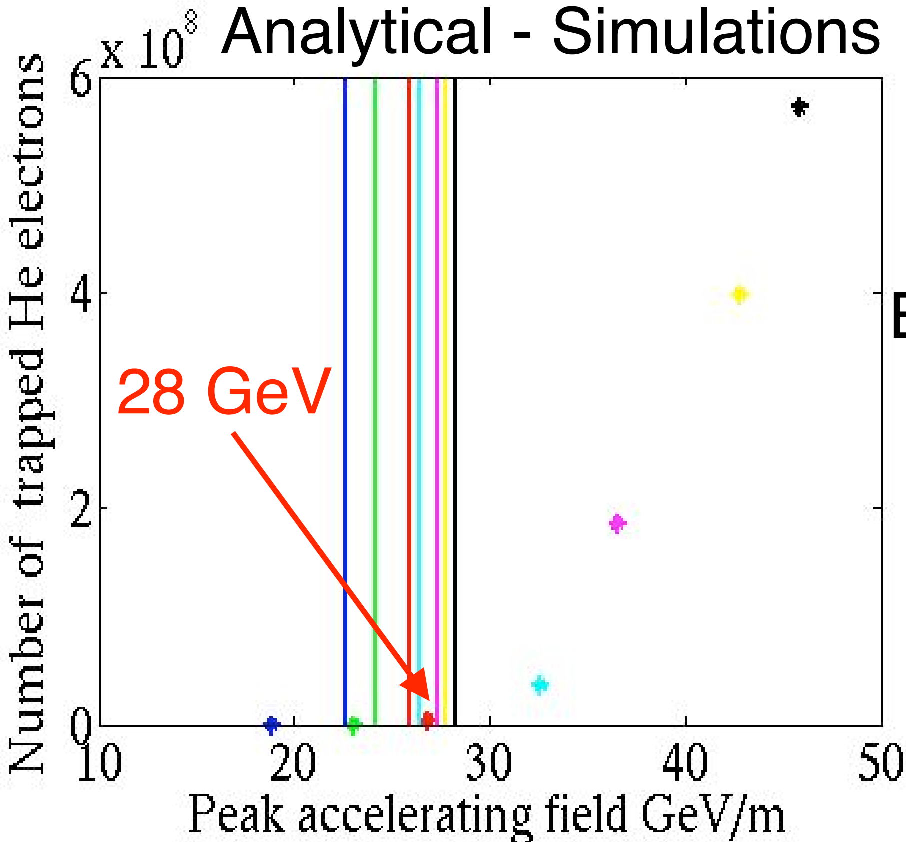
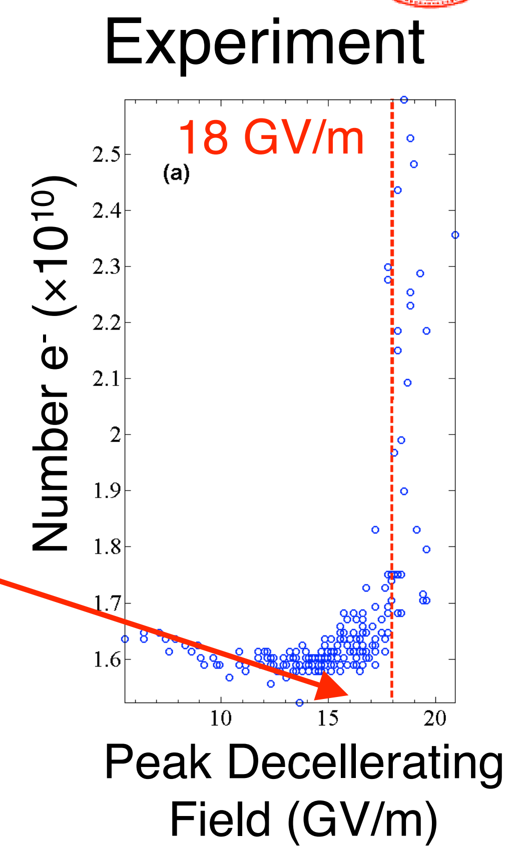
THRESHOLDS COMPARISON



Beam charge is varied from 0.4 to 1 times 1.8×10^{10} e^-/bunch

$E_{decell}=E_{decell.}/1.8$

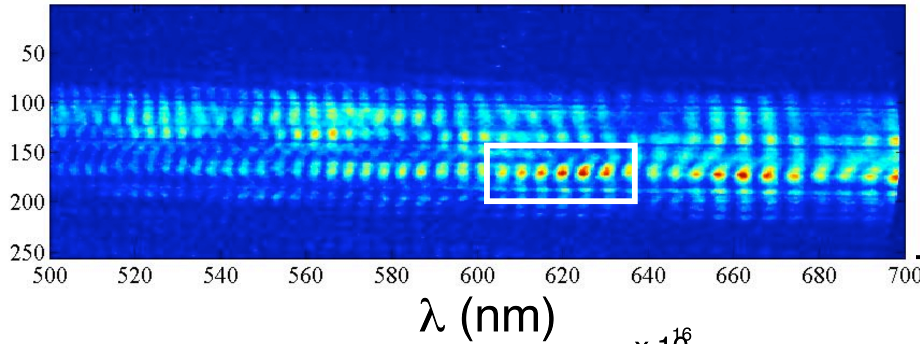
16 GV/m



➡ Excellent "analytical model" - simulations - experiment agreement!!!

TRAPPED e⁻ CHARCTERISTICS

Spectrum of trapped e⁻ TR or Cherenkov visible light:

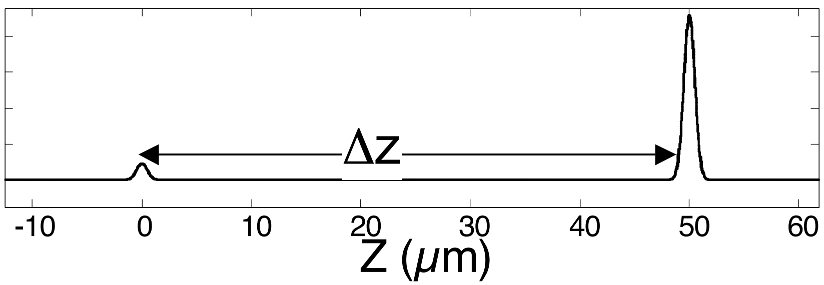


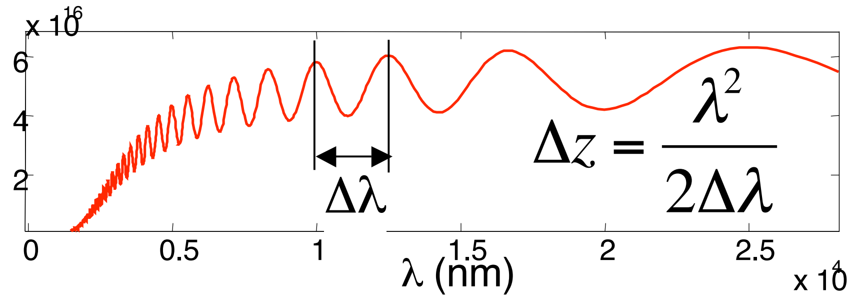
Spectral interferences

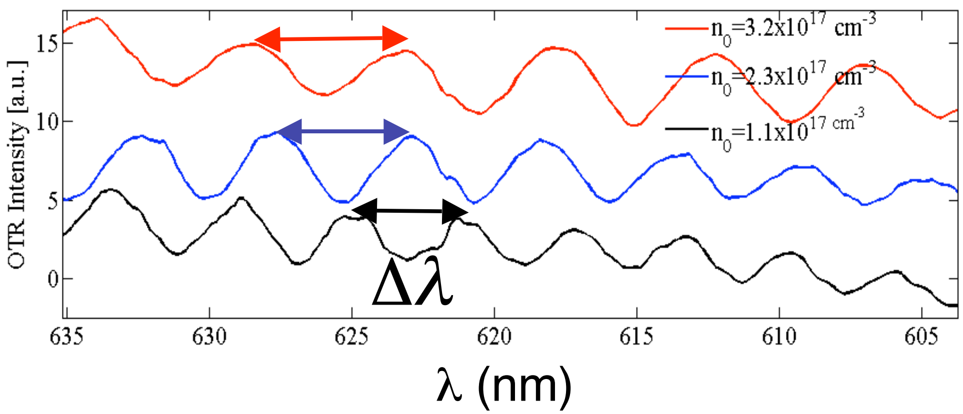
⇓

Coherent,

+10³-10⁵ times more light







n_e ($\times 10^{17}$ cm^{-3})	Δz (μm)	λ_p (μm) calc.*
1.1	102	101
2.3	84	70
3.2	72	59

* $\lambda_p = \frac{2\pi c}{\omega_p} = 2\pi c \Big/ \left(\frac{n_e e^2}{\varepsilon_0 m}\right)^{1/2}$

➡ Trapped particles are emitted in multiple, ultra-short bunches (≈μm), spaced by Δz="λ_p"

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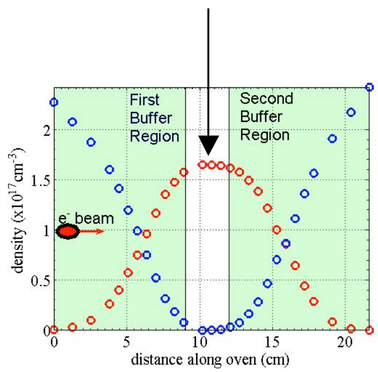
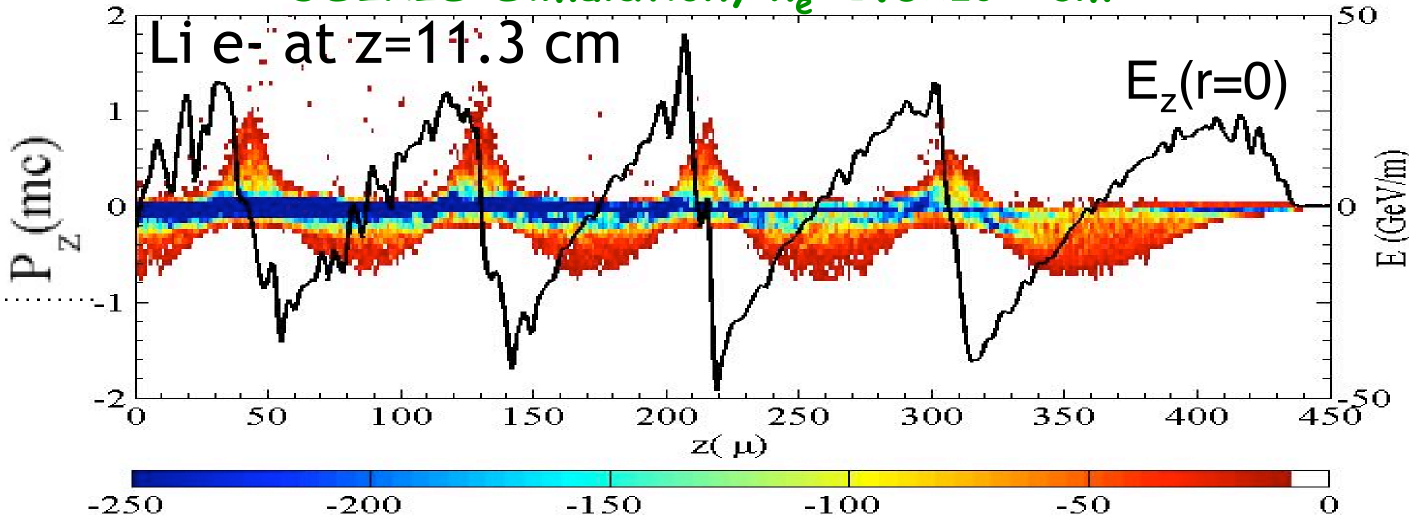
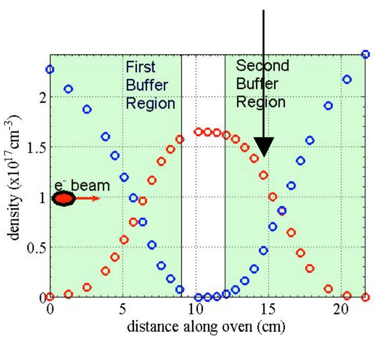
TRAPPED PARTICLES CHARCTERISTICS

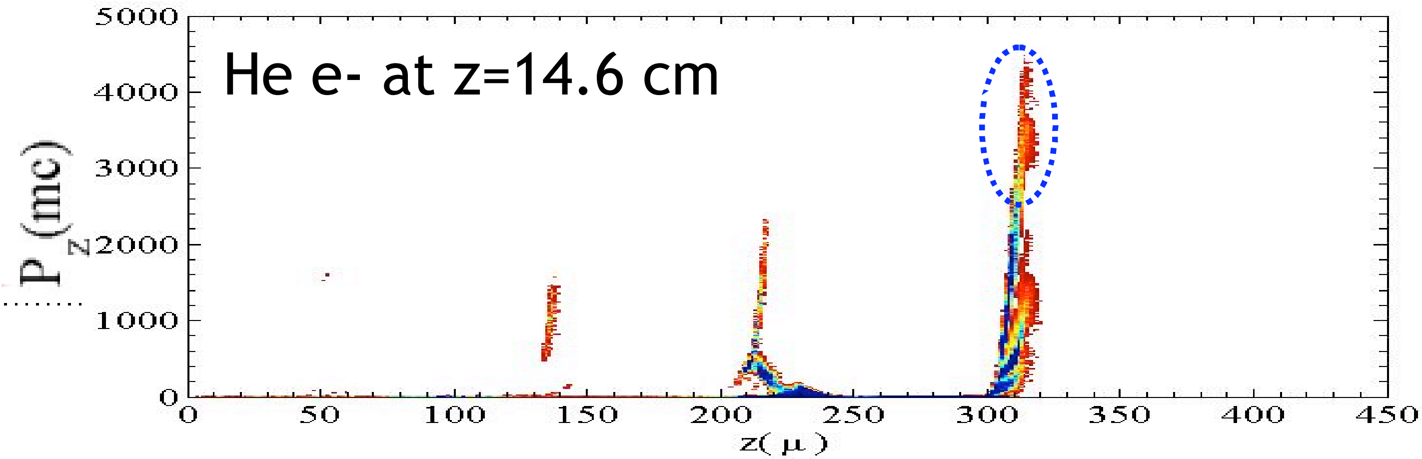
OSIRIS Simulation, $n_e=1.6\times10^{17}$ cm^{-3}





➡ Li e^- do not get trapped (low oscillation energy)

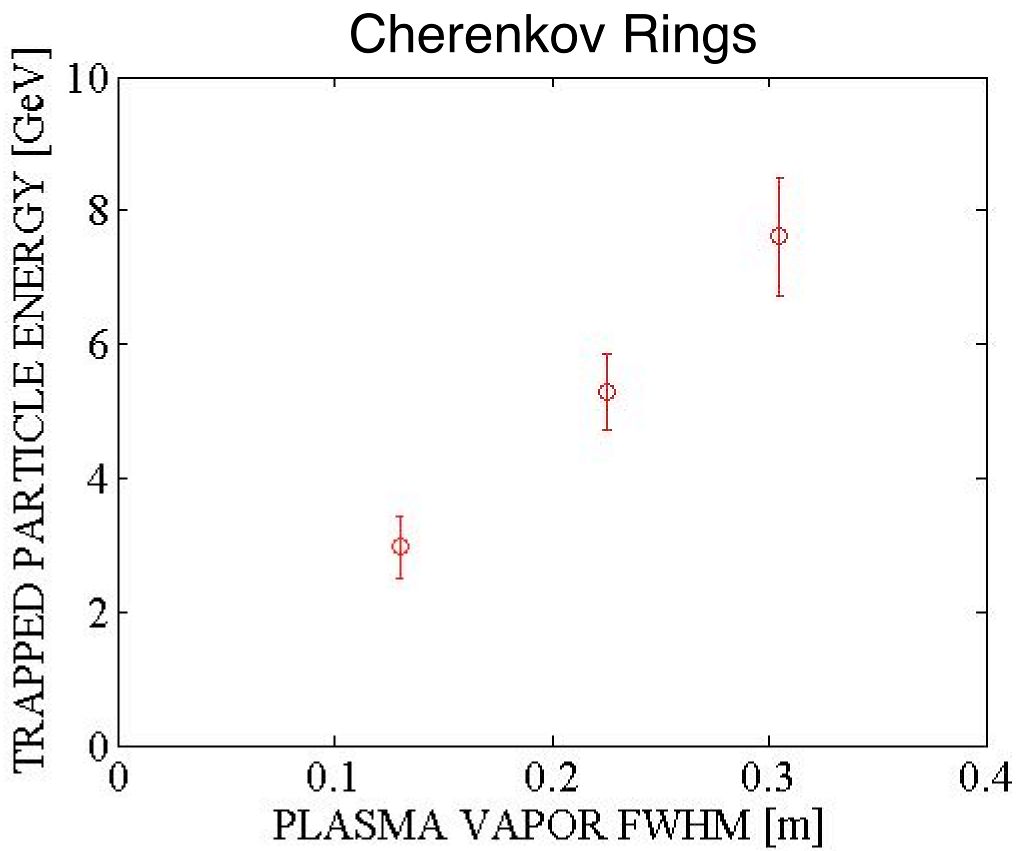


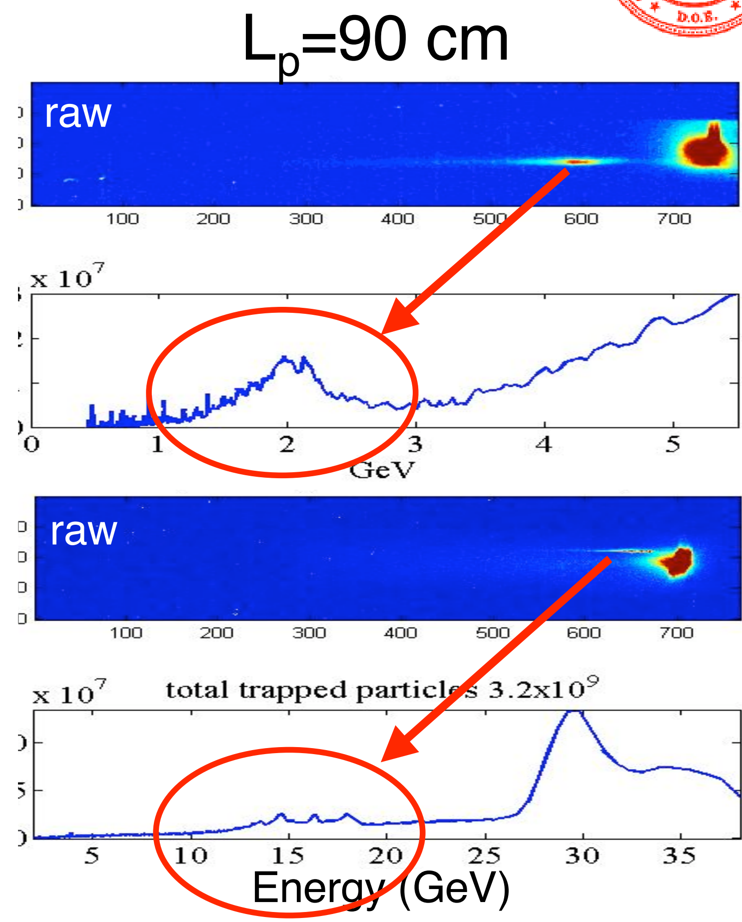


➡ Multiple short bunches He e^-, gain up to 2 GeV in <10 cm

TRAPPED e$^-$ ENERGY

n_e=2.7x10^{17} cm^{-3}





- Trapped e$^-$ energy scales with plasma length
- Trapped e$^-$ energy up to 18 GeV over 90 cm
- Trapped e$^-$ with ΔE/E<1, and may have very low ε

SUMMARY & CONCLUSIONS

- Particle trapping plays a very important role in plasma accelerators

- Observed trapped e$^-$ in a PWFA at $E_{max} << \underbrace{\frac{mc\omega_p}{e}}\sqrt{2}\left(\gamma_\phi - 1\right)^{1/2}$ Akhiezer-Polovin

- He e$^-$ ionized inside the PWFA wake follow Dawson's trapping condition

- Trapping value agree: experiments-simulation-"analytical" model

- Ionization trapping is a "new" injection mechanism

SUMMARY & CONCLUSIONS

- Trapped e^- have very interesting properties:
  - Multiple bunches
  - Multi-GeV energies, ΔE/E<1?
  - Short features (<600 nm or 2 fs??)
  - Low emittance?

Applications? (FEL, …)

- More diagnostics are needed for the trapped particles (time structure, emittance, …)

- Investigate trapping of positrons in e^+-driven PWFA

Rosenzweig, PRA 38, 7, 3634 (1988)

SABER South Arc Beam Experimental Region

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THANK YOU
to my colleagues
of the *E-167* Collaboration:

I. Blumenfeld, F.-J. Decker, P. Emma, M. J. Hogan, R. Iverson, R. Ischebeck, N.A. Kirby, P. Krejcik, R.H. Siemann, D. Walz

Stanford Linear Accelerator Center

D. Auerbach, C. E. Clayton, C. Huang, C. Joshi, K. A. Marsh, W. B. Mori, W. Lu, M. Zhou

University of California, Los Angeles

T. Katsouleas, E. Oz, P. Muggli

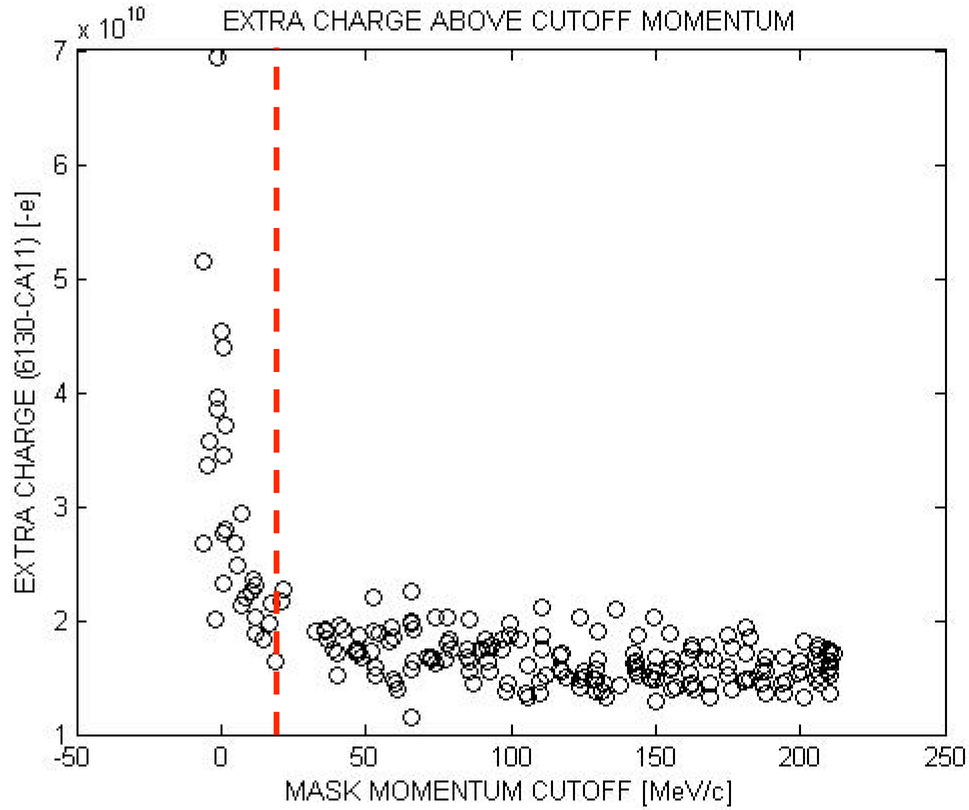
University of Southern California

and of the *E-157/162/164/164X* Collaborations

THANK YOU
to SLAC

THANK YOU
to DoE

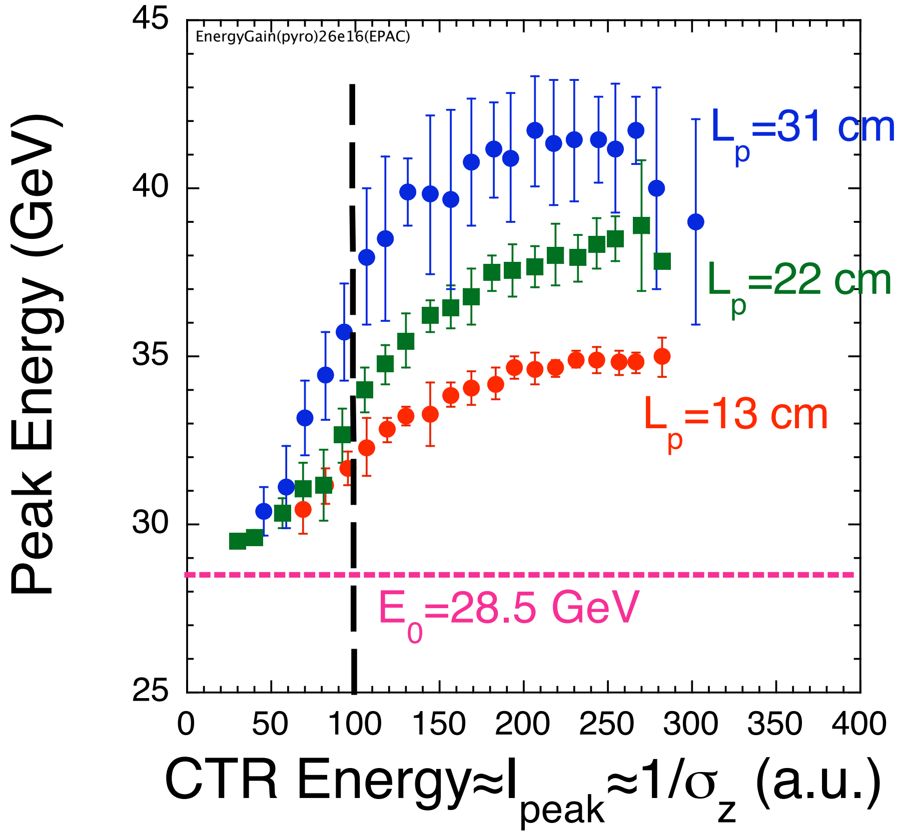
TRAPPED PARTICLES ENERGY

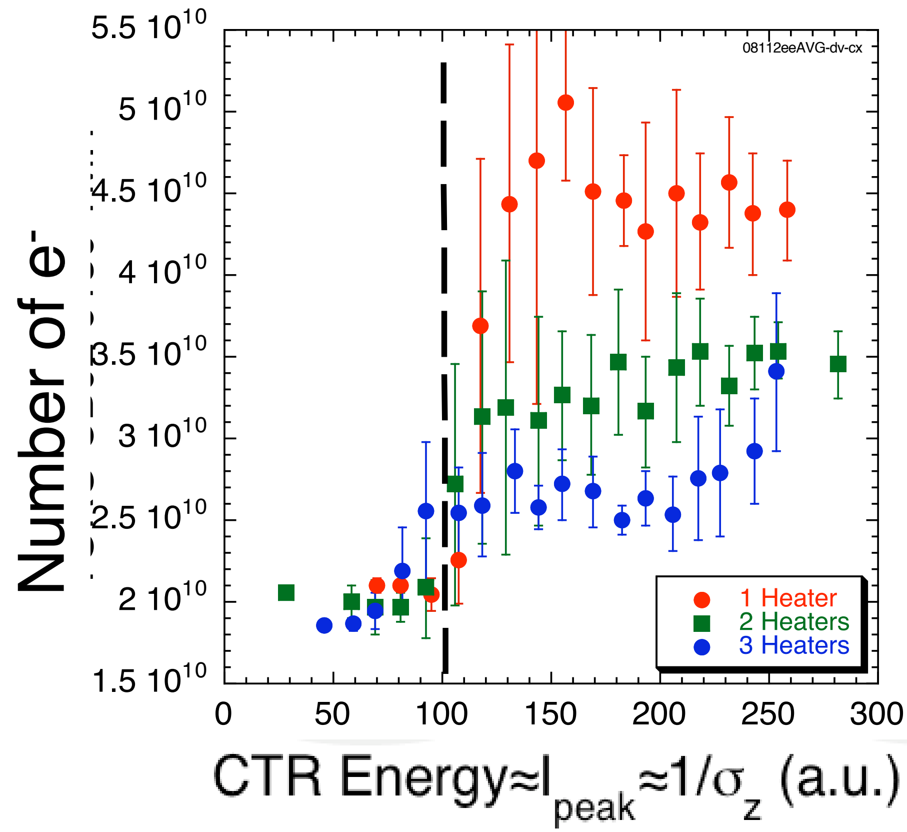


- Most of the excess charge is at < 20 MeV
- Trapped charge originate from 2nd Li/He boundary

ENERGY GAIN VS. BUNCH LENGTH

$n_e=2.6\times10^{17}cm^{-3}$





- Energy gain increases bunch peak current or σ_z^{-1}
- Loading of the wake by the trapped e^-?

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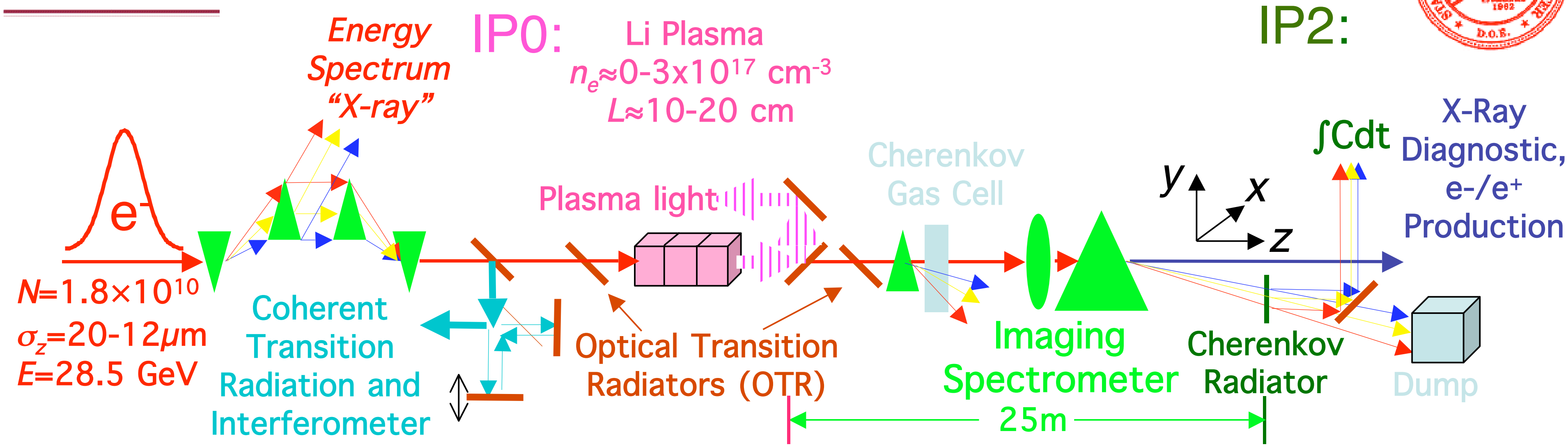
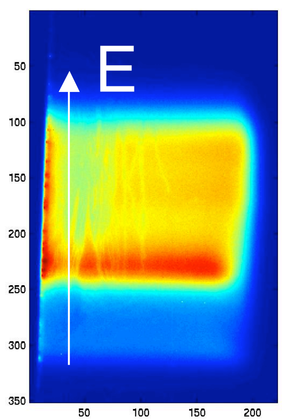
EXPERIMENTAL SET UP (GENERIC)

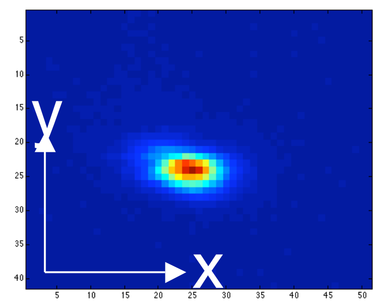


- X-ray Chicane



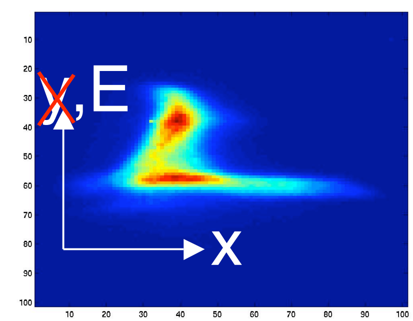
- Coherent Transition Radiation (CTR)
- CTR Energy≈I_{peak}≈$1/\sigma_z$

- OTR



-Spatial
-resolution ≈9 μm

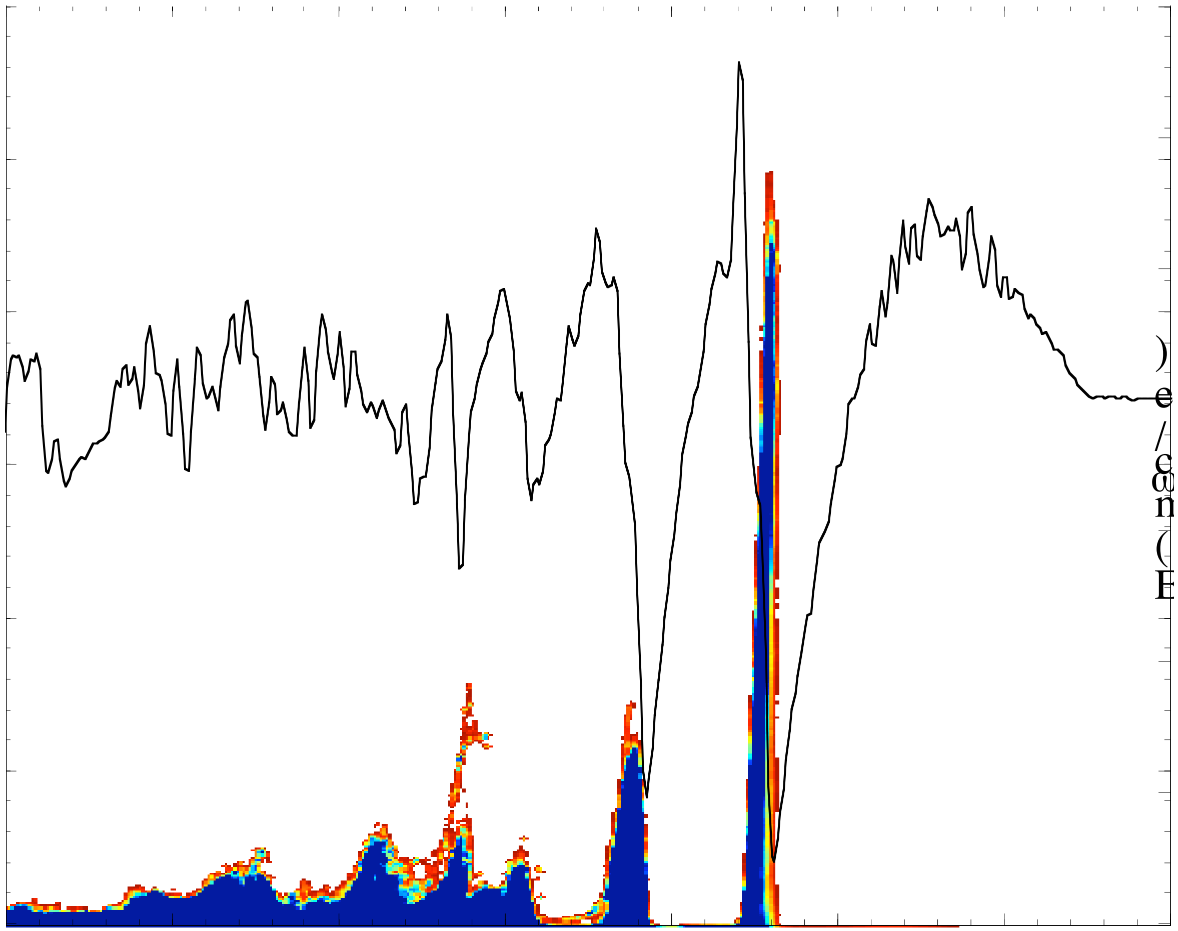
- Cherenkov (aerogel)



- Spatial resolution ≈100 μm
- Energy resolution ≈30 MeV

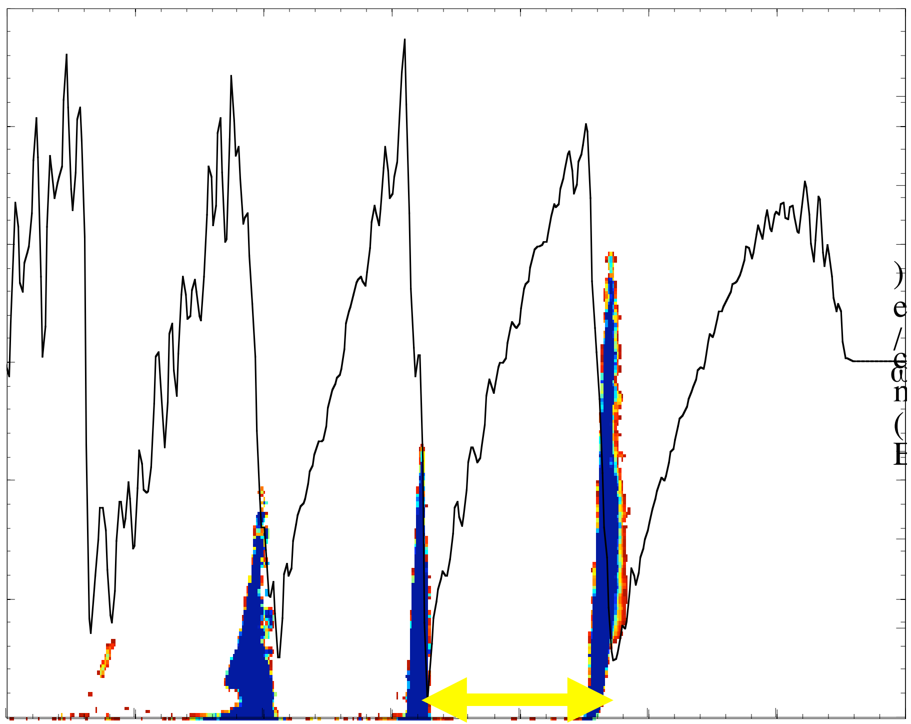
-Energy
resolution ≈60 MeV

High current drive beam drive



$\lambda_p = 52$ microns

1.6e17 hpc simulation lower current driver beam



$\lambda_p =$ 97 microns

Parameters of OSIRIS Simulation For The Full E-164X PWFA Experiment

Beam Spot Size (σ_r) gaussian	12 μ
Beam FWHM (non-gaussian longitudinal distribution)	70 μ
Beam Energy	28.5 GeV
Number of Beam e^-	1.88 x 10^{10}
Li Gas Density (n_0)	1.6 x 10^{17} cm^{-3}
Number of Simulation Cells	500 x 600 moving
Beam Particles/cell	25
Gas Particles/cell	1
dt ($1/\omega_p$)	0.0286 $\sqrt{3.2}c/\omega_p$
Cell Size Δz x Δr	0.05 x 0.02

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Analytical Model of Trapping

Constant of motion for arbitrary wave potentials of the form,
A= A(zct), $\Phi=\Phi(z\_ct)$

$$\gamma mc - P_z + q\frac{\Psi}{c} = \text{constant}; \qquad \Psi = \Phi - A_z$$

For Particles Born at Rest on Axis at a phase $\Psi_0 \sim \Psi_{min}$

$$\gamma mc + q\frac{\Psi_{\min}}{c} = \text{constant}$$

The trapping condition for these particles:

$$mc - \gamma mc + \gamma m V_p \le \frac{q}{c}(\Psi_{\max} - \Psi_{\min})$$

Making Use of The Linear Region of Wake

$$1-\frac{V_p}{c}\approx\frac{1}{2\gamma_p^{\,2}}<<\frac{1}{\gamma}\quad \&\,\gamma\approx\gamma_p$$

$$mc^2\leq \mathrm{q}(\Psi_{\max}-\Psi_{\min})$$

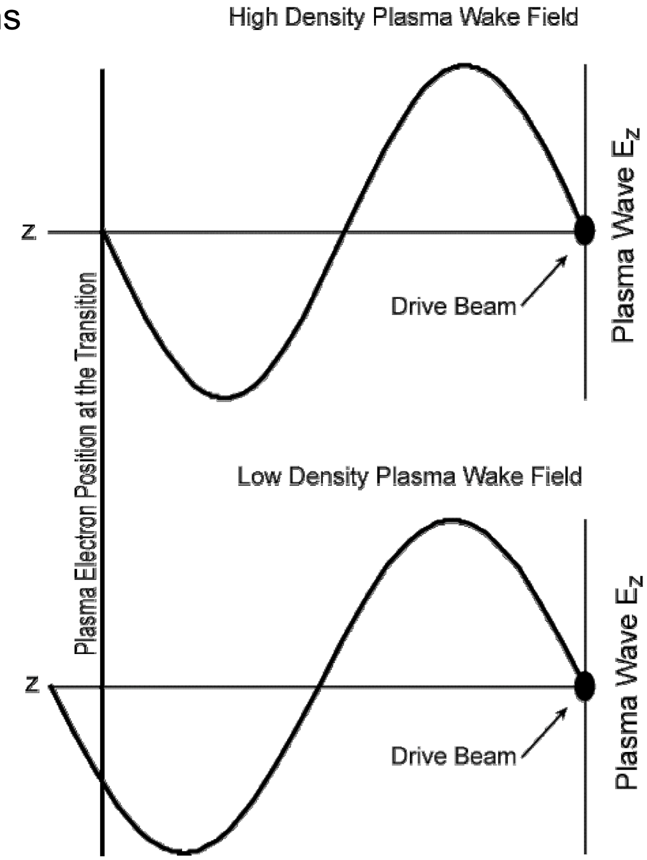
Over the linear region

$$E_z=-\frac{\partial\Psi}{\partial\xi}\qquad\qquad E_z=k(\xi-\xi_{\min})$$

$$(\Psi_{\max}-\Psi_{\min})=E_{\max}(\xi_{\min}-\xi_p)/2$$

Plasma Density Transition Trapping

Plasma Density Transition Trapping is a self-trapping scenario that uses the rapid change in the wake field wavelength at a steep drop in the plasma density to dephase plasma elections into an accelerating phase of the wake.



- Automatic injection of substantial charge into the accelerating phase.
- Operates in the PWFA "Blow Out" regime where $n_{beam} > n_{\mathrm{plasma}}$ or in strongly driven LWFAs.
- The length of the plasma density transition must be shorter than the plasma skin depth $k_p^{-1} = c/\_p$ for significant trapping to occur.
- Brightness of the trapped beam scales linearly with plasma density and surpasses state-of-the-art photoinjectors at densities higher than about 10^{17} cm^{-3}.

Major Transition Trapping Papers:

Concept Proposed - H. Suk, *et al.,* Phys. Rev. Lett. **86**, 1011 (2001)
Analysis of Trapped Beam Brightness and Scaling - M.C. Thompson, *et al*., Phys. Rev. STAB **7**, 011301 (2004)
Demonstration of sub-skin depth plasma density transitions - M.C. Thompson, *et al.,* Rev. Sci. Instrum. **76**, 013303 (2005).

U C L A

LWFA "bubble" regime

S.P.D. Mangles *et al.*, Nature **431**, 535 (2004)
C. Geddes *et al.*, Nature **431**, 538 (2004)
J. Faure *et al.*, Nature **431**, 541 (2004)

Breaking of plasma waves: "Injector" for LWFA

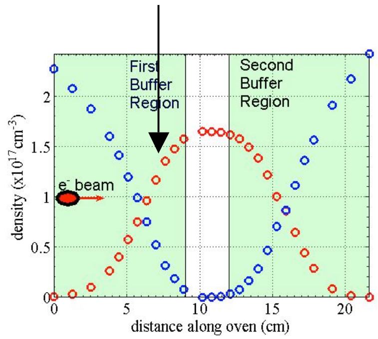
C. Coverdale *et al.*, Phys. Rev. Lett. **74**, 4659 (1995)
A. Modena *et al.*, Narture **337**, 606 (1995)

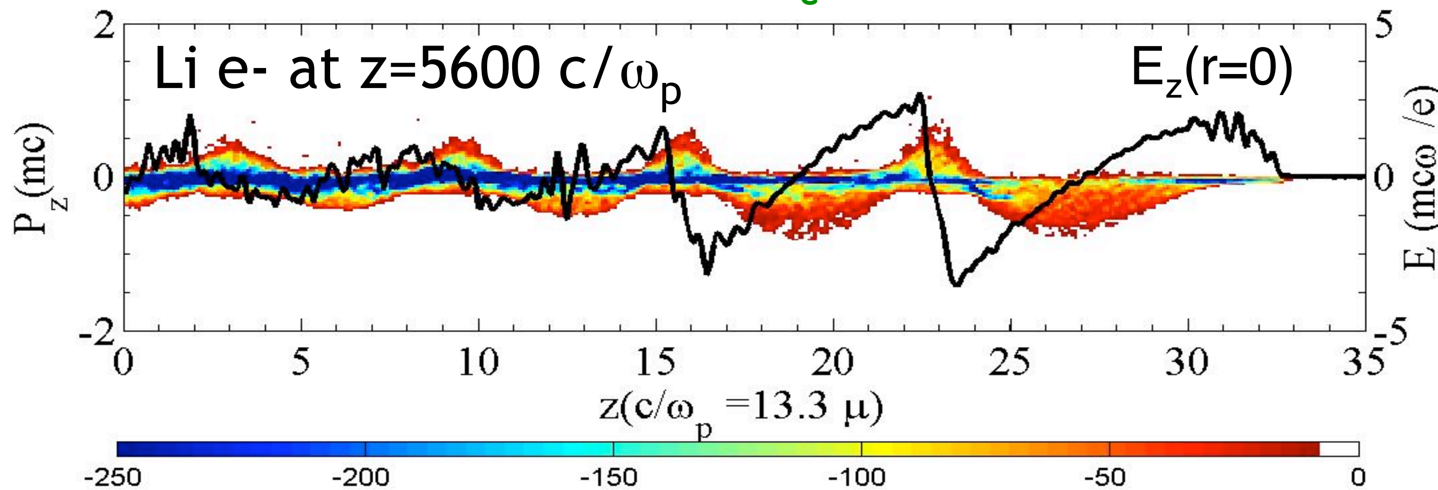
Controlled injection/trapping in LWFA

D. Umstadter, J. Kim, and E. Dodd, Phys. Rev. Lett. **76**, 2073 (1996)
E. Esarey *et al.*, Phys. Rev. Lett. **79**, 2682 (1997)

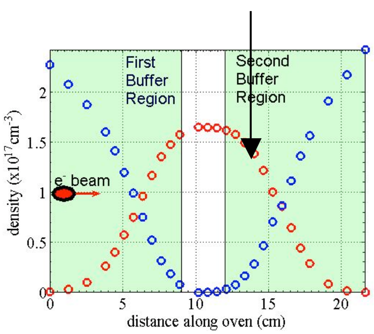
TRAPPED PARTICLES CHARCTERISTICS

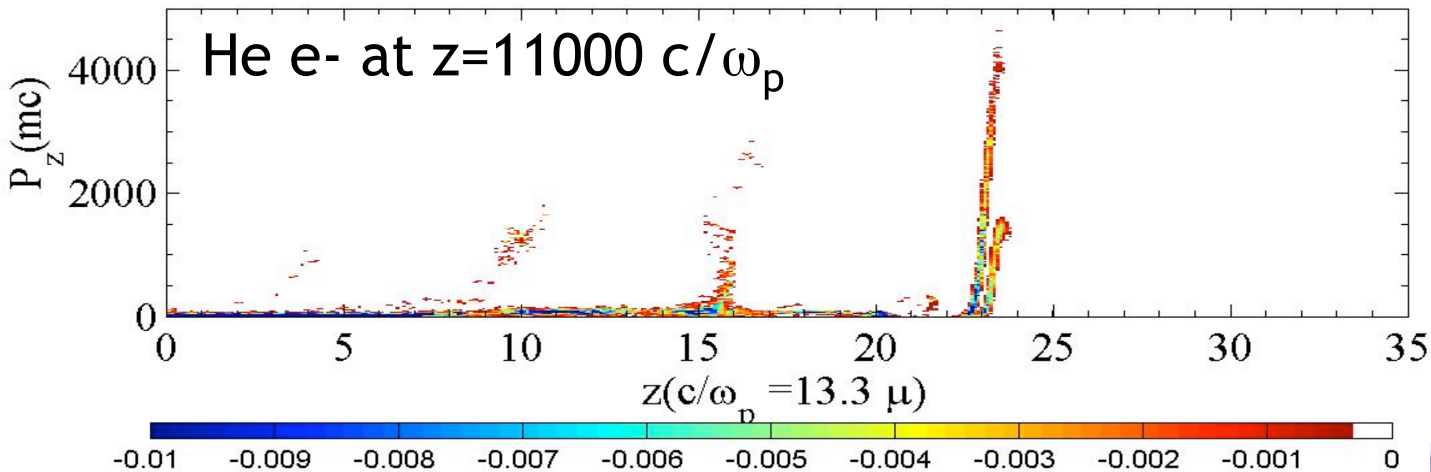
OSIRIS Simulation, n_e=1.6×10^17 cm^-3





➡ Li e⁻ do not get trapped (low oscillation energy)





➡ He e⁻ gain up to 2.5 GeV in 10 cm

"ANALYTICAL" THRESHOLD EXPRESSION

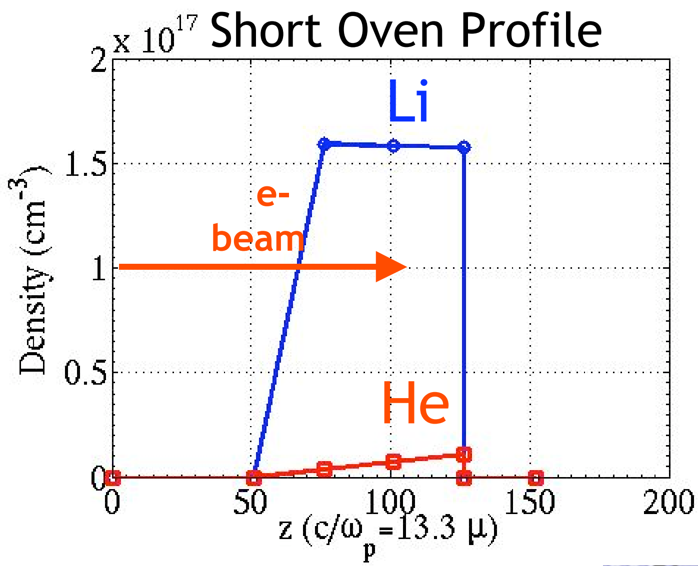
When Normalized to Simulation Units

$$E_{max} \geq \sqrt{\frac{2kmc^2}{e}} \quad E' = \frac{e}{mc\omega_p}E;\ k' = \frac{e}{m\omega_p^{\ 2}}k \qquad E_{max} \geq \sqrt{2k'}$$

Short simulations to test trapping theory

Recover Dawson's value??

Simulation Parameters: the same as the full e164X run except spot size is 2.4 μ to mock focusing of the beam and beam is propagated only a short portion of the buffer region



U C L A

CONTROLLED INJECTION

"all optical"

- Transverse injection
  Umstadter, PRL 76, 2073 (1996).

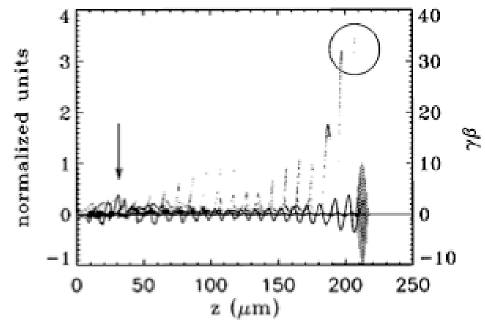
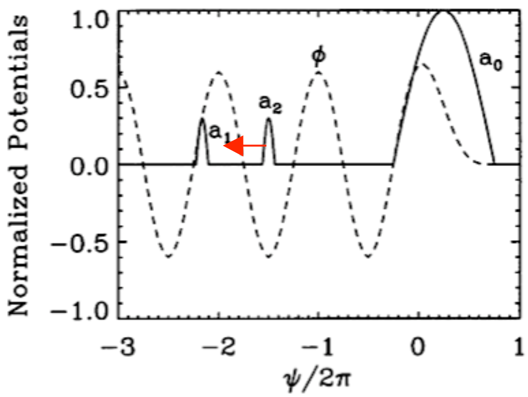


FIG. 3. A PIC simulation with an injection pulse of $b_0 = 2.0$; shown are the pump intensity **a**, the wakefield, and the longitudinal momentum $(\gamma\beta)_z$ of a number of the simulation electrons. By generating a series of "fresh" acceleration buckets, the pump laser pulse, propagating from left to right, is leading the trapped electrons out of the region disturbed by the injection pulse at $z = 30\ \mu$m, indicated by the arrow. The main part of a group of electrons that were trapped in the simulation is circled.

- Co-linear injection,
  Esarey, PRL 79, 2682 (1997).



$\omega_1 = \omega_0$
$\omega_2 = \omega_0 - \Delta\omega$
$\lambda_p = 100\ \lambda_0$

FIG. 1. Profiles of the pump laser pulse a_0, the wake ϕ, and the forward a_1 injection pulse, all of which are stationary in the $\psi = k_p(z - v_{p0}t)$ frame, and the backward injection pulse a_2, which moves to the left at $\simeq 2c$.

External injection

- PBWA, LWFA, PWFA

Requires:
Short bunches ($\sigma_z \ll \lambda_p$)
Temporal synchronization ($\Delta t \ll 2\pi/\omega_p$)

SELF-INJECTION

news and views

Geddes,C.G.R.et al.Nature 431,538 (2004).
Mangles,S.P.D.et al.Nature 431,535 (2004).
Faure,J.et al.Nature 431,541 (2004).

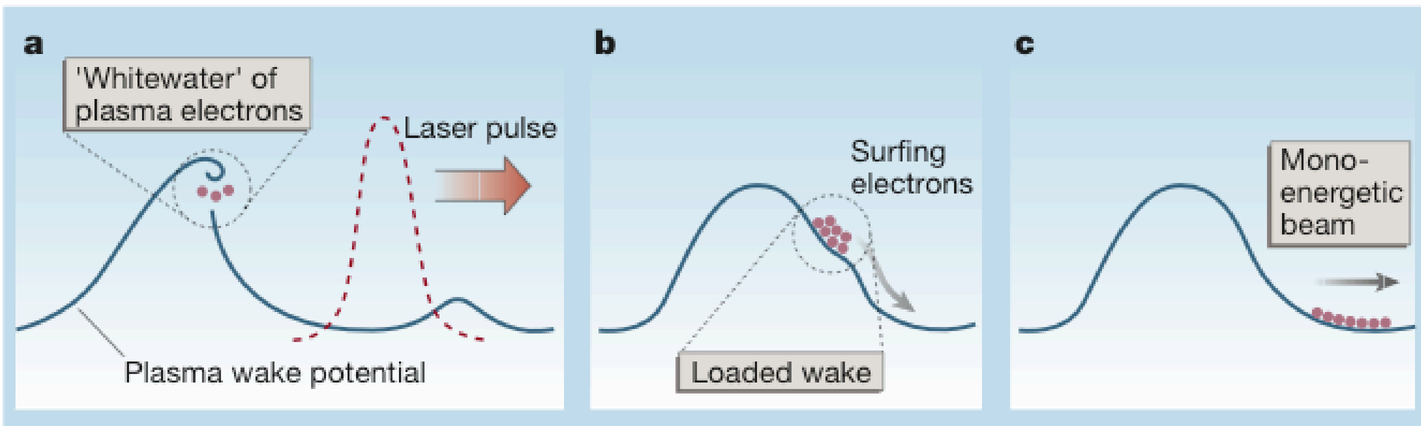


Figure 1 **Wakefield acceleration.** a, **In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the 'whitewater' and surf the wave.** b, **The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma.** c, **As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy.** Katsouleas, Nature 431,515 (2004).

➡ Self-injection ➡ $\Delta E/E<<1$

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INJECTION

- Transverse injection, Umstadter, PRL 76, 2073 (1996).
- Co-linear injection, Esarey, PRL 79, 2682 (1997). ← LOA, this workshop

news and views Katsouleas, Nature 431,515 (2004).

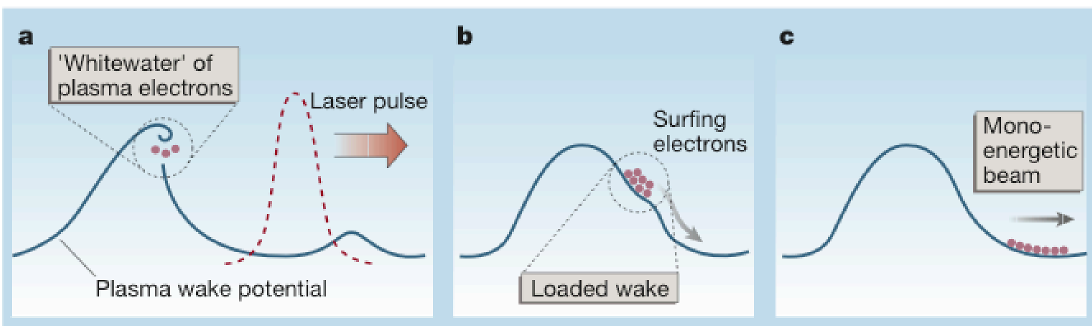
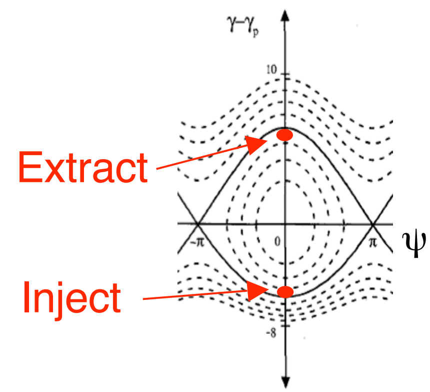


Figure 1 **Wakefield acceleration.** a, **In a plasma excited by a laser pulse, the wake potential rises until it steepens and breaks. Electrons from the plasma are caught in the 'whitewater' and surf the wave.** b, **The load of the electrons deforms the wake, stopping further trapping of electrons from the plasma.** c, **As the electrons surf to the bottom of the wake potential, they each arrive bearing a similar amount of energy.**



Geddes,C.G.R.et al.Nature 431, 538 (2004).
Mangles,S.P.D.et al.Nature 431, 535 (2004).
Faure,J.et al.Nature 431, 541 (2004).

- Self-injection → $\Delta E/E \ll 1$
- External injection:PBWA, LWFA, PWFA

Requires: Short bunches ($\sigma_z \ll \lambda_p$), temporal synchronization ($\Delta t \ll 2\pi/\omega_p$)

WAVE BREAKING

Rosenzweig, PRA 38, 7, 3634 (1988)

Dawson, Phys. Rev. 113, 2 (1959)

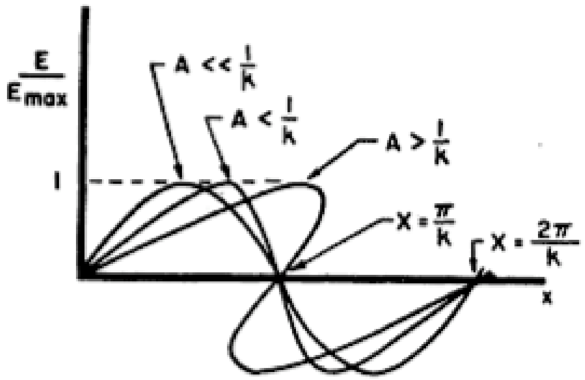


FIG. 1. E/E_{max} as a function of x, for various values of A.

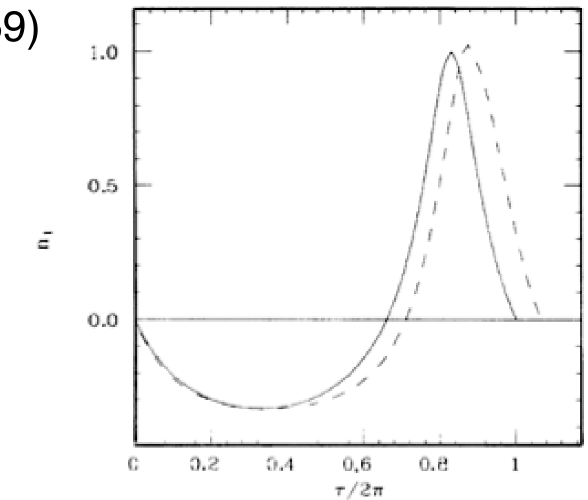


FIG. 1. Perturbed normalized electron densities n_1/n_0 for one cycle of a nonlinear plasma wave, from solutions of the cold fluid equations with maximum velocity $\beta_m = 0.5$. The solid line represents the nonrelativistic solution, the dotted line shows the correct relativistic solution. The profiles are similar, but there is already a significant period lengthening associated with the relativistic mass increase of the oscillating electrons.

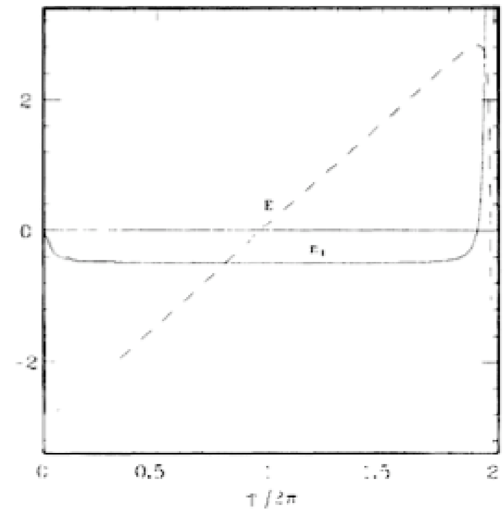


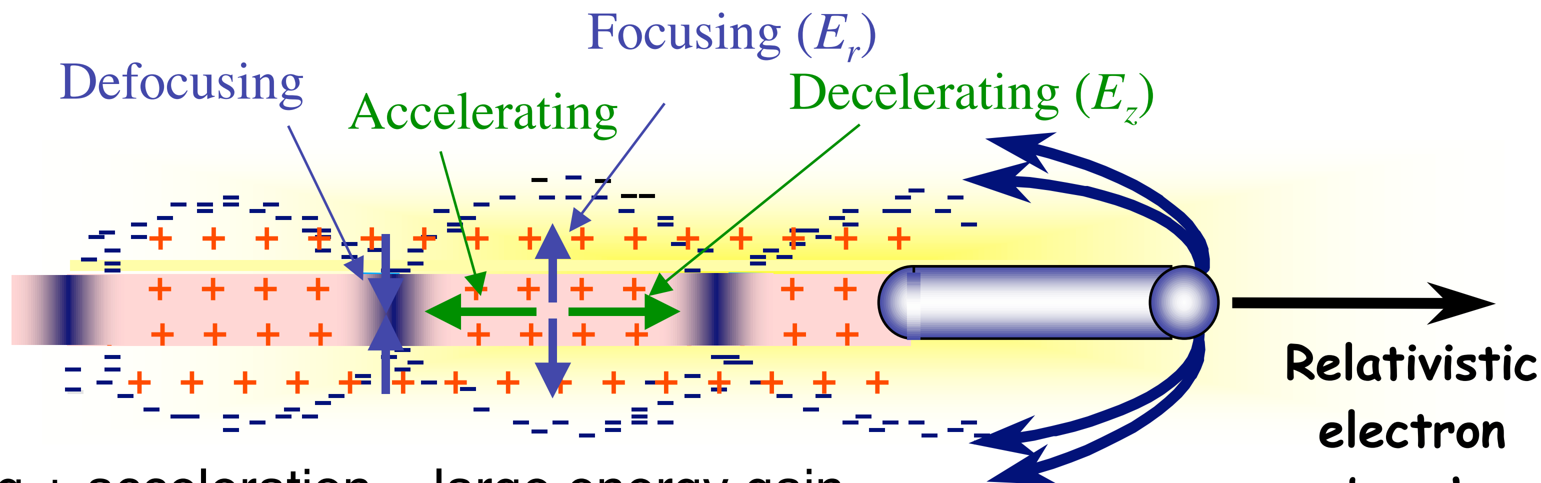
FIG. 2. The perturbed plasma electron density normalized to n_0 and electric field normalized to $m_e c\omega_p/e$ for a strongly nonlinear plasma wave with $\beta_m = 0.98$, $\gamma_m \simeq 5$, $eE_m/m_e c\omega_p \simeq 2.84$, and maximum $n_1/n_0 = 24$ (peak is off scale). The period has expanded to twice the nonrelativistic limit, and the electric field is nearly a sawtooth pattern, with a long linear rise.

- $V_{plasma\ electrons} \approx c$, $v_\phi \approx c$
- $V_{thermal} \approx v_\phi$
- Injection and trapping

U C L A

PLASMA WAKEFIELD ACCELERTAOR (e⁻)

PWFA = beam-driven plasma accelerator



- Focusing + acceleration = large energy gain
- Single bunch => particles at all phases => ΔE/E≈200%
- Wavebreaking limit: cold-relativistic

Akhiezer, Polovin, JETP 3, 5 (1956)

$\gamma_\phi=\gamma_b$

$$E_{max} = \frac{mc\omega_p}{e}\sqrt{2}\left(\gamma_\phi - 1\right)^{1/2} \quad \overset{?}{\longleftrightarrow} \quad E_{acc} \cong 110(MeV/m)\frac{N/2\times10^{10}}{\left(\sigma_z(\mu m)/600\right)^2}$$

SLAC: $N=1.8\times10^{10}$
$\gamma=55686$ (28.5 GeV)
$\sigma_z=30\ \mu m$
$n_e=2.6\times10^{10}\ cm^{-3}$

1.7 TeV/m >> 39 GeV/m

➡ No trapping?

WAVE BREAKING - TRAPPING

Dawson, Phys. Rev. 113, 2 (1959)

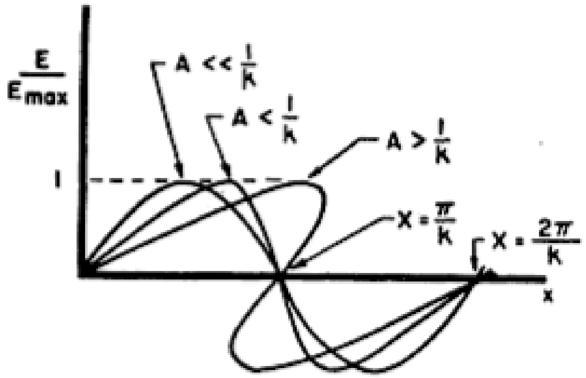
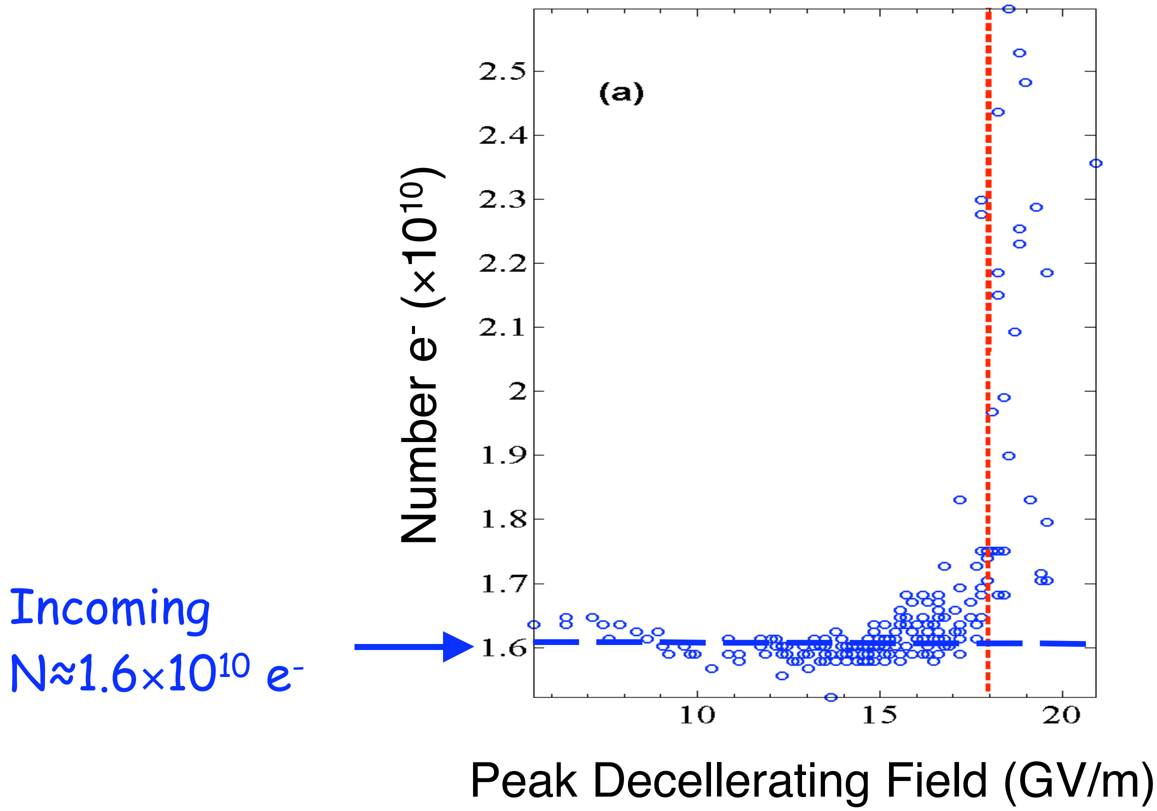


FIG. 1. E/E_{max} as a function of x, for various values of A.

- Harmonics of ω_p, sine to “sawtooth” wave
- Wave-particles dephasing
- Wave breaking → Injection and trapping

EVIDENCE FOR TRAPPED PARTICLES



- Excess charge appear with threshold at ≈18 GV/m
- Excess charge of the order of incoming charge, 1.6-1.8×10^{10} e^-