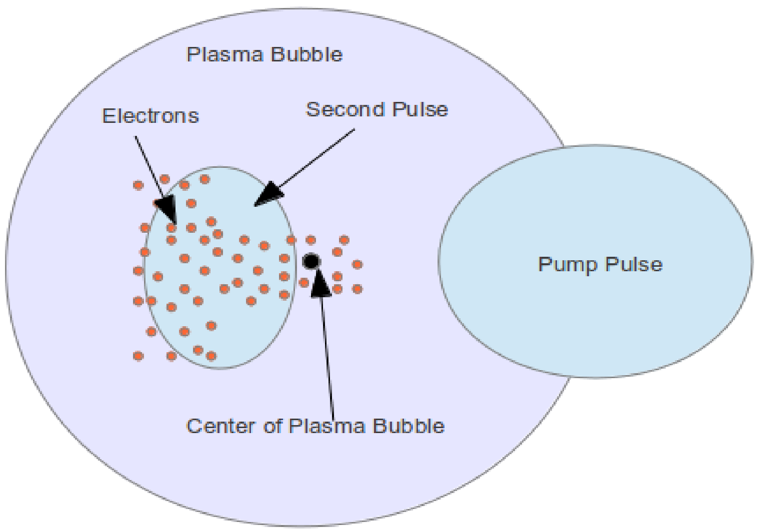
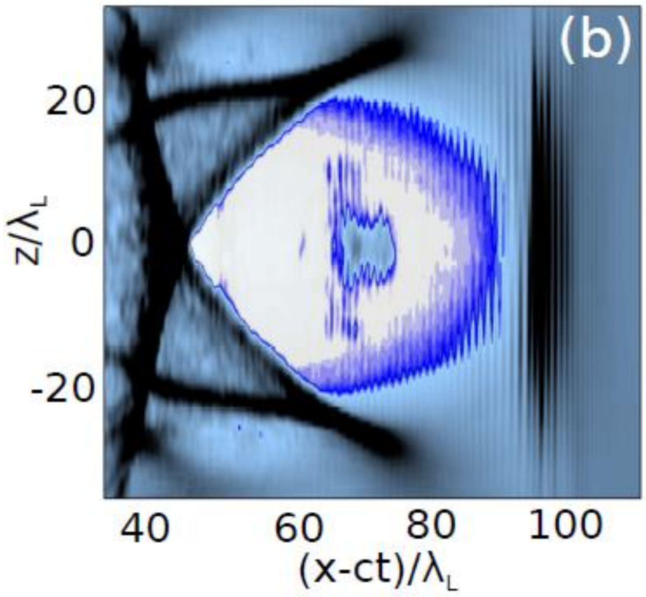
Synergistic Direct/Wakefield Acceleration In the Plasma Bubble Regime Using Tailored Laser Pulses

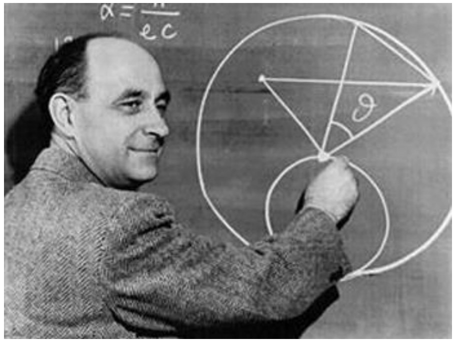
Gennady Shvets, The University of Texas at Austin

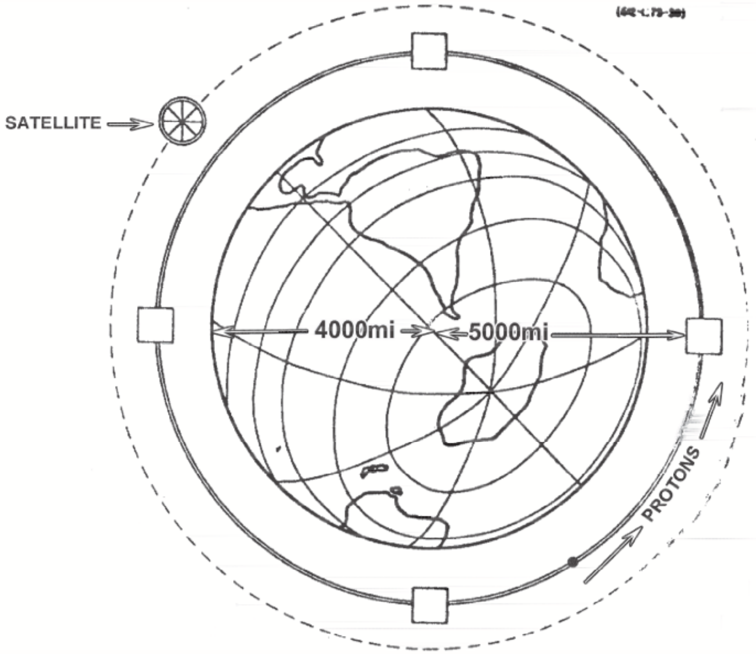




John Adams Institute for Accelerator Science, Oxford, UK, May 25, 2016

History of Accelerators: Higher Energies from Bright Ideas





"Fermi predicted that future accelerators would grow in power and size. They would not be built on the earth but around it, and physics laboratories would be in outer space… You may expect that at some future time accelerators will change the aspect of the earth and make it resemble the planet Saturn", Laura Fermi, 1974.

Prediction: 20 TeV CM energy by 1994 at a cost of $170B

NB: SSC would have been 40 TeV CM if it was not cancelled in 1993 (!!)

"What can we learn with High-Energy Accelerators", Retiring Presidential Address of APS, Columbia, 1954

How big are today's accelerators?

***Tevatron: 1 TeV/6km proton/antiproton** **LHC: 7 TeV/27km proton-proton**

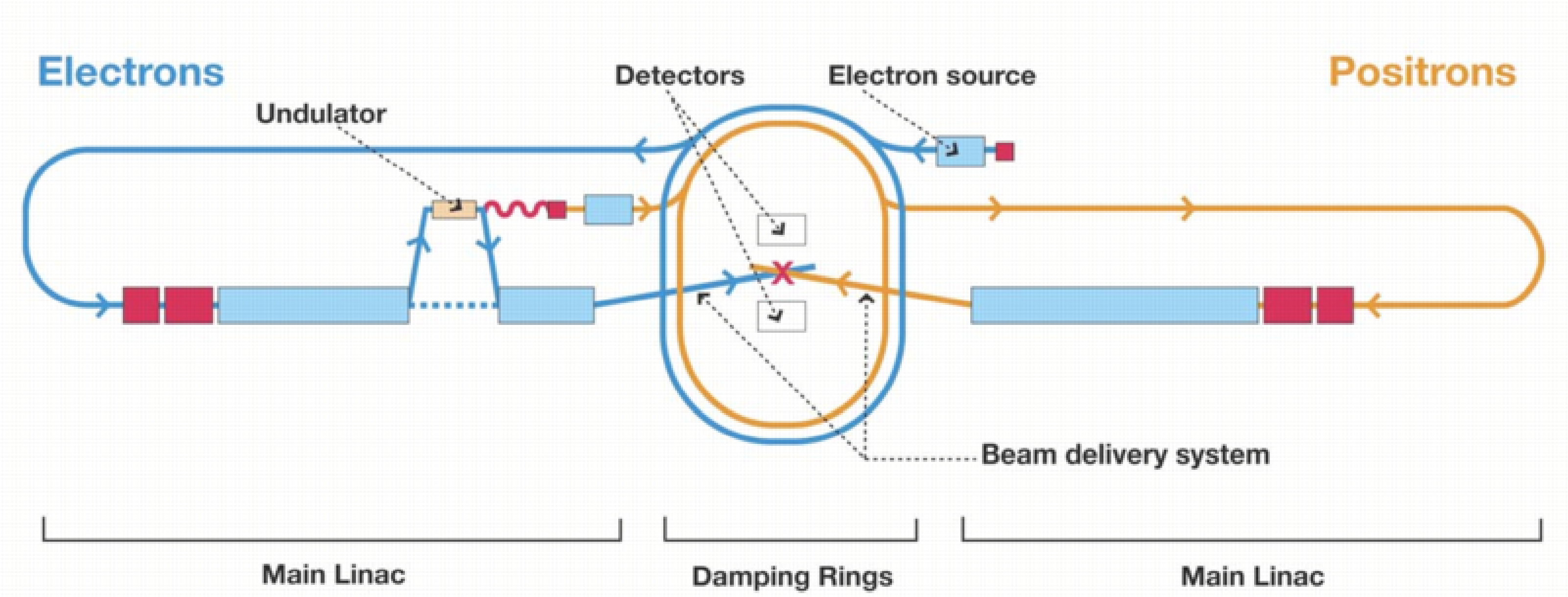
- **Hadrons are made of quarks → need high energy/proton → huge radius for reasonable magnetic field strength**
- **Rings don't work for high energy e-p → need linacs**

$$\frac{dE}{dz} \propto \frac{E^4}{m^4 R^2}$$

Major problem: synchrotron radiation

*Bad picture: 3km Main Injector Ring looks larger than the Tevatron! ☺

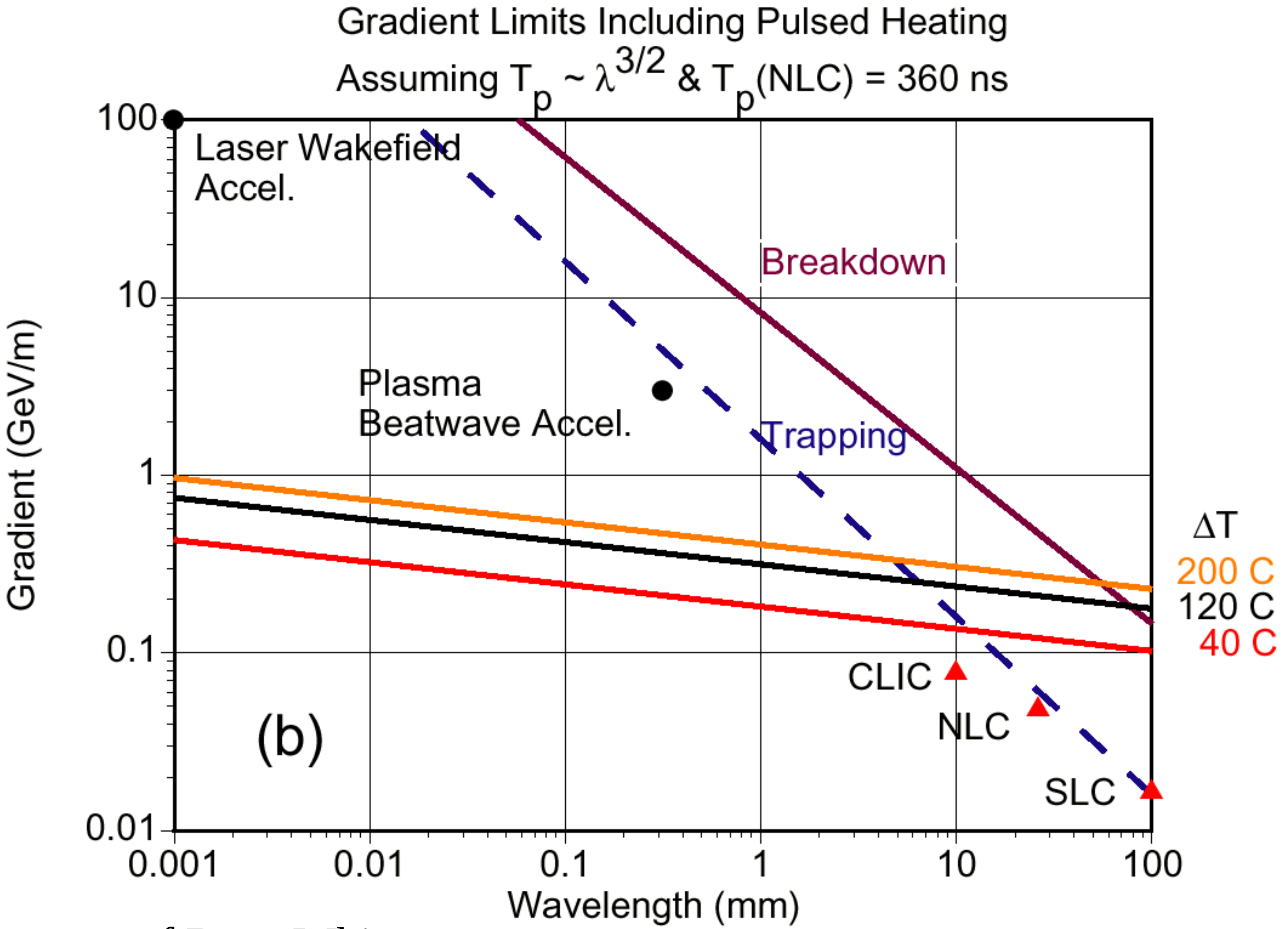
Linacs are for Leptons: International Linear Collider (ILC), Next HEP Project (?)



- SLC 2-mile linac: 50 Gev x 50 GeV collider with L = 10^{30} cm^{-2} sec^{-1}
- Conventional linacs are very long: 30km for 500 GeV
- Accelerating gradient in SC cavities: 32 MV/m
- High gradient acceleration enables miniaturization

High accelerating gradients → high frequencies

$$\frac{eE_{trap}}{m} \times \frac{1}{\omega} = c \quad \Longrightarrow \quad E_{trap} = 10 \text{ MeV/m x f [GHz]}$$

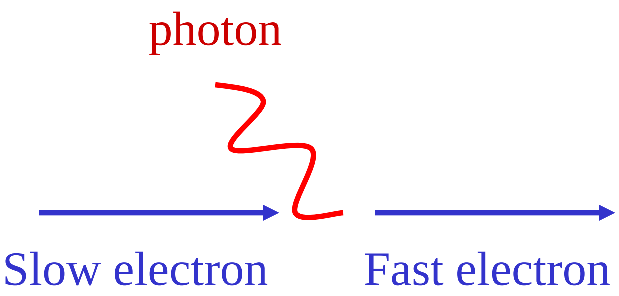


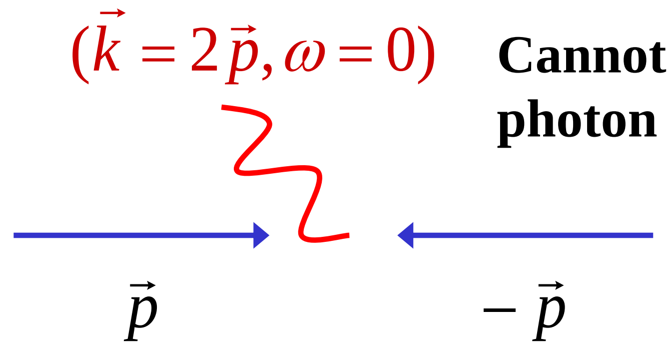
Use lasers whenever you can → highest frequency

Courtesy of Dave Whittum

The Basics of Laser Acceleration

Linear in electric field acceleration in vacuum is impossible (Lawson-Woodward-Palmer's theorem)





Cannot stop a photon in vacuum!

Near-field accelerators:

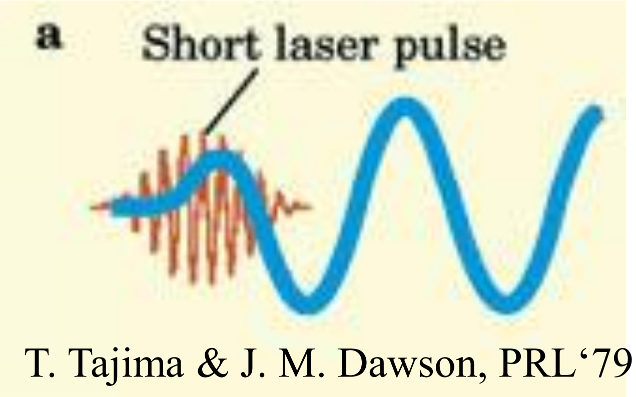
possess non-radiative field components due to boundaries (inverse Smith Purcell, PBG, surface wave, plasma wakefield, …)

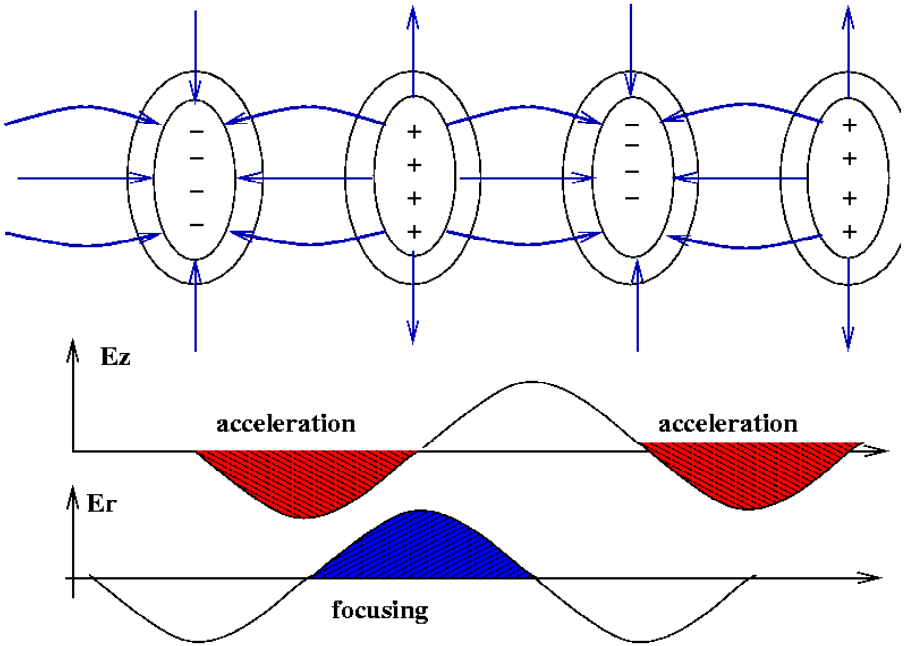
Far-field accelerators:

electrons execute transverse motion in external DC fields (IFEL, inverse CARM, inverse Ion Channel Laser)

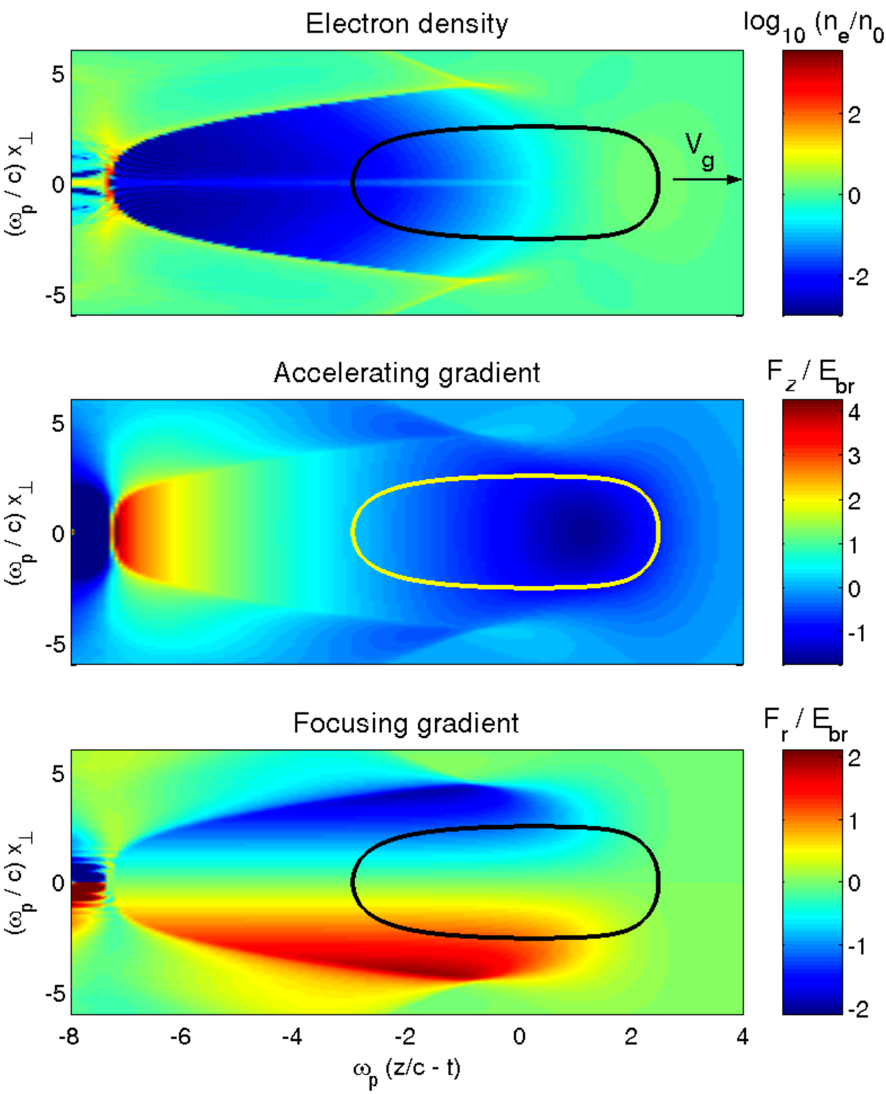
??

Plasma wave as a near-field accelerator

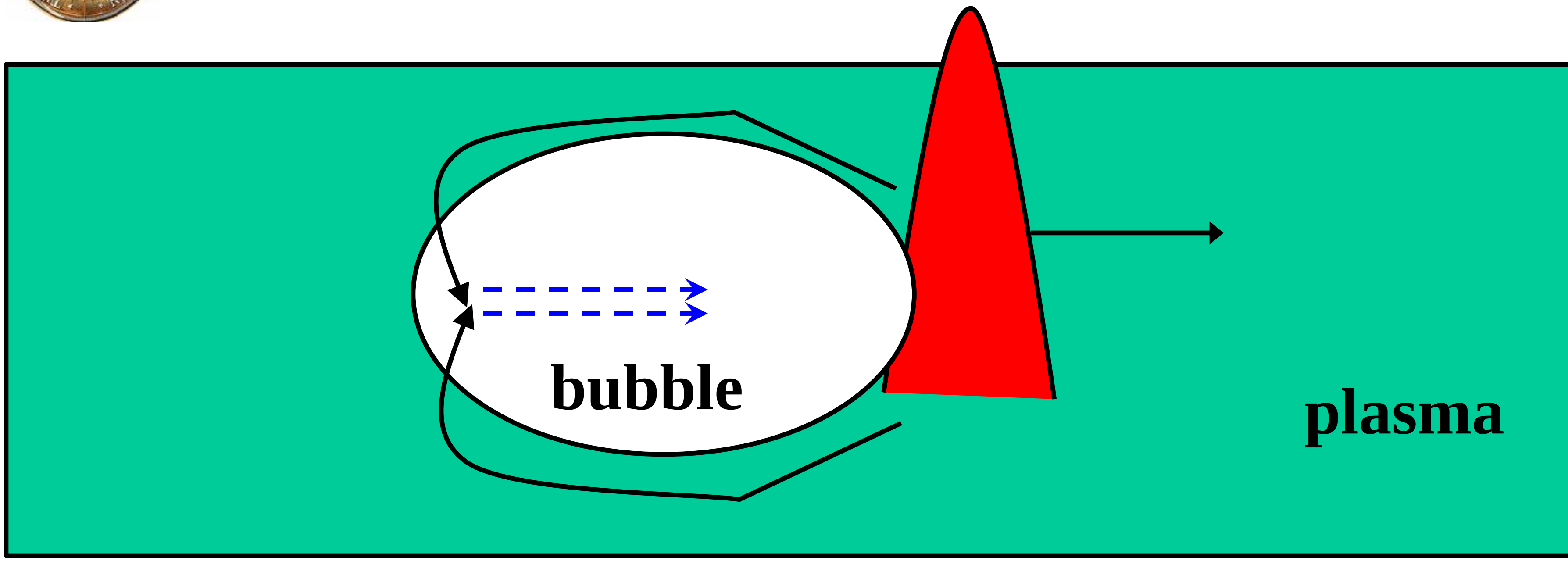


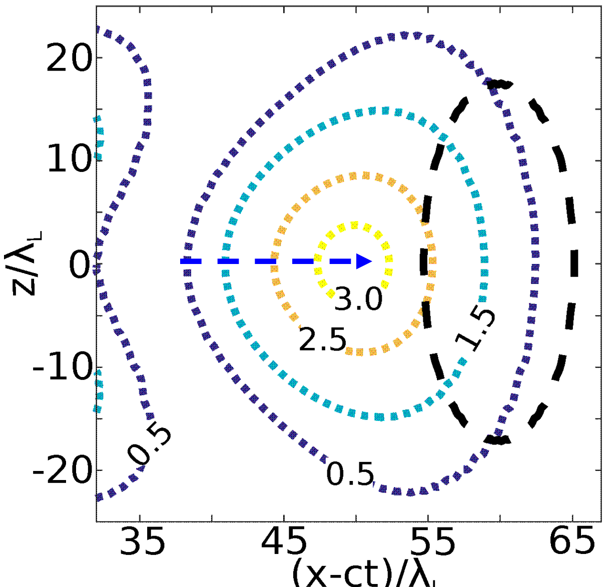


Ultimate nonlinear wake: plasma bubble



Plasma bubble: the workhorse





Particle advances inside bubble → gains energy from low-frequency electric field → energy gain is limited by dephasing

$$H_{MF} \approx \frac{p_x}{2\gamma_b^2} - \Psi \rightarrow \Delta p_x = 2\gamma_b^2 \Delta\Psi$$

Can we do better??

Far-field Accelerators

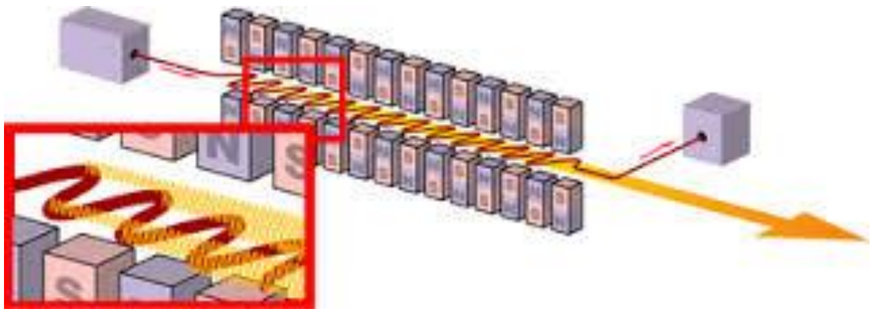
Far-field accelerators (no boundaries, plasmas, etc):

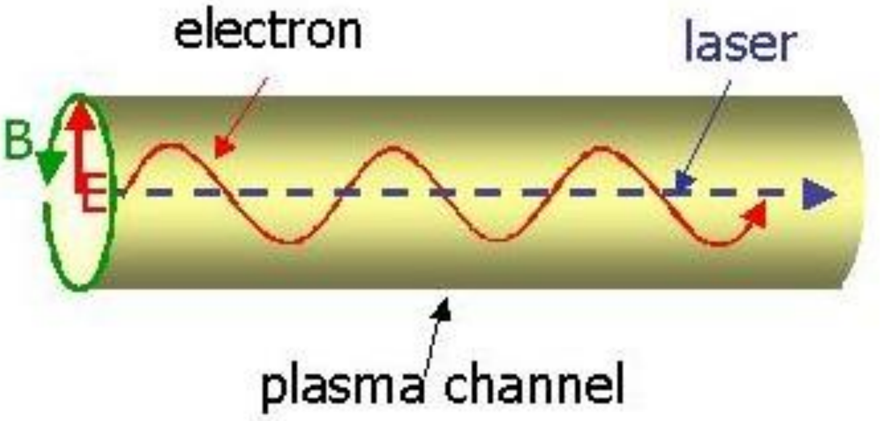
•Inverse free-electron laser (IFEL): $\omega_L - k_L v_x = k_w v_x$

•Cyclotron resonance laser accelerator: $\omega_L - k_L v_x = \Omega_c/\gamma$

•Inverse ion-channel laser (a.k.a. DLA): $\boldsymbol{\omega_L - k_L v_x = \omega_\beta}$

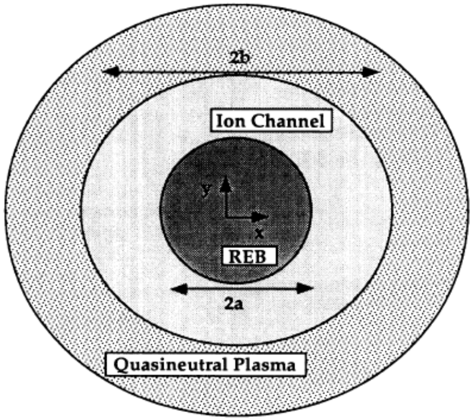
Drawbacks: (a) accelerating gradient reduces with γ, (b) large transverse undulating motion, (c) difficult to maintain resonance condition





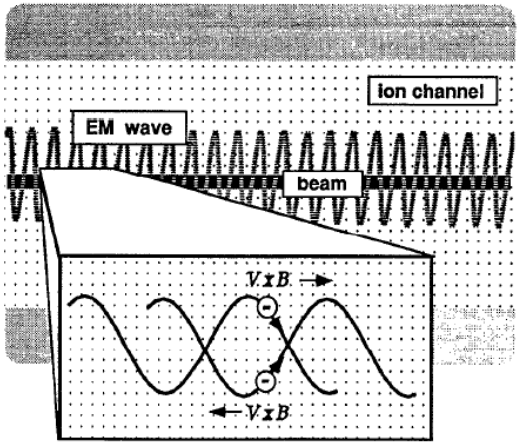
$\boldsymbol{d\gamma/dz \propto 1/\gamma}$ IFEL curse

DLA History: From Plasma Channels…

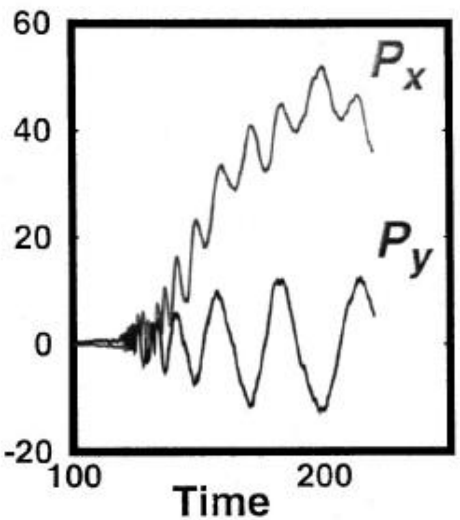


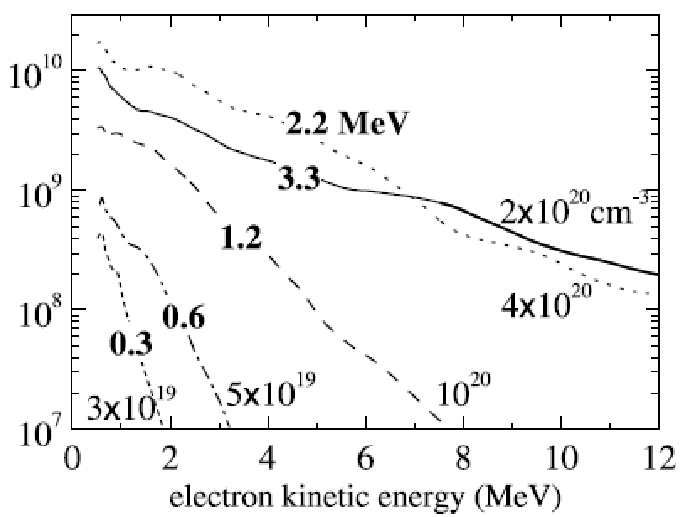
Dave Whittum, Andy Sessler, and John Dawson invent an ion channel laser

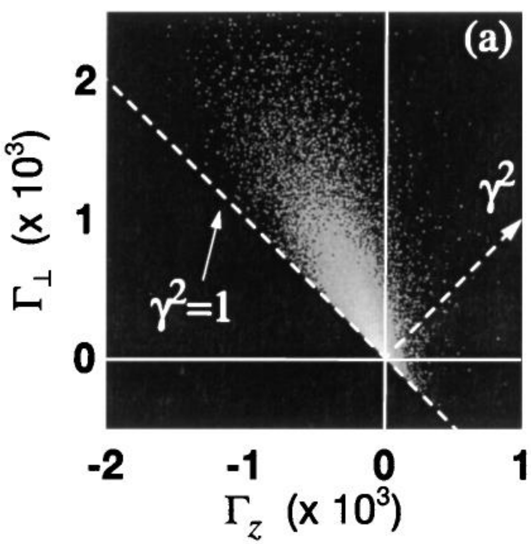
D. H. Whittum et. al., PRL'90; Phys. Plasmas '92



The MPQ team proposes and realizes the inverse ion channel laser

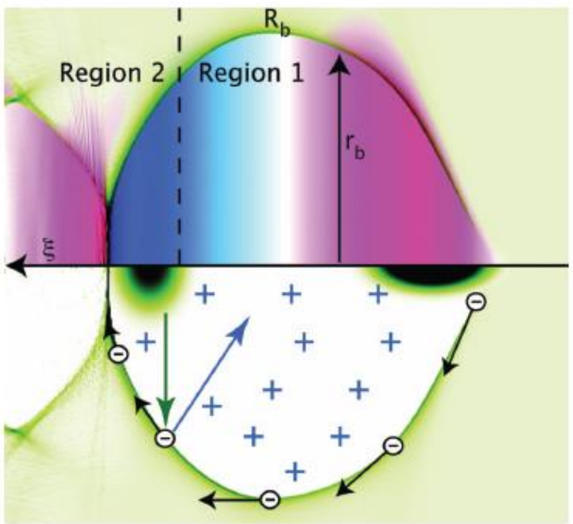






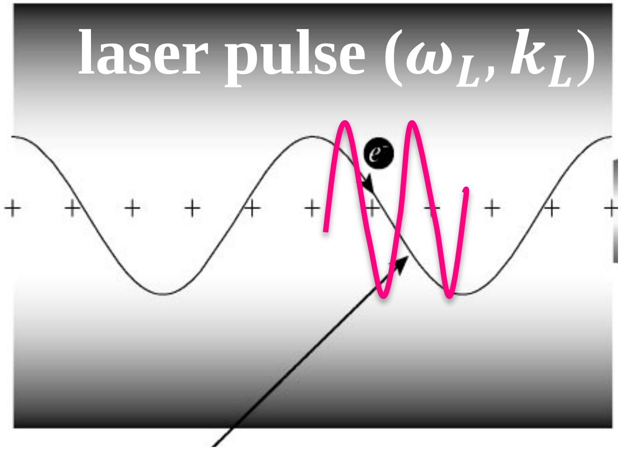
A. Pukhov et. al., PoP'99; C. Gahn et. al., PRL'99

Electrons motion inside the bubble and Direct Laser Acceleration



Electrons execute betatron motion with frequency ω_β

Transverse energy $\epsilon_\perp$ is reduced due to the conservation of the action $I_\perp = \epsilon_\perp/\omega_\beta$



Betatron motion

Betatron frequency

$$\omega_\beta = \omega_p/(2\gamma)^{1/2}$$

Transverse energy

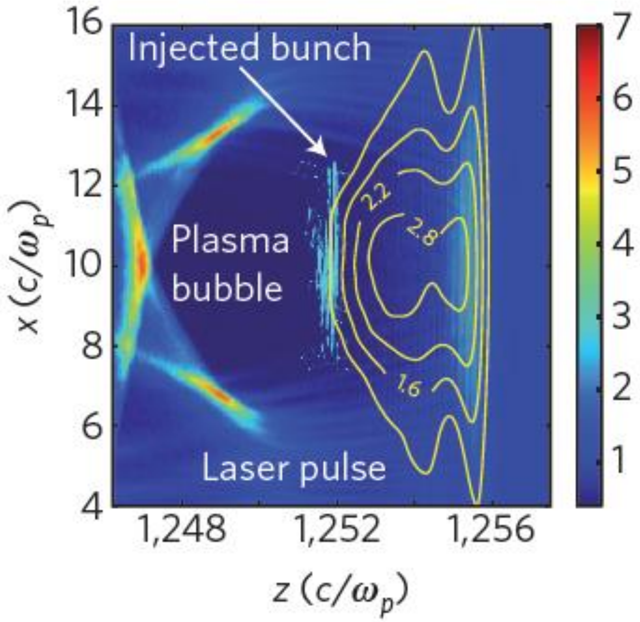
$$\epsilon_\perp \equiv p_\perp^2/2\gamma m_e + \omega_p^2 m_e^2 z^2/4$$

Break the adiabatic invariant by introducing an additional resonant laser pulse → DLA

$$\omega_L - k_L v = (2n+1)\frac{\omega_p}{\sqrt{2\gamma}}$$

$$\Delta\gamma = \frac{\Delta\epsilon_\perp/mc^2}{1 - c/v_{ph}}$$

Earlier indications?

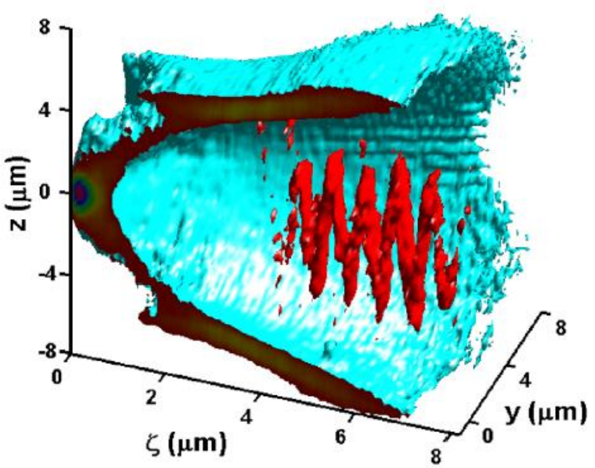


Dino Jaroszynski produces MeV Gamma rays, possibly via DLA mechanism inside a bubble!!

S. Cipiccia et. al., Nature Physics'2011

"In fact, this observation of high harmonic generation could provide the first (albeit somewhat indirect) experimental evidence of DLA, which has so far been elusive."

G. Shvets, Nature Physics'2011



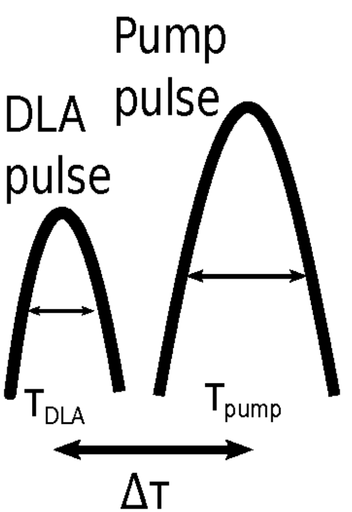
A great deal of theoretical work:

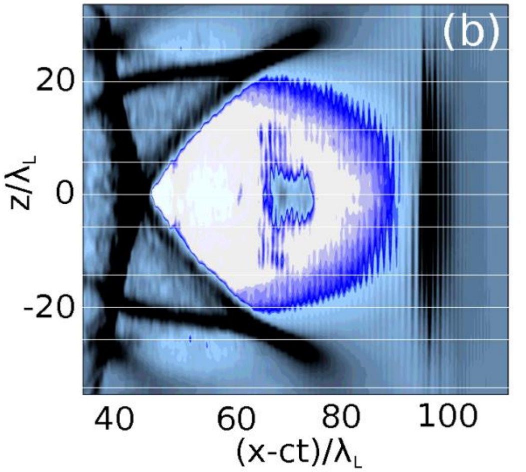
Nemeth, et al., PRL'07, PRL; Phuoc, et al., PoP'08, J. L. Shaw et. al., PPCF'14

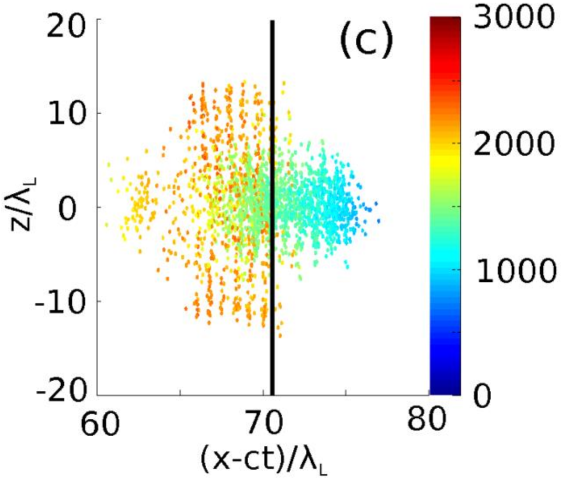
Big questions: (a) monochromatic beam? (b) best laser pulse format? (c) best injection approach? (d) major paradigm shift of LPAs in the making??

Outline of the Talk

- How LWFA and DLA can work together, delay dephasing, and bifurcate the phase space
- How to inject electrons into the plasma bubble and have them experience synergistic DLA/LWFA
- Constant gradient DLA in the decelerating phase of the wake
- Mix-and-match: combining multiple lasers for DLA + LWFA







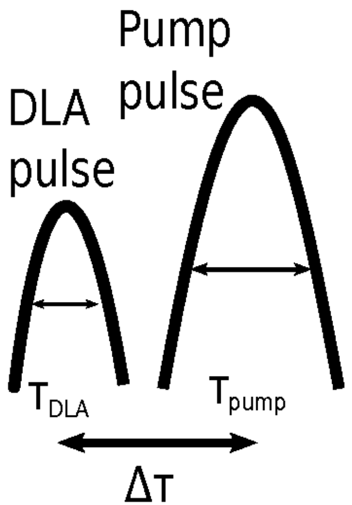
Can LWFA and DLA work together?

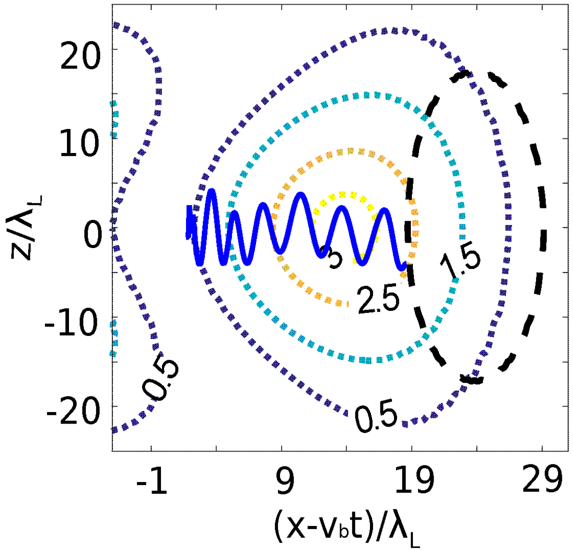
•DLA's resonance condition can be undone by rapid wakefield acceleration: $\omega_L(1 - v_x/v_{ph}) = \omega_p/\sqrt{2\gamma}$
•DLA requires large $\vec{v}_\perp$ because $A_L \propto \vec{v}_\perp \cdot \vec{A}_L$, but the conservation of $I_\perp$ reduces $|\vec{v}_\perp|$ during acceleration!

} LWFA is bad for DLA

•DLA laser pulse can distort the bubble and impede LWF acceleration or electron injection into the bubble
•Large amplitude of betatron oscillations may reduce the accelerating gradient experienced inside the bubble

} DLA is bad for LWFA



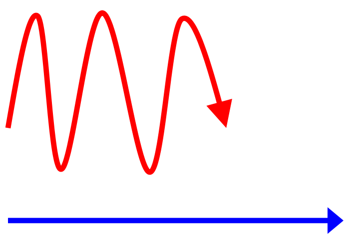


But the benefits of combining the two could be substantial!

X. Zhang, V. Khudik, and GS, PRL **114,** 184801 (2015)
X. Zhang, V. Khudik, A. Pukhov, and GS, PPCF **58,** 034011 (2016)

Benefits of Synergistic Laser Wakefield & Direct Laser Acceleration

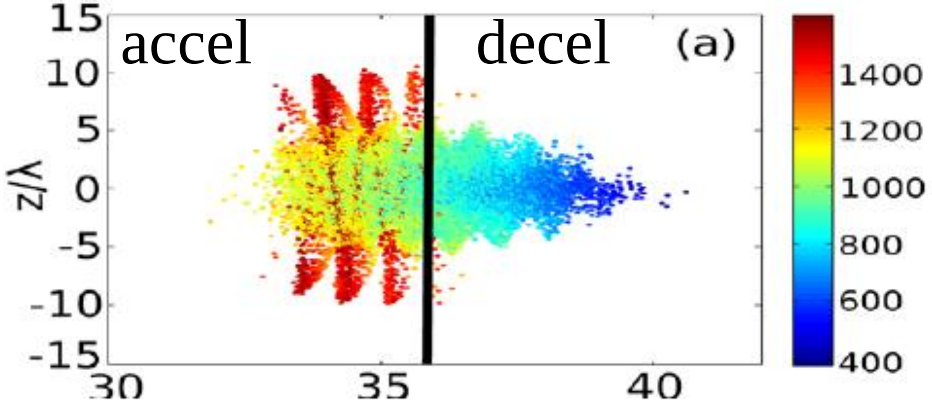
- **Cumulative energy gain from LWFA and DLA**
- **Potentially higher energy gain from LWFA due to delayed dephasing**



- **Large transverse momentum $K = p_\perp/mc$ → efficient source of X-rays and γ −rays up to K^3 harmonic of ω_L**
- **Combining multiple laser pulses (mid-IR + near-IR)**

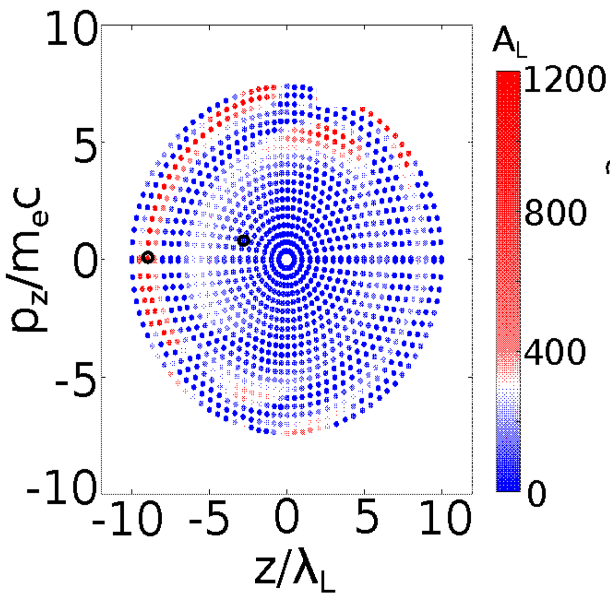
$$\frac{d\zeta}{d(ct)} \approx \frac{1}{2\gamma_b^2} - \frac{1 + \langle p_\perp^2/m_e^2 c^2 \rangle}{\gamma^2}$$

X. Zhang et. al., PRL **114,** 184801 (2015); PPCF **58,** 034011 (2016)

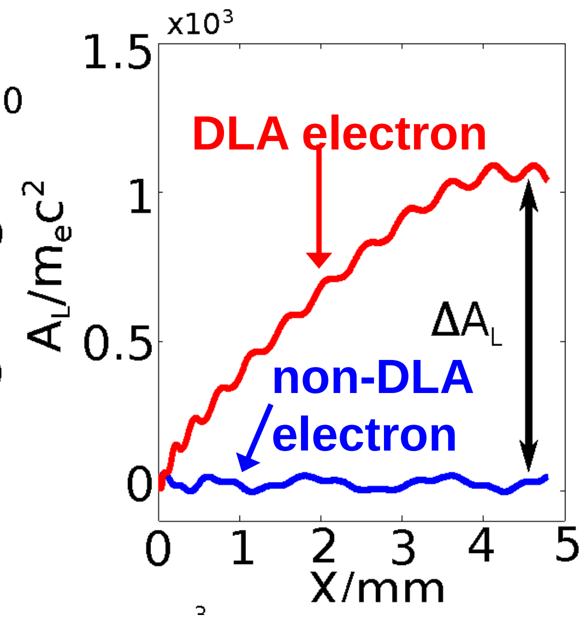


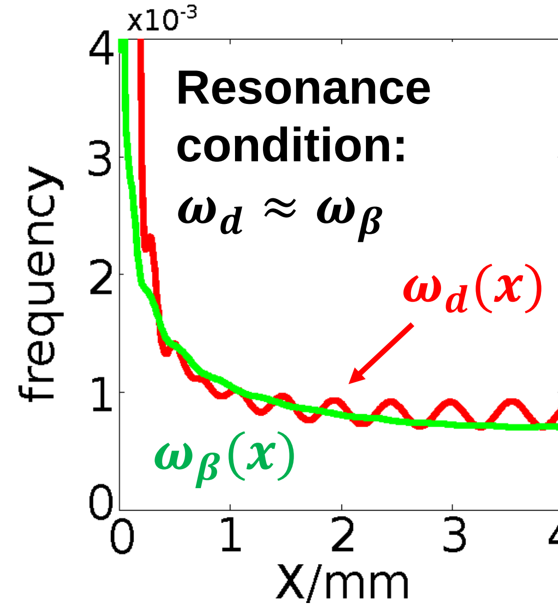
$$\zeta = x - v_b t$$

Synergistic DLA/LWFA: single-particle simulations of a particle swarm



Swarm of initial conditions ($\boldsymbol{p}_\perp, \boldsymbol{r}_\perp$)





$$\omega_d = \omega_L \left(\frac{1 + \langle p_z^2/m^2c^2 \rangle}{2\gamma^2} + \frac{1}{2\gamma_{ph}^2} \right)$$

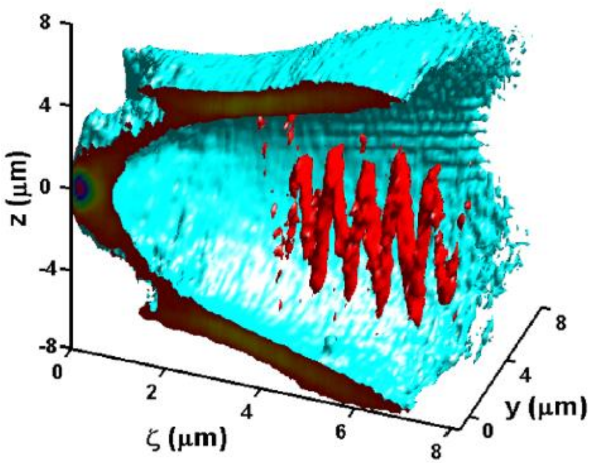
Necessary ingredients of DLA/LWFA synergy:

(a) electron injection with large transverse energy

(b) strong overlap between electrons and the laser

(c) betatron resonance between electrons and the laser

Can DLA happen in a plasma bubble?



Pump pulse creates a bubble

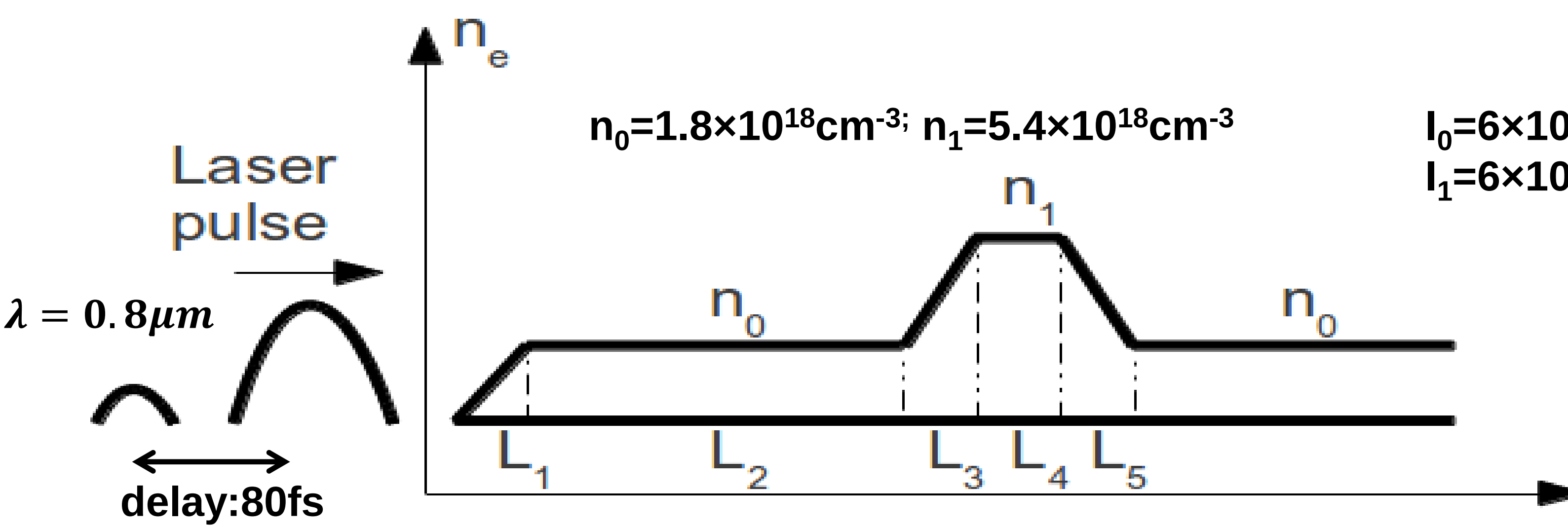
↓

Density bump "shakes" the bubble → side-injection with large $p_\perp$ → facilitates DLA

↓

Self-injected electrons interact with the weaker laser pulse delayed by Δτ=80fs

Density ramp injection scenario

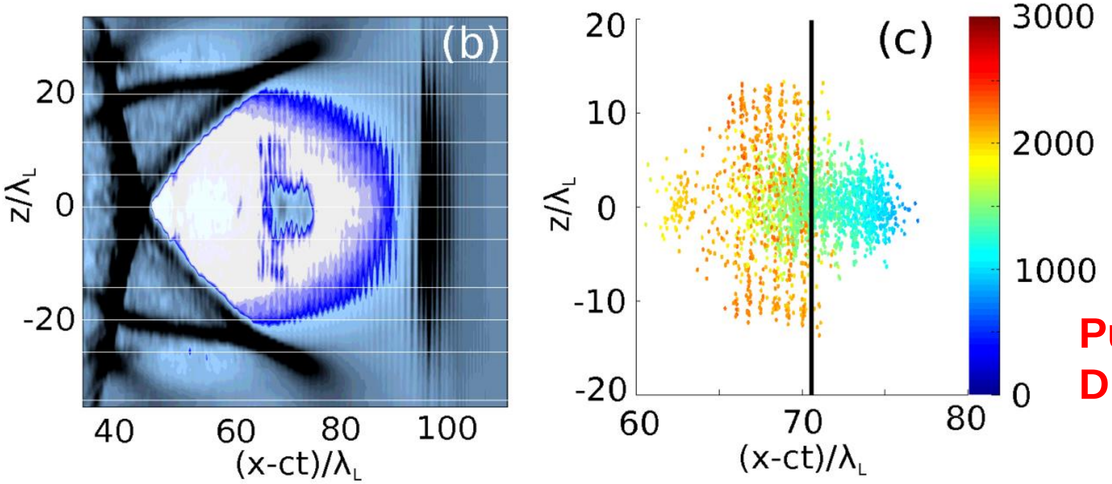


L_2 =1.6mm, $L_3 = L_4 = L_5 \approx 100\mu m$

X. Zhang et. al. PRL **114,** 184801 (2015)

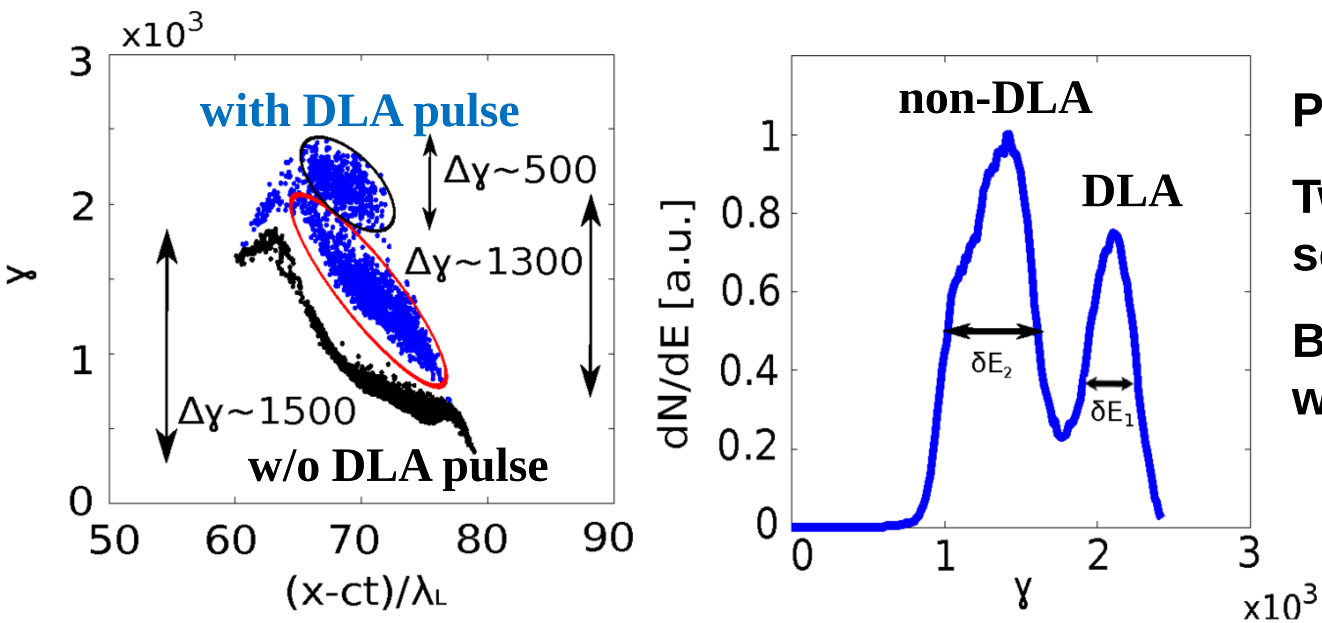
DLA inside a plasma bubble

after 1cm propagation



Electrons separated into two groups → DLA electrons with large $p_\perp$ gain more energy and fall behind the non-DLA ones

Pump: $a_L = 5.3, \tau_L = 70fs, w_0 = 20\mu m$
DLA : $a_L = 1.7, \tau_L = 35fs, w_0 = 20\mu m$



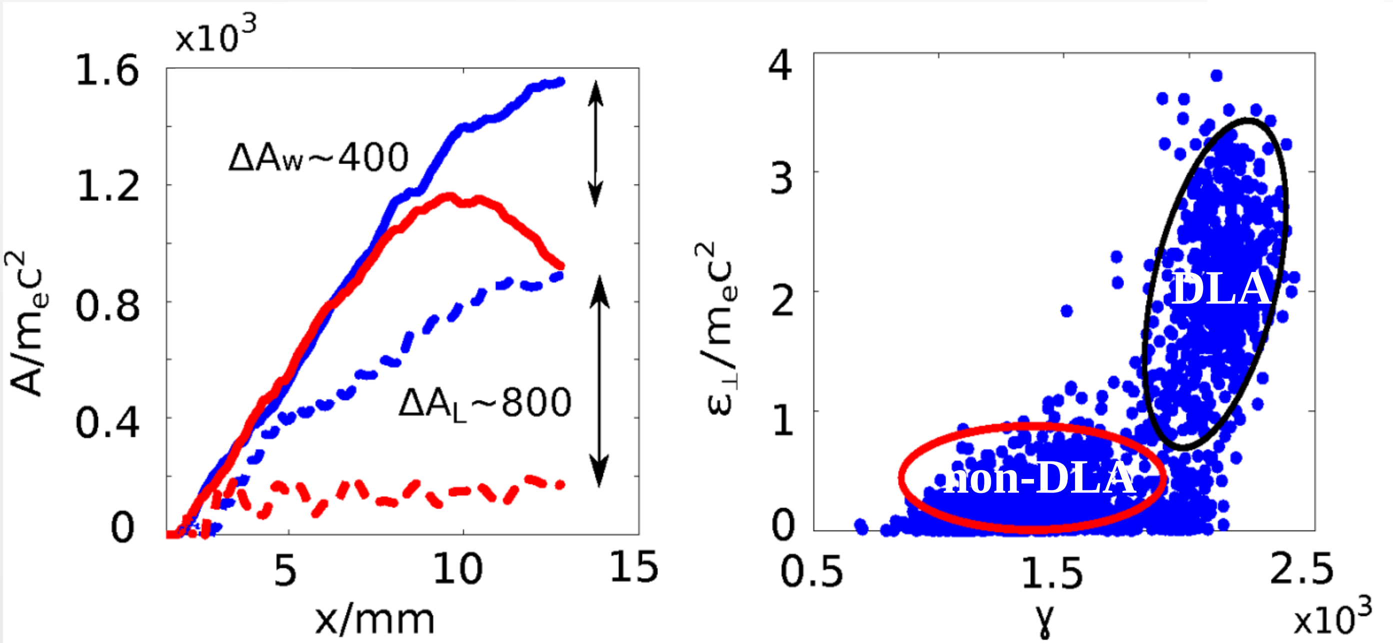
Phase space bifurcation

Two-peak spectrum separated by 400 MeV

Bifurcation is absent without DLA pulse

X. Zhang et. al. PRL **114,** 184801 (2015)

Phase Space Correlations: Key to Synergy



DLA electrons → strong correlation between total energy γmc^2 and transverse energy

$$\epsilon_\perp = \frac{p_z^2}{2\gamma m} + \frac{m\omega_p^2 z^2}{4}$$

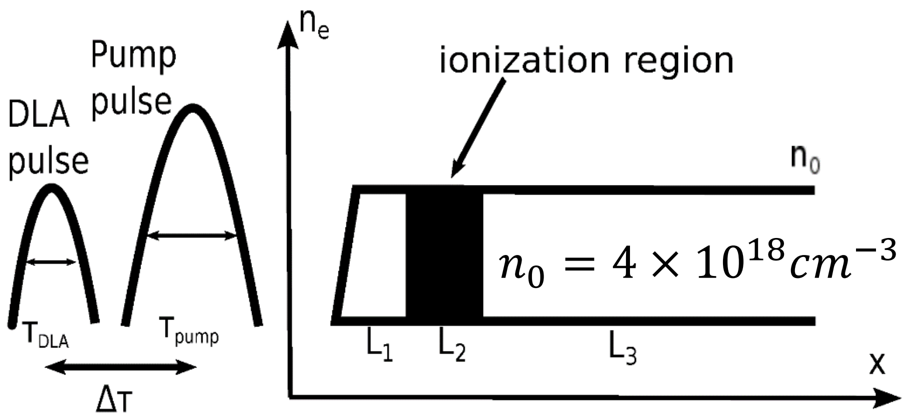
Strong bifurcation in $(\epsilon_\perp, \gamma)$ phase space

$$\frac{d\zeta}{d(ct)} \approx \frac{1}{2\gamma_b^2} - \frac{1 + \langle p_\perp^2/m_e^2c^2\rangle}{\gamma^2}$$

Synergy between DLA and LWFA → higher energy gain from the wake for the DLA population ← delayed dephasing!

DLA electrons gain extra 200 MeV from the wake and extra 400MeV from the laser (DLA)

DLA is compatible with ionization injection!



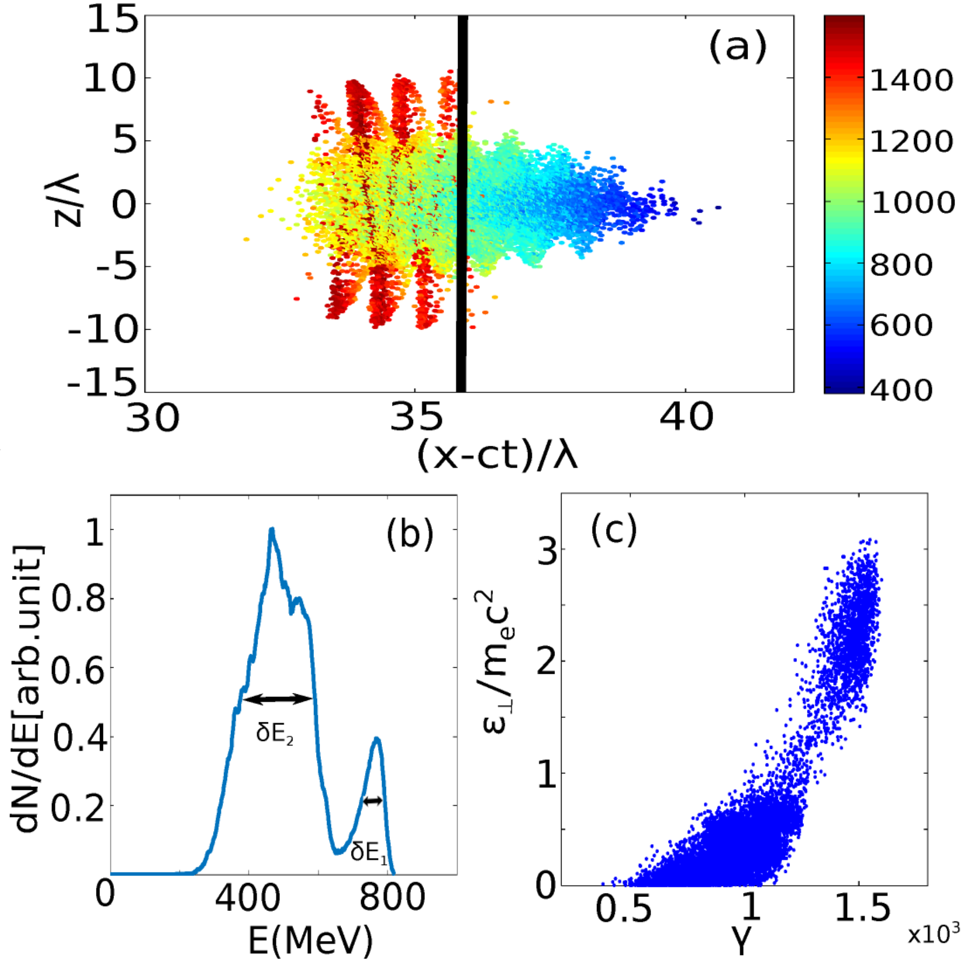
$$I_{\text{pump}} = 2.3 \times 10^{19} W/cm^2$$

$$I_{\text{DLA}} = I_{\text{pump}}/2$$

$$P_{\text{pump}} = 96\ TW$$

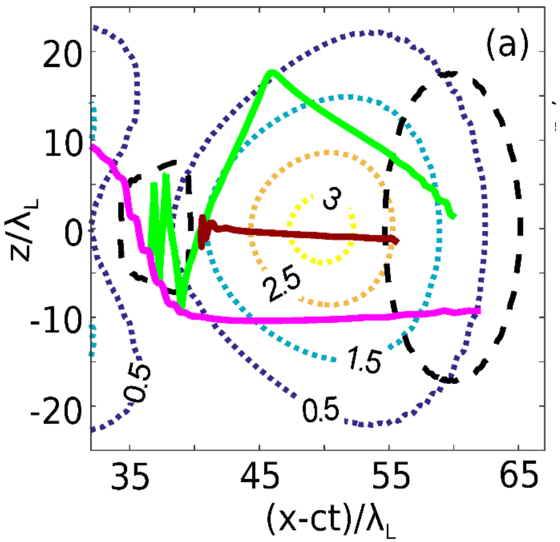
$$U_{\text{ion}} = 870 eV \rightarrow \text{from } O^{7+} \text{to } O^{8+}$$

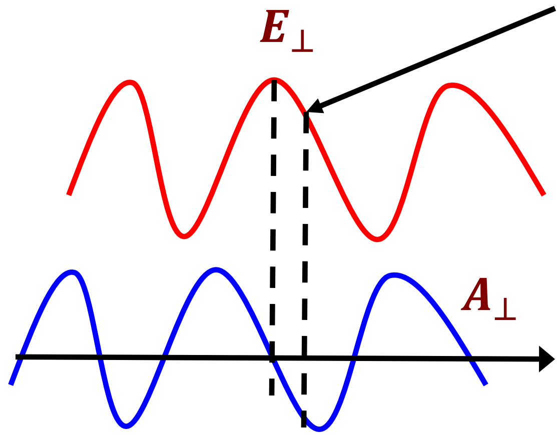
Electrons after 3mm



Off-axis or off-peak phase ionization produces DLA electrons!

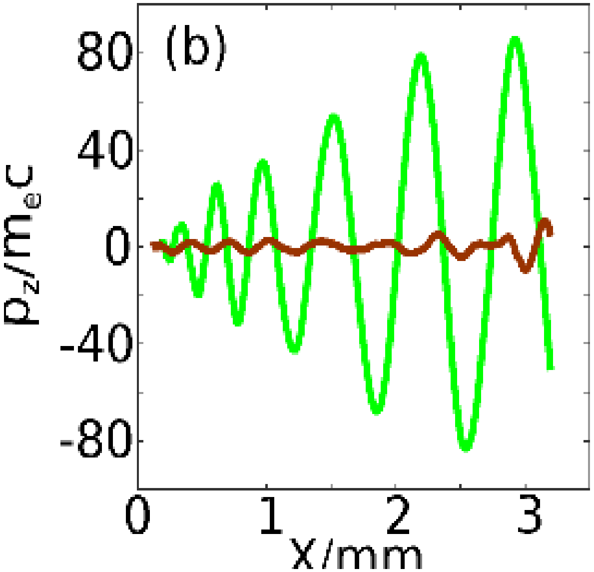
Off-peak phase ionization and "ricochet" DLA electrons: real atoms meet meta-atoms

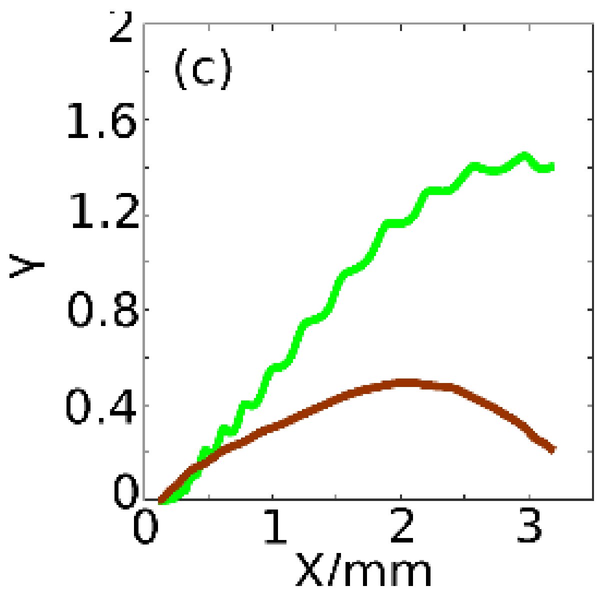




Off-peak ionization phase: electrons leave the laser pulse with finite transverse momentum

$$p_\perp + eA_\perp/c = eA_\perp(t_i)/c$$

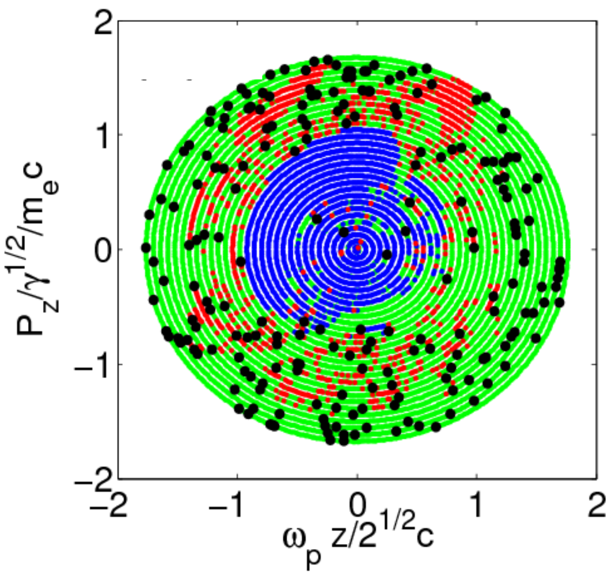


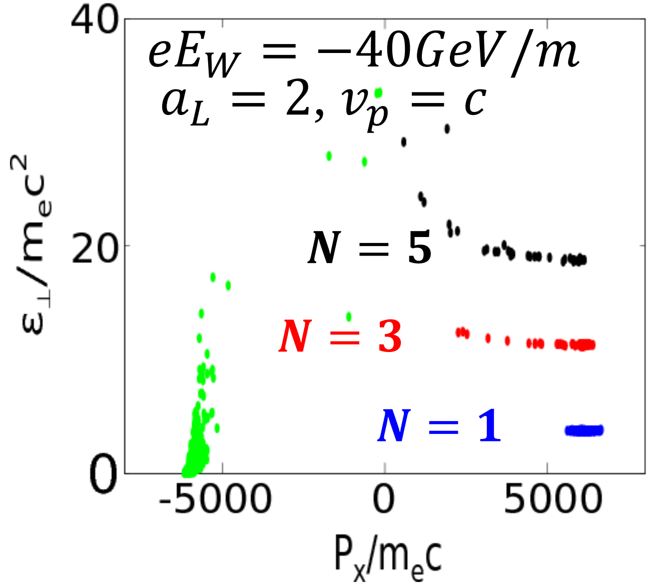


Ricochet electron starts out with large $p_\perp$, interacts with the DLA pulse → gains even larger $p_\perp$ and more energy

One Step Back, Two Steps Forward: Laser Wakefield Decelerator + DLA

Initial conditions

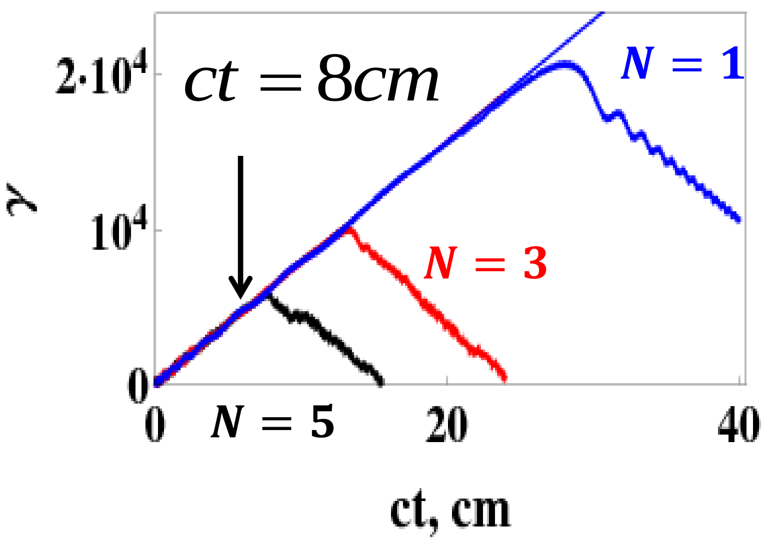


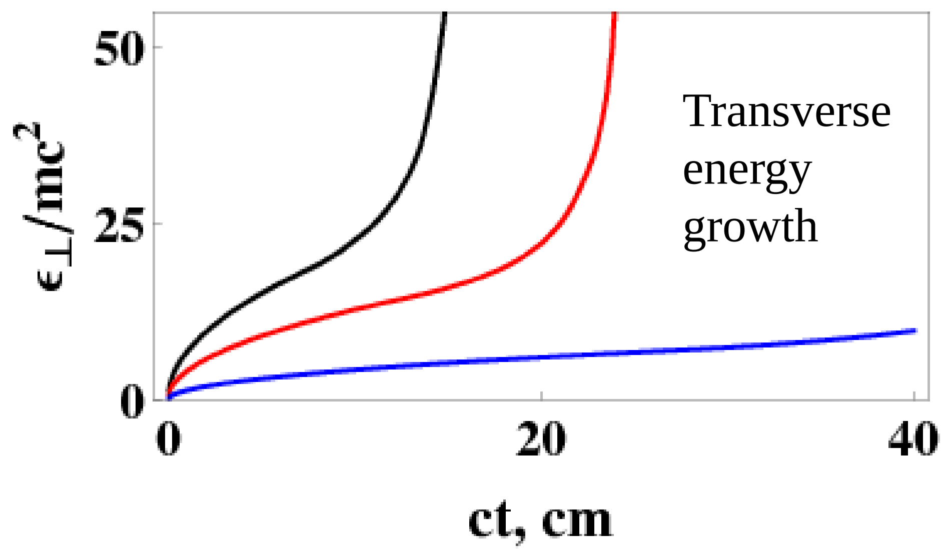


Model: constant <u>decelerating</u> field E_W

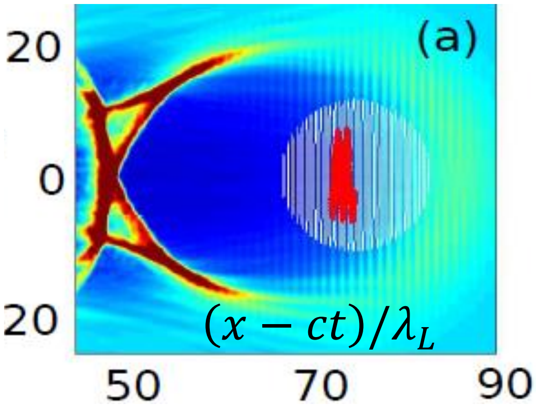
Multiple DLA harmonics:

$$\omega_L \frac{1 + \langle p_z^2/m^2c^2 \rangle}{2\gamma^2} = = N \frac{\omega_p}{\sqrt{2\gamma}}$$

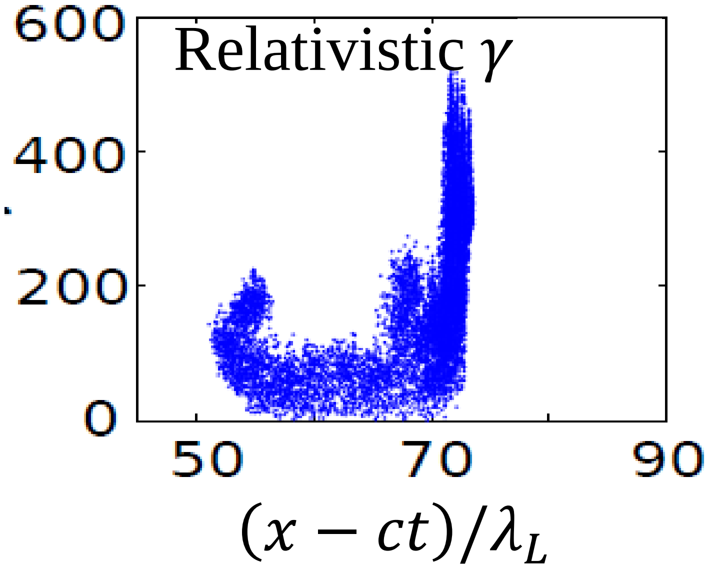


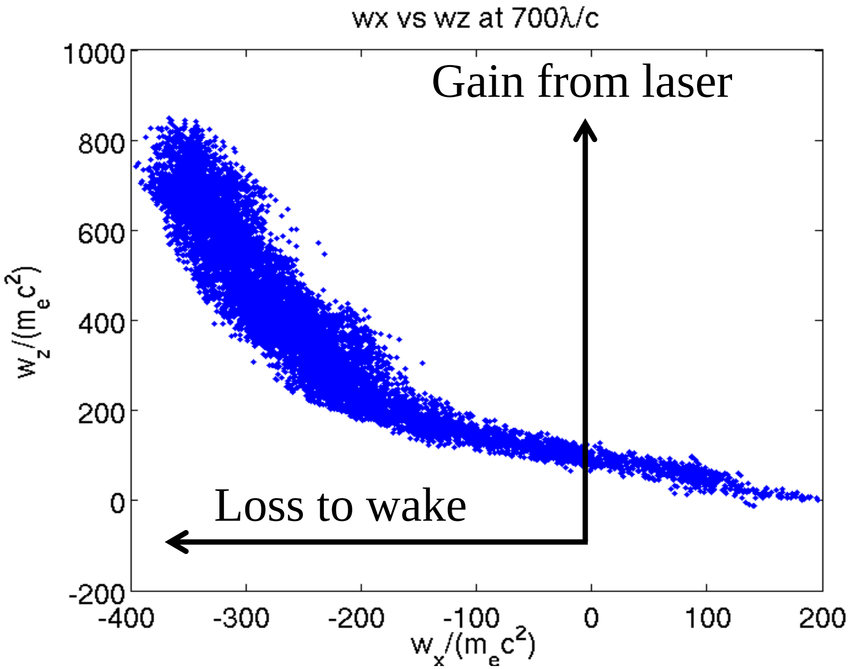


Who needs LWFA if DLA is so great?



$\lambda_1 = 0.8\mu m$ **pulse:**
$P_1 = 170$**TW** $(a_1 = 6)$
$\tau_1 = 35$**fs,** $w_1 = 12\mu$**m**
$n_0 = 4 \times 10^{18} cm^{-3}$
External injection into the decelerating phase
$p_{x0} = 25 m_e c$





The wake decelerates the electrons, but the DLA accelerates them at more than twice the deceleration rate!

The mix-and-match approach to LA: the case for combining near- and mid-IR lasers

- **Mid-IR lasers produce a large bubble $r_b \sim \lambda_p \sqrt{a_L}$ because less dense plasma is used → large-amplitude betatron oscillations are not a problem**
- **Vector potential $a_L \sim \lambda_L \sqrt{I_L}$ is large for modest laser intensity**
- **External electron injection into a large bubble is easy**
- **Unique opportunity for combining a mid-IR laser pulse (“work horse” that makes a bubble) with an ultra-short solid-state laser pulse (“surgical tool” that injects electrons, excites betatron oscillations, provides DLA)**

Electric field or vector potential?

Ponderomotive potential:

$$a_L^2 \sim \lambda_L^2 I_L$$

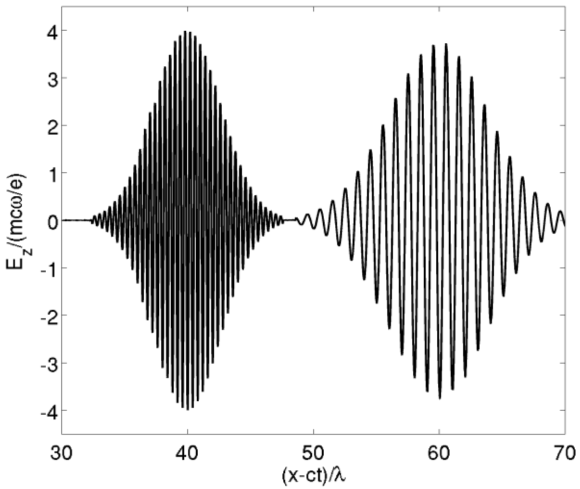
Ionization rate of neutral gasses:

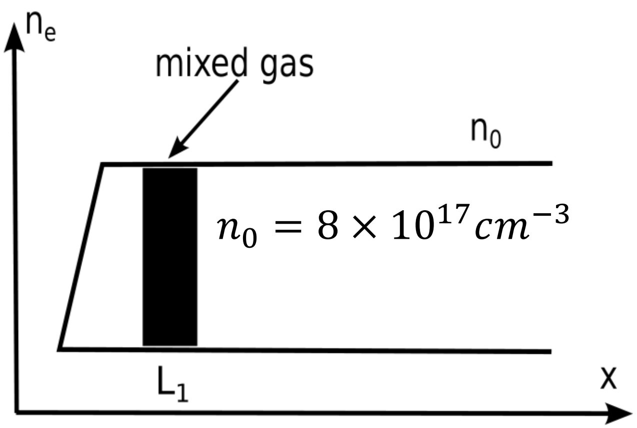
$$E_L \sim \sqrt{I_L}$$

Direct Laser Acceleration gradient:

$$\vec{E}_L \cdot \vec{v}_\beta \sim \sqrt{I_L}$$

Injection, LWFA, and DLA using a sequence of $2.0\mu m$ and a $0.8\mu m$ laser pulses



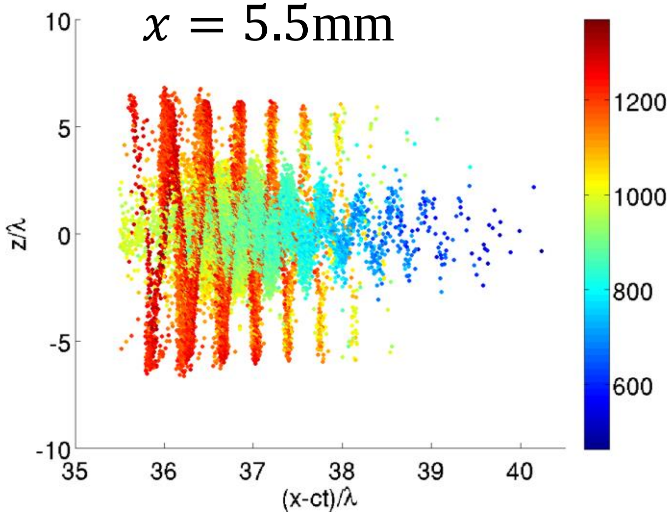


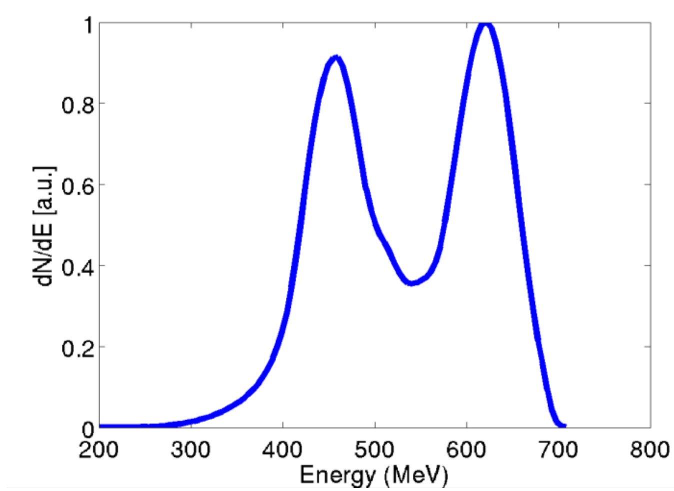
$\lambda_0 = 2\mu m$ pulse:
$P_0 = 65$TW ($a_0 = 3.7$)
$\tau_0 = 45$fs, $w_0 = 30\mu m$

$\lambda_1 = 0.8\mu m$ pulse:
$P_1 = 33$TW ($a_1 = 1.6$)
$\tau_1 = 30$fs, $w_1 = 20\mu m$

Time delay: $\Delta t = 120$fs

$x = 5.5$mm

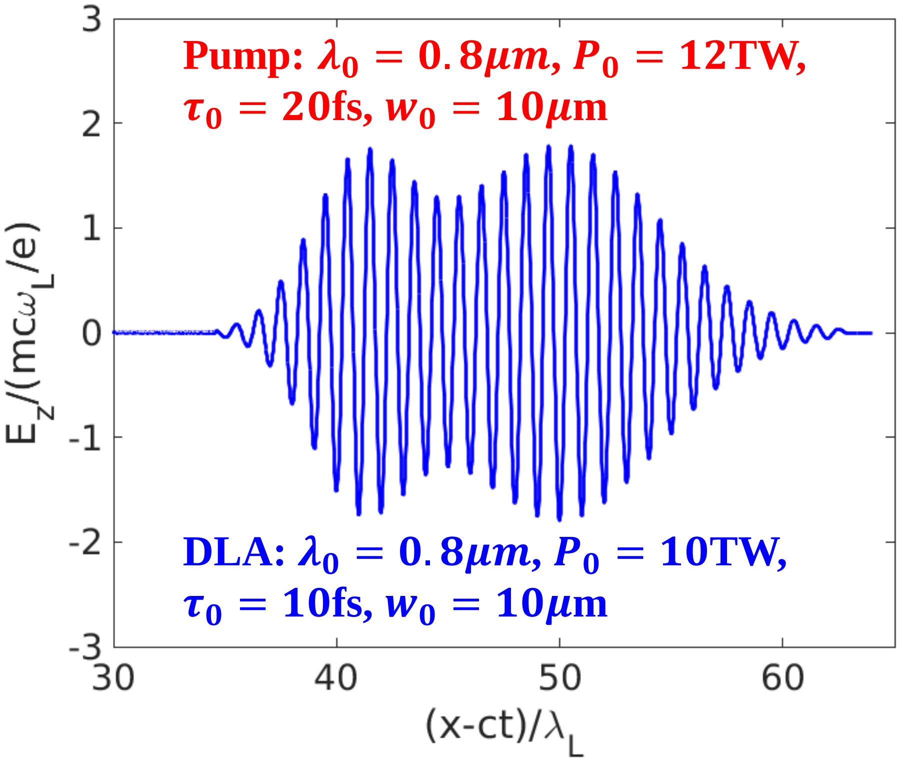


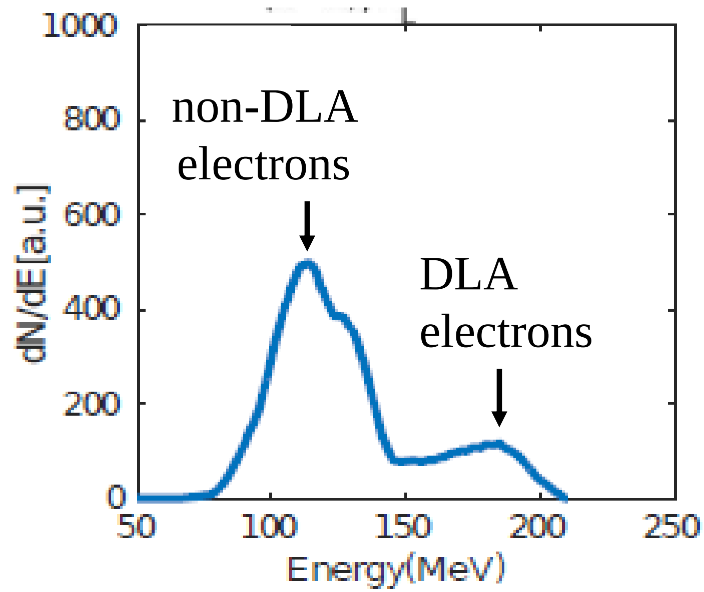


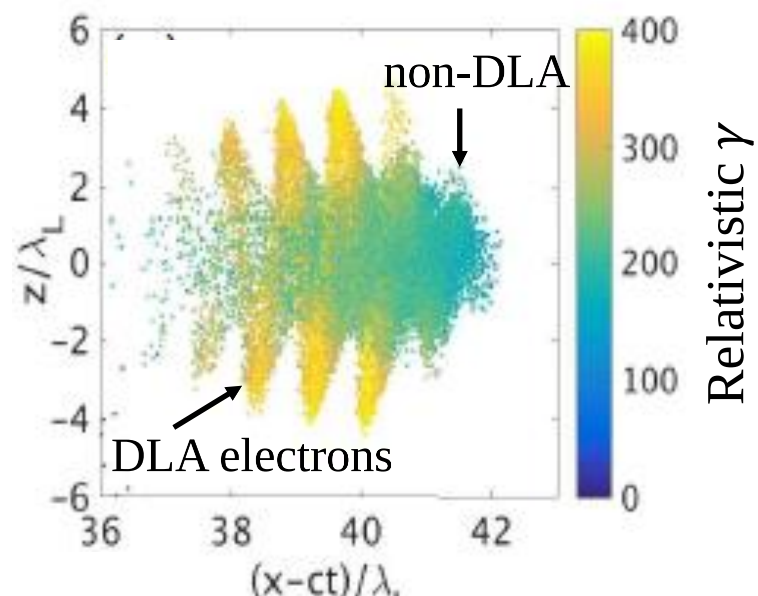
Electrons gain 400MeV from wake and 200MeV from $\lambda = 0.8\mu m$ laser: 1st harmonic DLA

$$\omega_L(1 - v_z/v_p) = \omega_\beta$$

DLA on a budged: 10 TW-scale laser systems







Large number of DLA electrons can be observed at much lower laser powers and higher plasma densities ($n_0 = 1.5 \times 10^{19} cm^{-3}$)

Time delay: $\Delta\tau = 24fs$

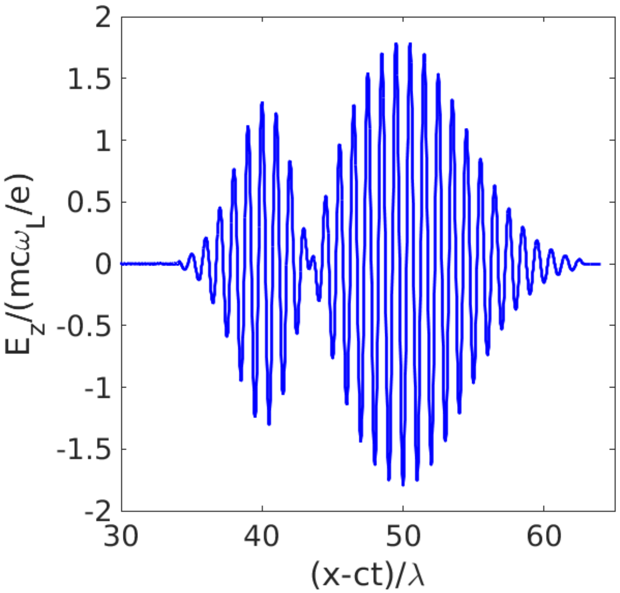
Problem: time delay jitter!

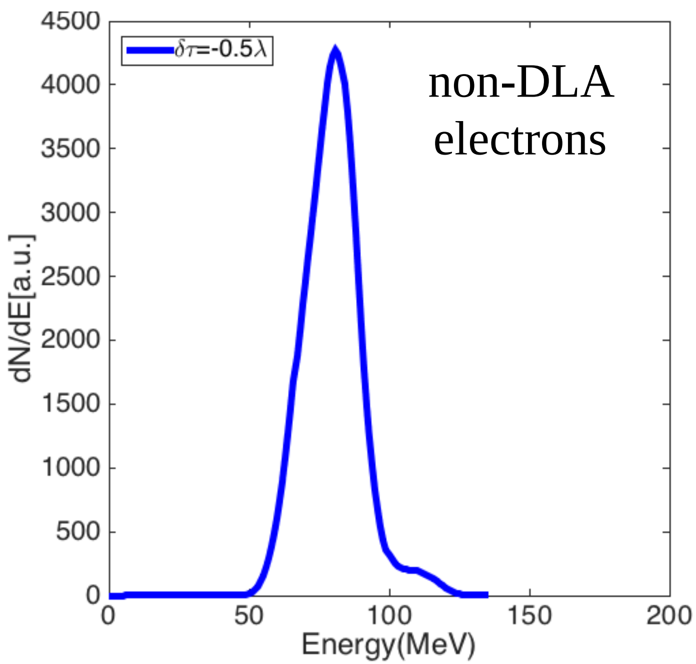
Sensitivity to the time delay jitter

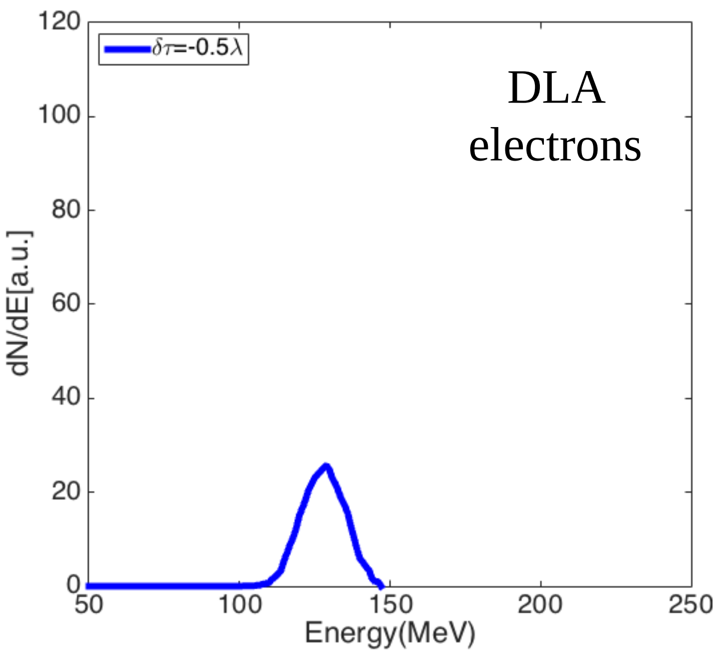
Destructive interference: $\delta\tau = -\lambda/2c$

The bubble is not distorted → large number of trapped non-DLA electrons

Few DLA electrons





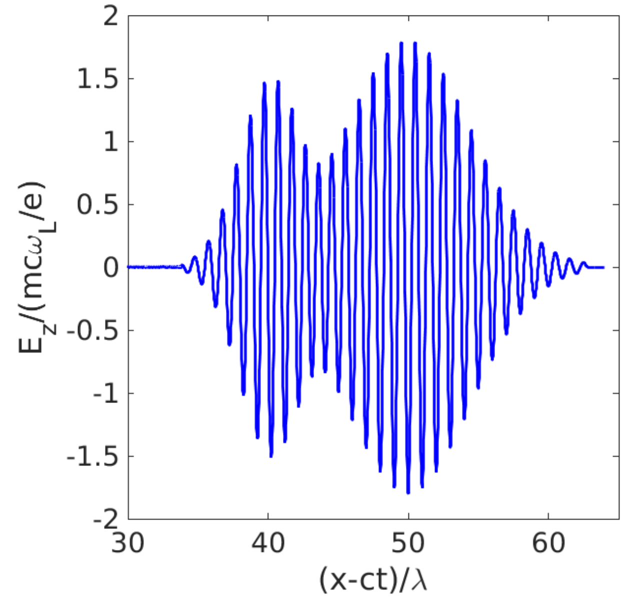


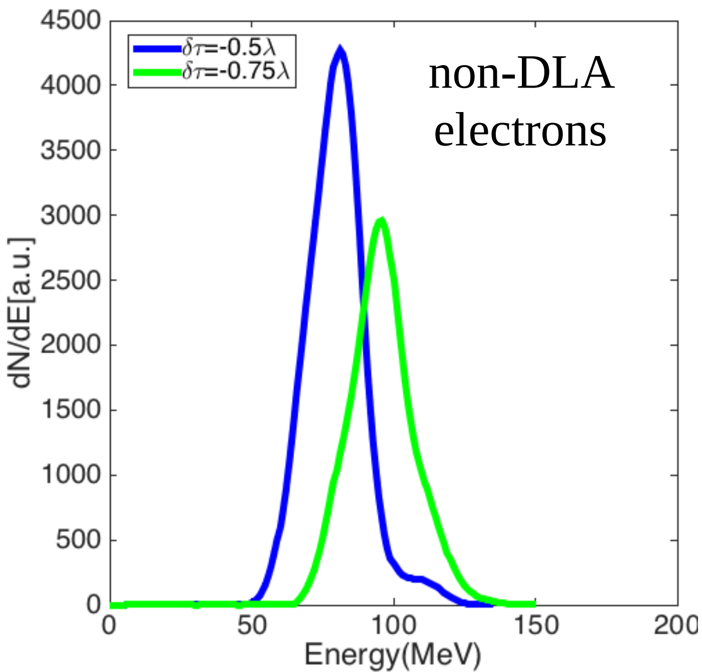
Sensitivity to the time delay jitter

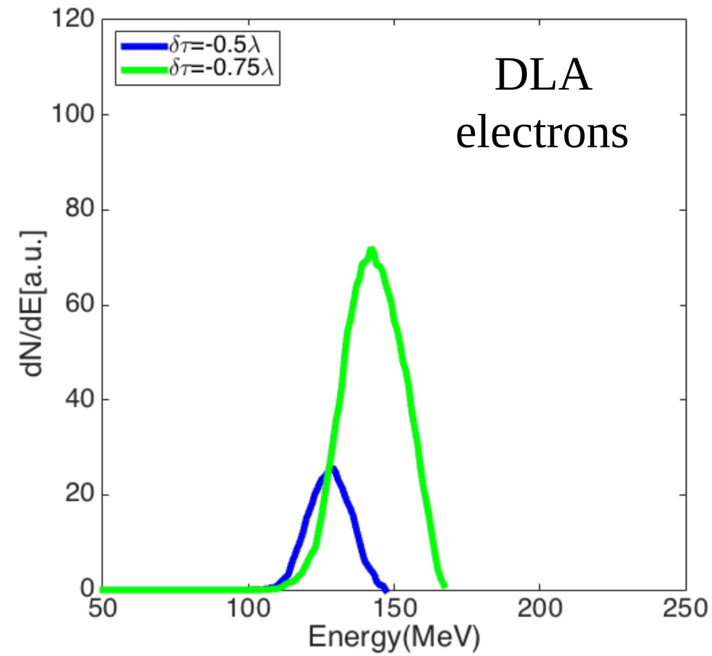
"Average" interference: $\delta\tau = -3\lambda/4c$

The bubble is slightly distorted → smaller number of trapped non-DLA electrons

More DLA electrons





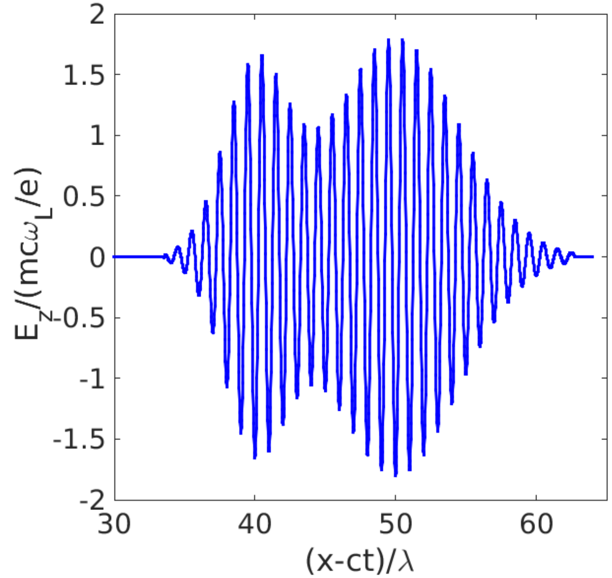


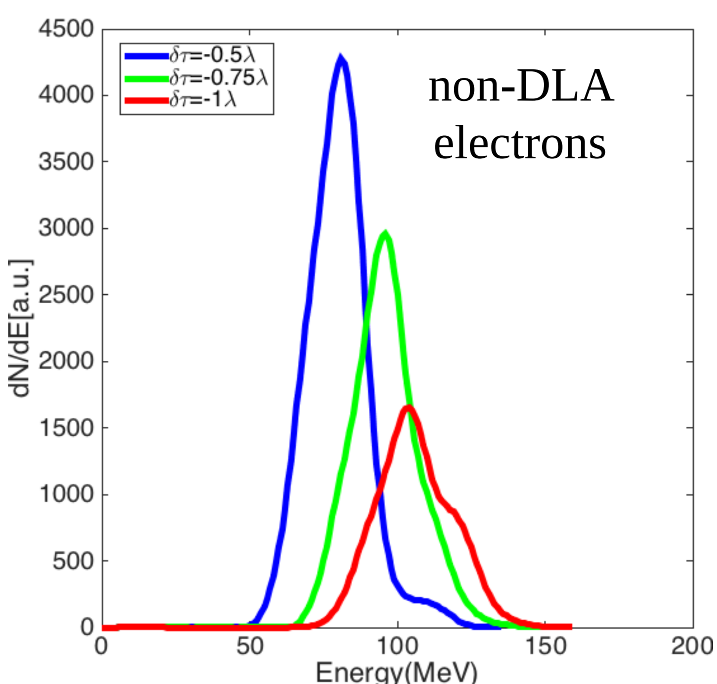
Sensitivity to the time delay jitter

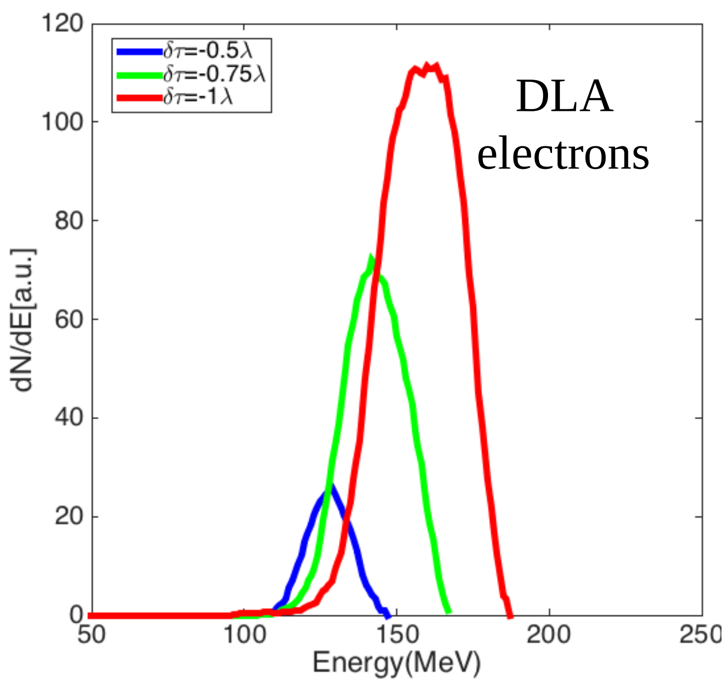
Constructive interference: $\delta\tau = -\lambda/c$

The bubble is strongly distorted → small number of trapped non-DLA electrons

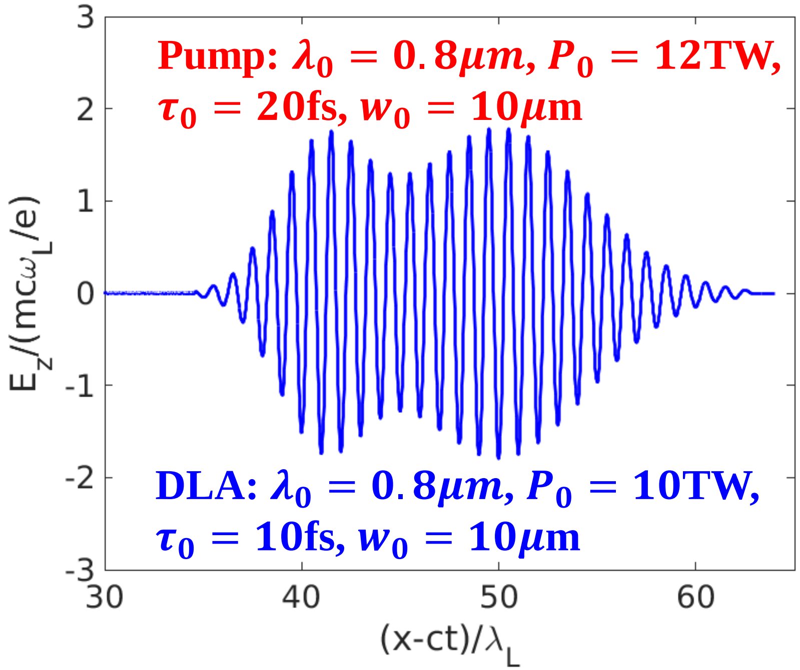
Many more DLA electrons

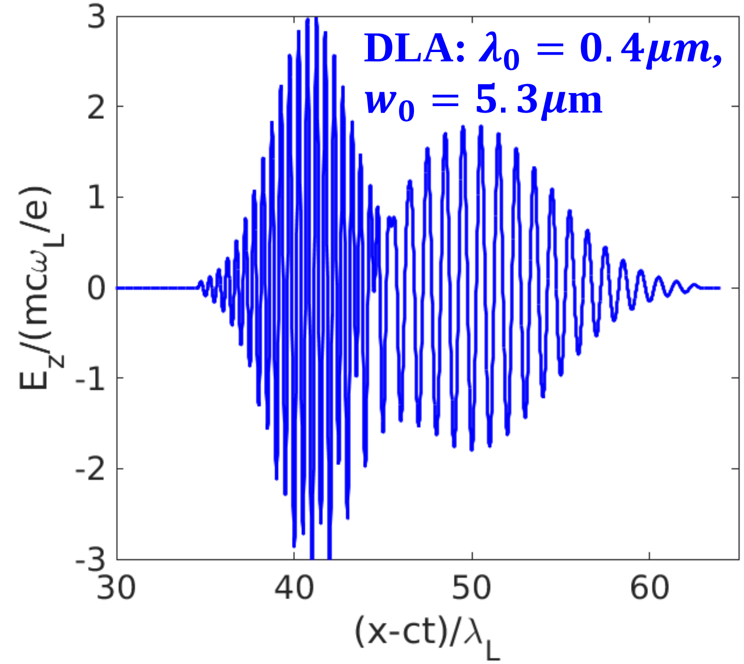


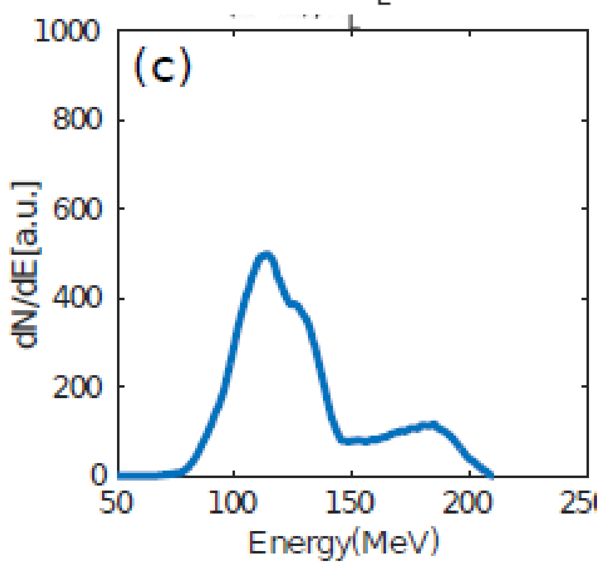




Frequency doubling of the DLA pulse

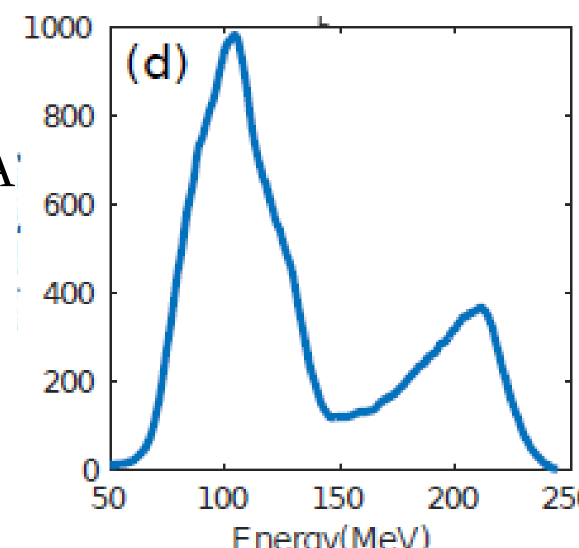






Reduced λ: no bubble distortion → improved DLA and non-DLA electron yields

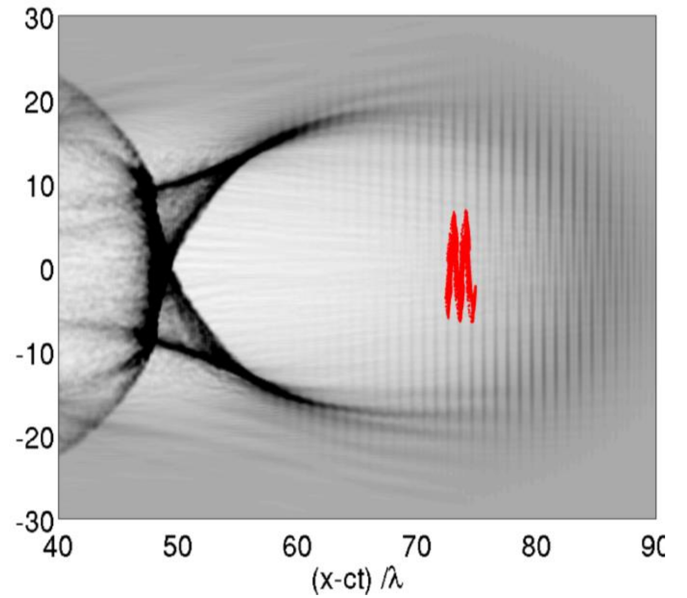
No interference → reduced jitter sensitivity

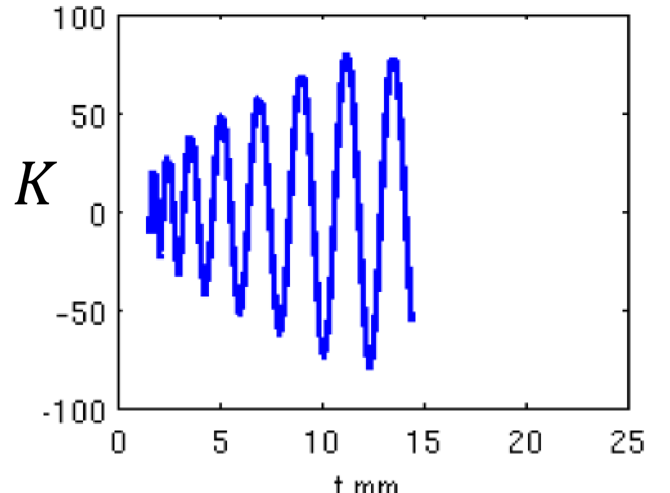


How the entire LPA paradigm may be changed by Direct Laser Acceleration

- Synchronization of externally injected beam is the key to injecting into the decelerating phase
- The main role of the bubble is not accelerate but to provide focusing field to undulating electrons
- Excellent source of X-ray and Gamma-ray radiation because of the large undulator parameter $K = p_{\perp}/mc$

$$\omega_c \sim 2\gamma^2 \omega_\beta \frac{K^3}{1+K^2} \sim K^3 \omega_L$$





Conclusions and Outlook

- The synergy between DLA and LWFA acceleration mechanisms can be realized using novel pulse formats (e.g. trailing bump, near-IR laser trailing a mid-IR laser, etc.)

- New physics: delayed dephasing due to electrons' betatron motion → electrons advance slowly inside the bubble

- Side-injection maximizing transverse electron momentum can be realized using a sharp density bump or ionization injection

- Unique acceleration opportunities for externally injected electrons → Constant Gradient Direct Laser Acceleration by injecting into the decelerating phase of the bubble