Prospects of laser wakefield electron accelerator - mechanisms, specifications, and potential applications

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National Central University

Courtesy of DESY/Science Communication Lab

Topics

- Mechanism of laser wakefield accelerator
- Properties of laser wakefield electron beams
- Current development
- Application
  - X-ray generation
  - Particle collider
  - Cancer therapy

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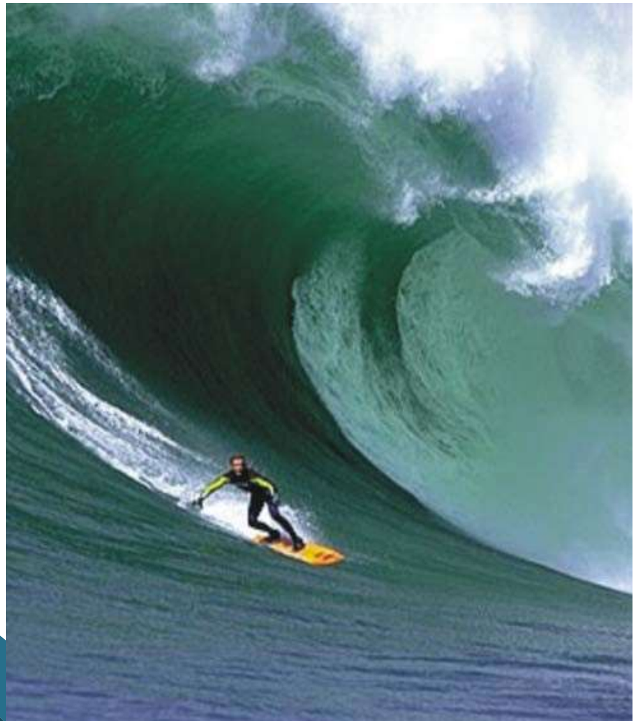
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson
Department of Physics, University of California, Los Angeles, California 90024
(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density 10^{18}W/cm^2 shone on plasmas of densities 10^{18} cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



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Classical RF accelerators v.s. plasma

Maximal accelerating fields due to breakdown:

E_{max}=20MV/m

10-30km long accelerators to generate TeV

expensive

In plasmas there is no breakdown ! much higher accelerating fields in plasma density oscillations – plasma waves

E=100GV/m - 1TV/m 10^3-10^4 x higher fields than in RF acceler

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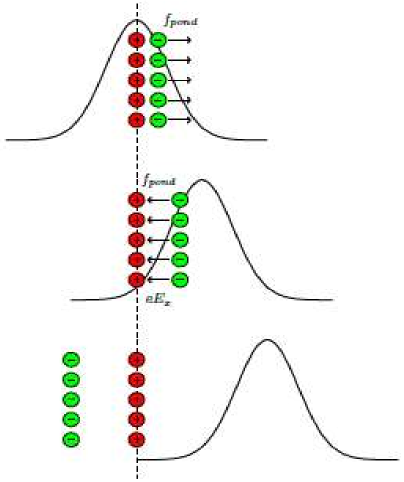
Generation of Wakefield



Laser energy ➡ Plasma Wave

Plasma Wave ➡ Electrons

Plasmas can support large Electrostatic fields of 100 GV/m for $n_e = 10^{18} cm^{-3}$

Quiver motion:

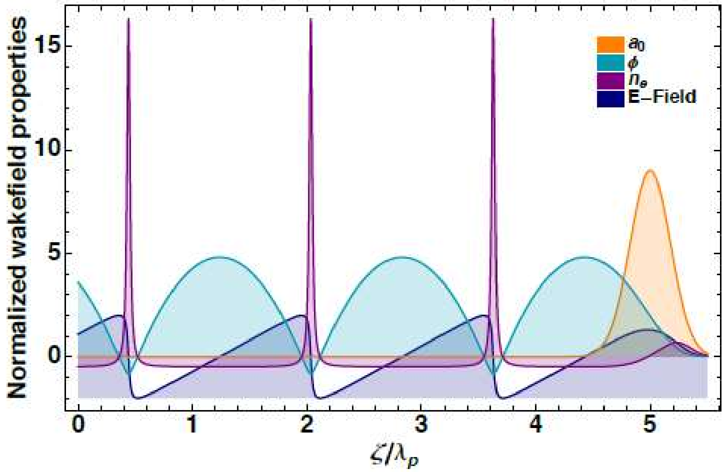
$$a_0 = \frac{eE}{m\omega c} = 1 \Leftrightarrow I = 10^{18} W cm^{-2}$$

Ponderomotive force:

$$< F^{(2)}\ (r,t) >= -\frac{1}{4}\frac{e^2}{m\omega^2} \nabla\, E(r,t)^2$$

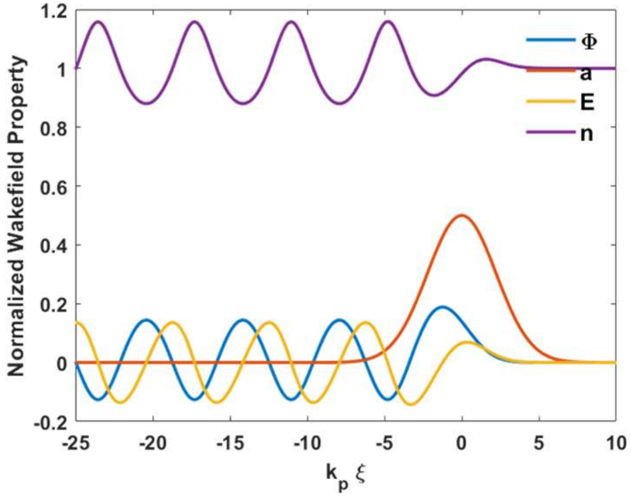
Resonant Excitation:

$$c\tau_{pulse} \approx \frac{\lambda_p}{2} = \frac{\pi c}{\omega_p} \sim \frac{1.7 \times 10^{10}}{\sqrt{n_e}}$$

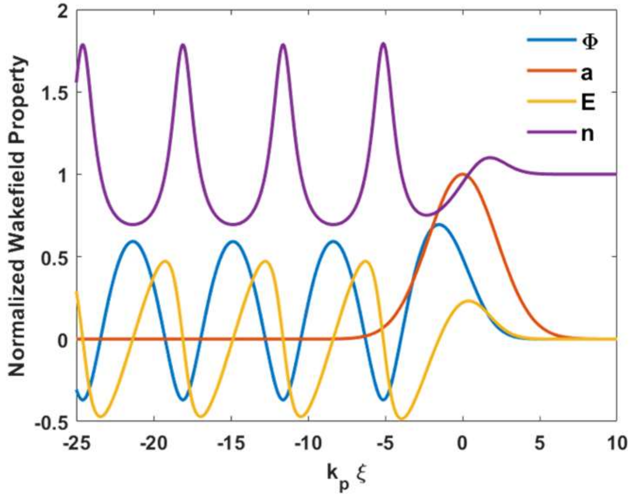


1D description, linear and non-linear plasma waves

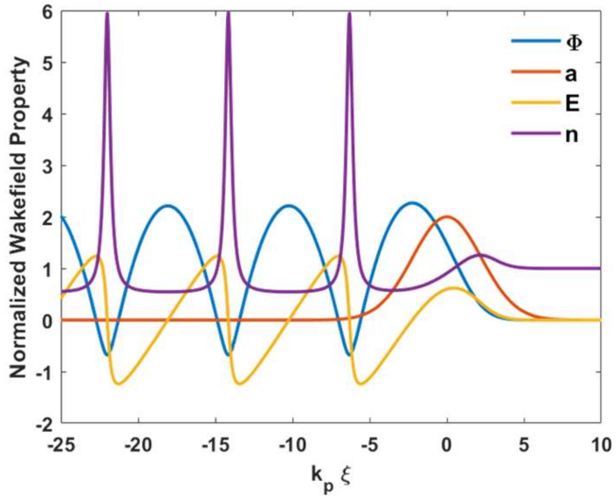
$a_0 = 0.5$



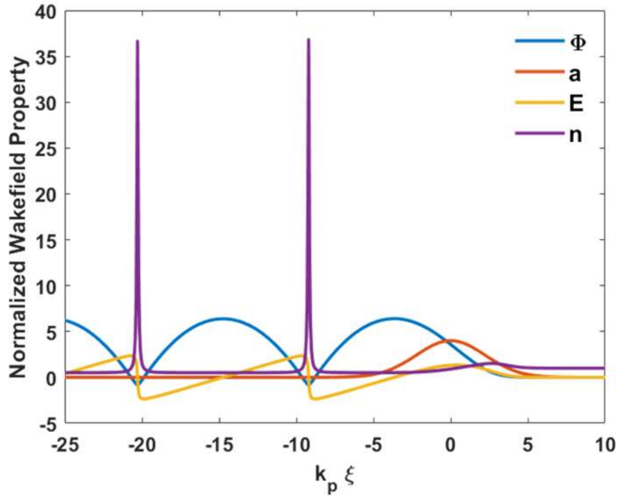
$a_0 = 1$



$a_0 = 2$



$a_0 = 4$



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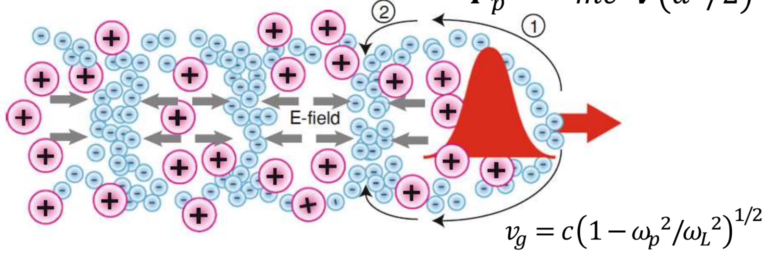
Wakefield excitation

T. Tajima & J.M. Dawson, Phys. Rev. Letter 43, 267 (1979)

Laser field (vector potential a)



1-D linear approximation $a^2 \ll 1$ $\xi = z - ct$

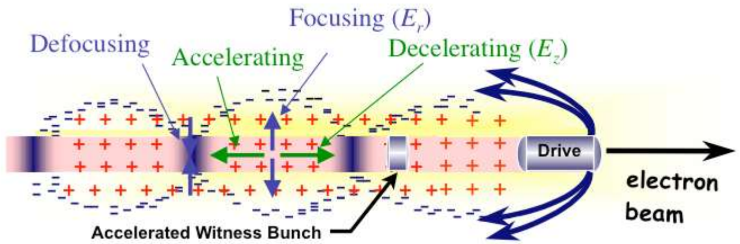
$$\underbrace{\left(\frac{\partial^2}{\partial\xi^2} + k_p^2\right)\frac{\delta n}{n_0}}_{\text{Plasma wave forced density oscillation}} = \nabla^2 \underbrace{\frac{a^2(\xi)}{2}}_{\text{Ponderomotive Force}}$$

1. ***The ponderomotive force (gradient of laser intensity) pushes electrons away from axis and generates a charge separation between ions and electrons***
2. ***The restoring force initiates a local density oscillation with frequency*** $\omega_p = (4\pi e^2 n_0/m_e)^{1/2}$

$$\text{vector potential } a_0 = \frac{eA}{mc} = 0.854\sqrt{I_{0\,[10^{18}\,W/cm^2]}} \cdot \lambda_{[\mu m]}$$

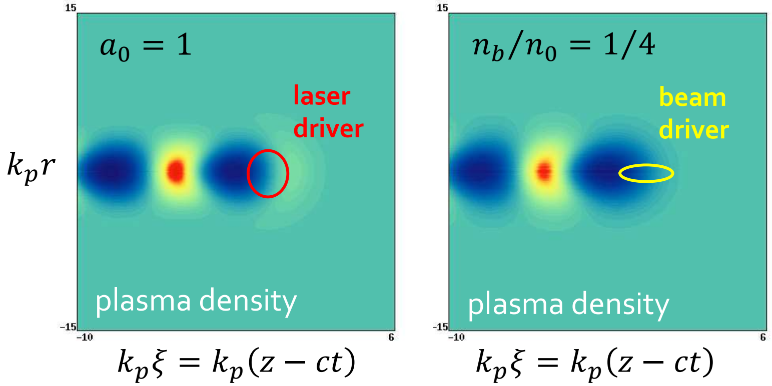
$$\text{wave number } k_p = \omega_p/c$$

Particle beam field



1-D linear approximation $n_b/n_0 \ll 1$

$$\left(\frac{\partial^2}{\partial\xi^2} + k_p^2\right)\frac{\delta n}{n_0} = -\underbrace{k_p{}^2\frac{n_b}{n_0}}_{\text{Space charge force}}$$



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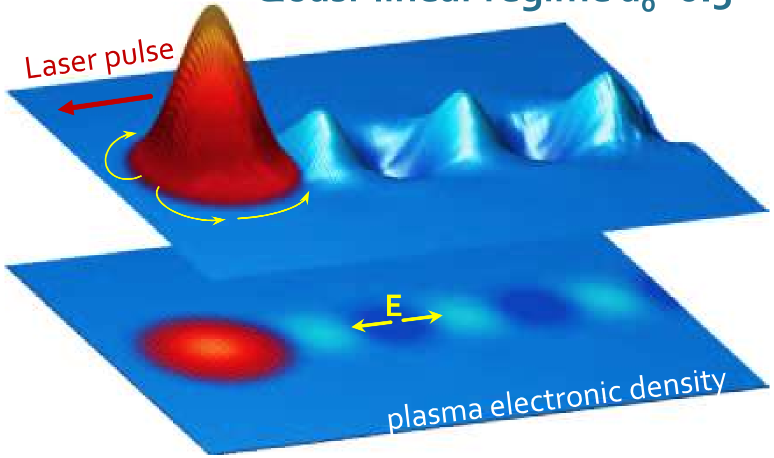
Characteristic scales of LPA

Quasi-linear regime a_0=0.5



➢ Plasma wavelength

$$\lambda_p \approx \mathbf{33\ \mu m} \,/\sqrt{n_{0\,(10^{18} cm^{-3})}}$$

- for ~ 10^{18} cm^{-3} → λ_p ~ 30 µm
- LPA produce ultrashort bunches

➢ Accelerating field

assumption: in linear regime, all electrons oscillate at ω_p

$$E_0 = m_0 c \omega_p / e \approx \mathbf{96\ GV/m} \cdot \sqrt{n_{0\,(10^{18} cm^{-3})}}$$

- for ~ 10^{18} cm^{-3} → E_0 ~ 100 GV/m
- Accelerating gradients several orders of magnitude larger than conventional RF cavities

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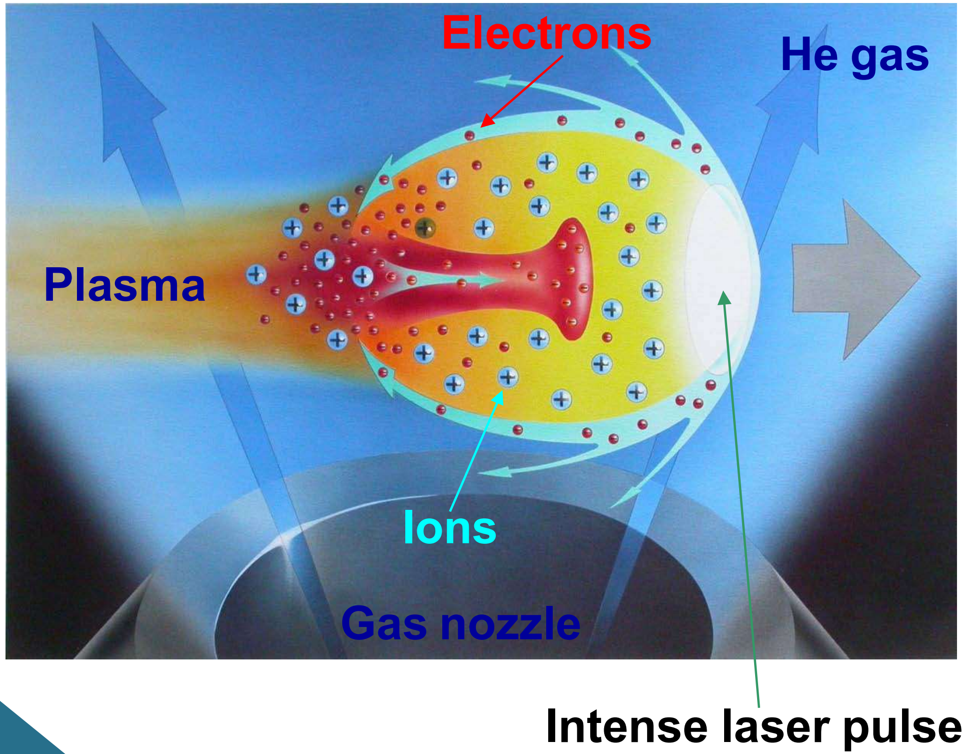
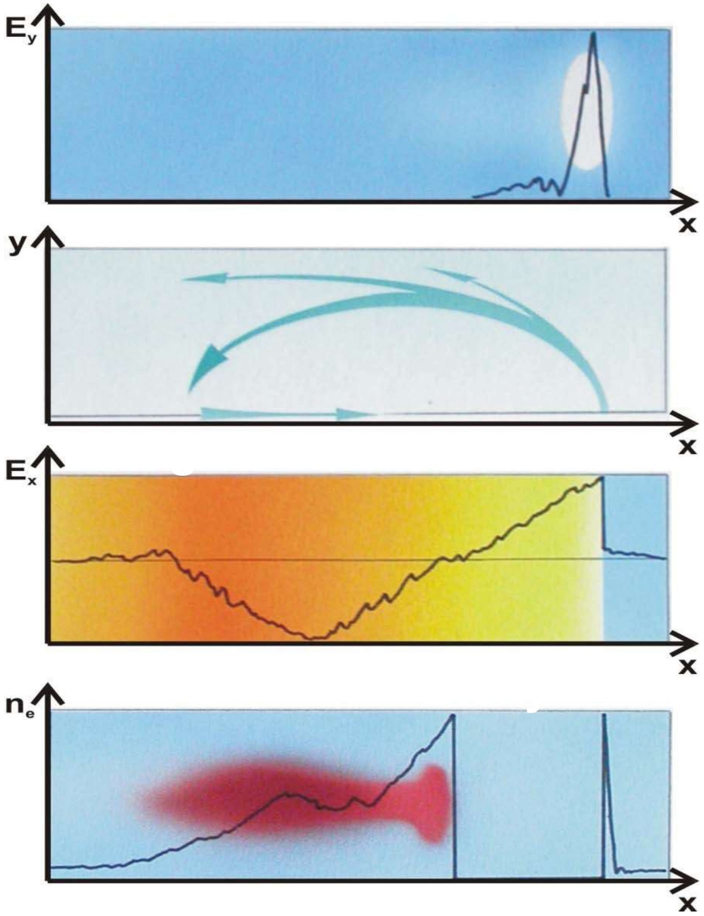
„Bubble acceleration“ principle





Pukhov & Meyer-ter-Vehn, Appl. Phys. B 74, 355 (2002)

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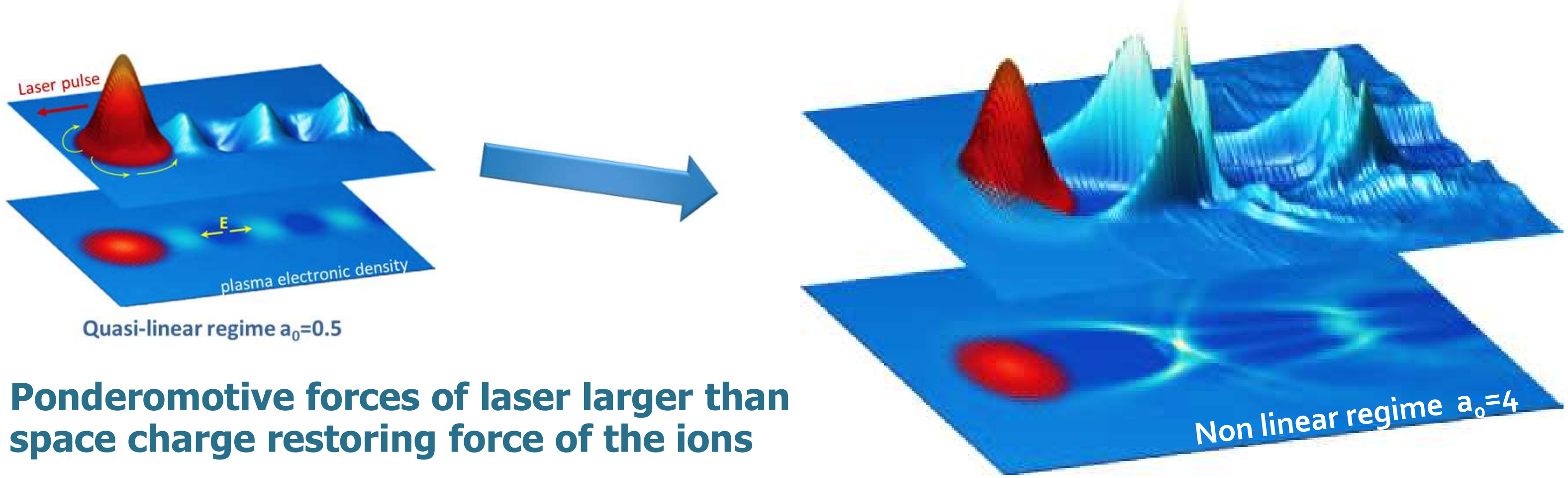
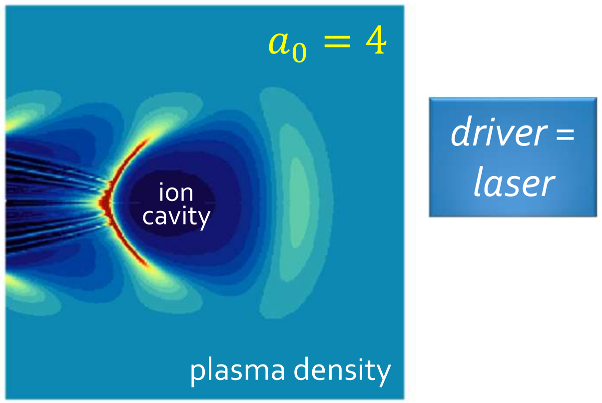
3D non-linear regime (bubble regime)

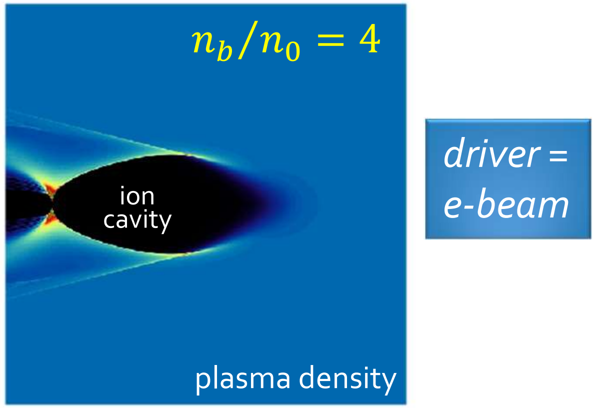


- **Ponderomotive forces of laser larger than space charge restoring force of the ions**

⇒ All electrons of the plasma are expelled

⇒ ionic cavity ⇒ linear fields





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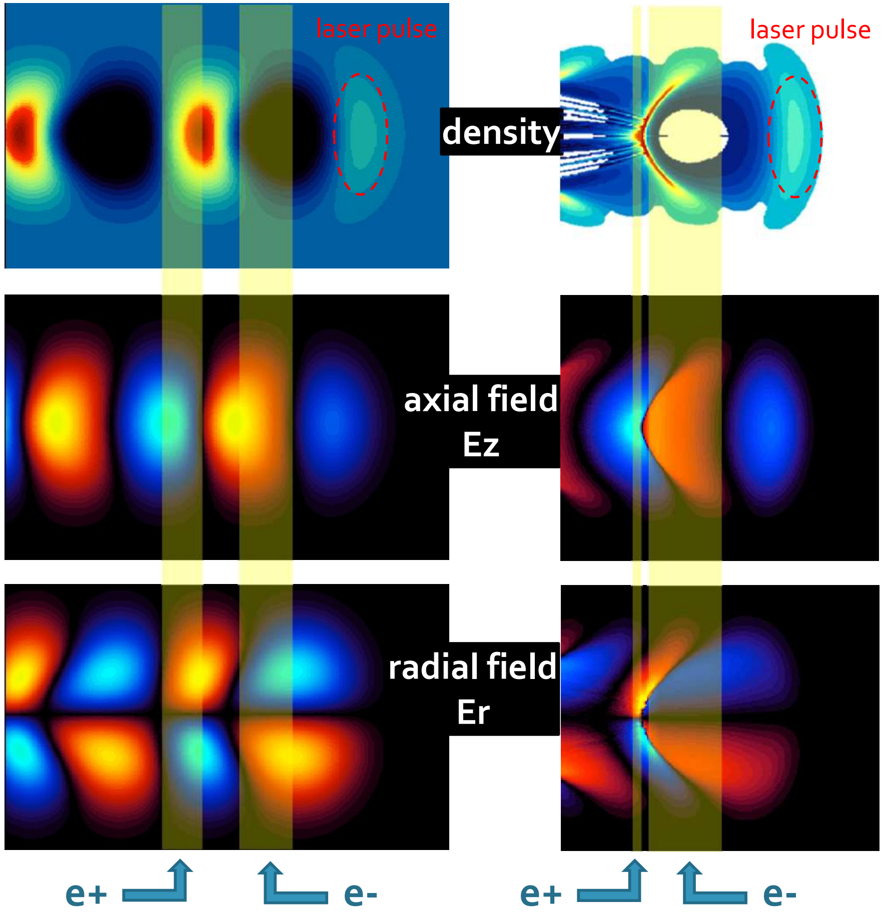
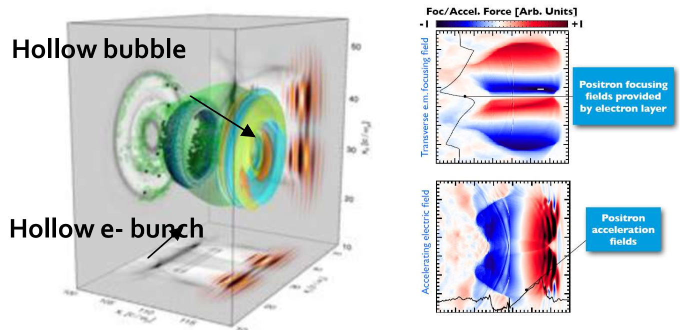
Useable phase range (accelerating & focusing)

Quasi linear regime $a_0 \sim 1$ Non linear regime $a_0 \geq 4$



- ❑ **Quasi linear regime**
  quasi-symmetric ranges of useable phases
- ❑ **Bubble regime**
  very asymmetric regions
  - focusing for e-
  - defocusing for e+
- ❑ **Ideas for e^+ focusing**
  - Combine multiple laser modes
  - Use of orbital angular momentum lasers (OAM) to drive doughnut wakefields



J. Vieira and J.T. Mendonça, PRL 112, 215001 (2014)

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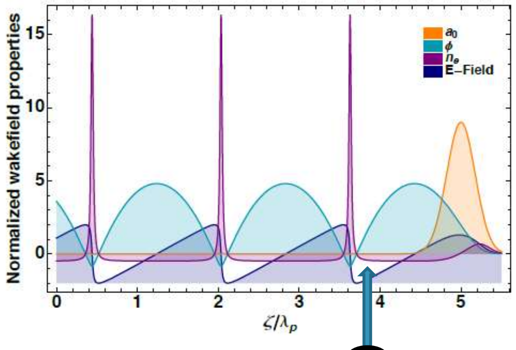
Injection in Wakefield

$a_0 \sim 1$

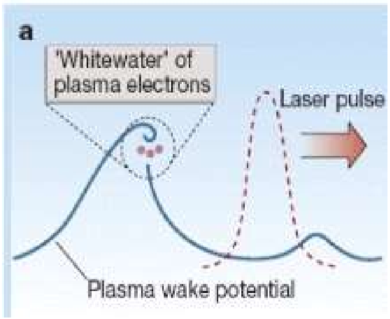
$c\tau_{pulse} \sim \lambda_p$



External Injection

$a_0 > 1$

$c\tau_{pulse} \sim \lambda_p$



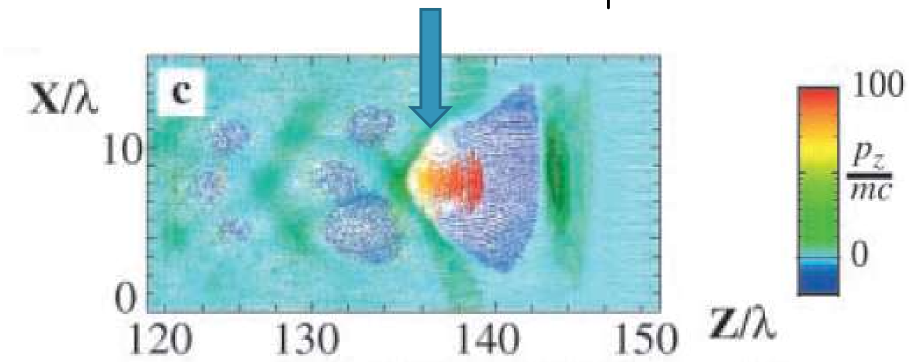
Wavebreaking

Self-injection

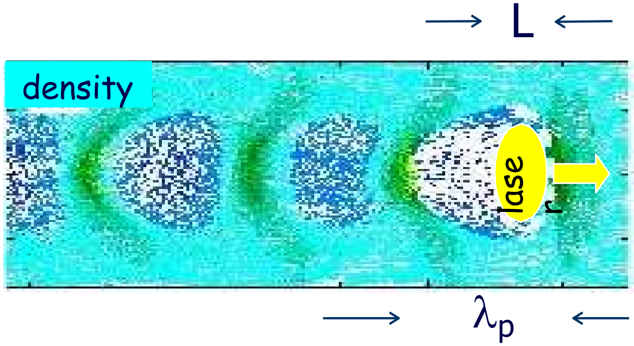
$a_0 \gg 1$

$c\tau_{pulse} < \lambda_p$

Wave breaks at first oscillation. No plasma wave



Phase velocity and γ_{ph} of laser wakefield



Short laser pulse
($L < \lambda_p = 2\pi c / \omega_p$)
excites plasma wave with large amplitude.

Light in plasma (linear approximation)

$$\omega_{Laser}^2 = \omega_p^2 + c^2 k_{Laser}^2$$

$$v_{\text{group}}^{\text{laser}} = \frac{d\omega_L}{dk_L} = c\sqrt{1 - \omega_p^2/\omega_L^2} \equiv v_{\text{phase}}^{\text{plasma}}$$

$$\gamma_{ph} = 1/\sqrt{1 - v_{ph}^2/c^2} = \omega_L/\omega_p = \sqrt{n_{\text{crit}}/n_e}$$

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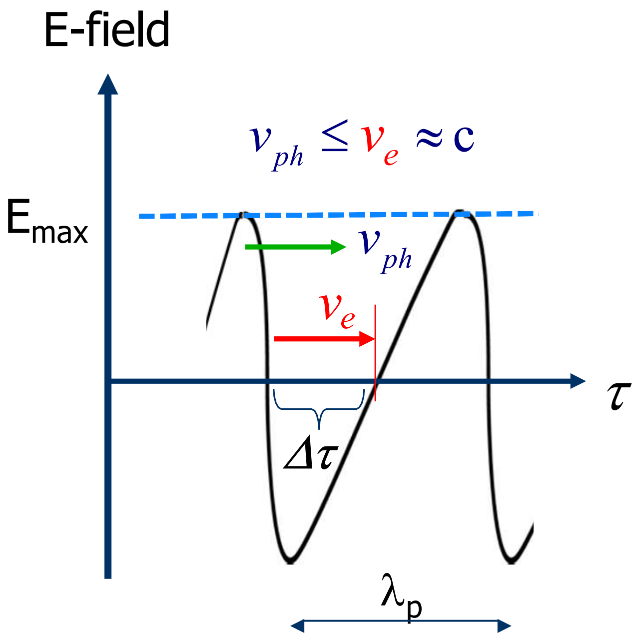
Dephasing length



Acceleration phase

$$\Delta\tau = \left|\omega_p (\Delta t - \Delta x / v_{ph})\right| = \pi$$

$T_d \cong L_d / c$ — Time between injection and dephasing

L_d — Dephasing length

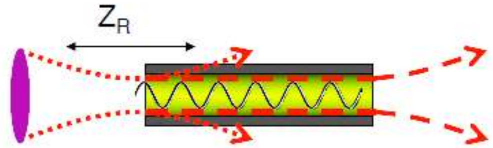
$$L_d = \frac{\pi/\omega_p}{(1/v_{ph} - 1/c)} \approx \frac{\pi/\omega_p \cdot 2c}{1 - v_{ph}^2/c^2} \approx \lambda_p \gamma_{ph}^2$$

Estimate of maximum particle energy

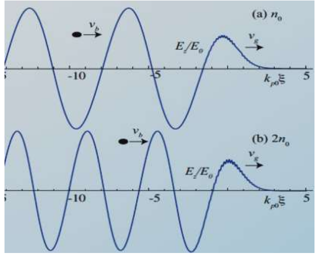
$$W_{max} \approx E_{max} L_d \approx \gamma_{ph}^2 (E_{max} \lambda_p)$$

Energy gain limitations

- ❑ Laser **Diffraction** ~ Rayleigh range
  - Controlled by relativistic self-guiding, pre-formed plasma channel, capillary guiding…



- ❑ Beam – plasma wave **Dephasing** $(v_p < v_{e-})$ $\quad L_{max} \propto n_0^{-3/2}$
  - Controlled by density tapering $\quad n_0 \nearrow \Rightarrow \lambda_p \searrow$

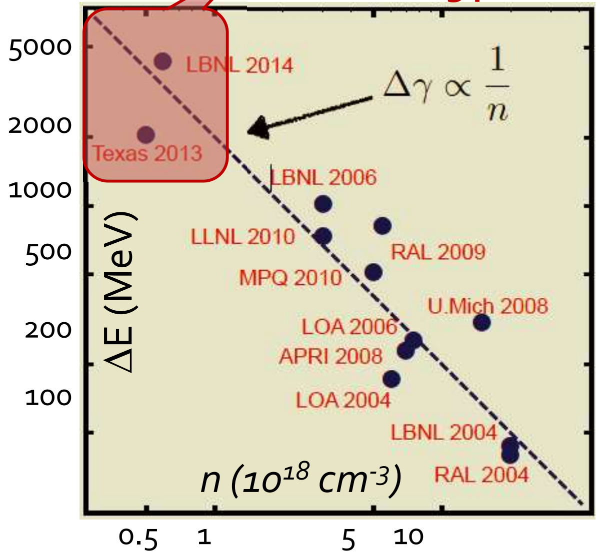


- ❑ Laser energy **Depletion** $\quad L_{deplete} \propto \lambda_p{}^3/\lambda_L{}^2 \propto n_0^{-3/2}$
  - Laser energy deposition into wave excitation

- ❖ Accelerating Gradient $\quad G \sim E_0 = mc\omega_p/e \propto \sqrt{n_0}$
- ❖ Energy Gain $\quad \boldsymbol{W = G \times L_{acc} \propto 1/n_0}$
- ❖ Laser peak power $\quad \boldsymbol{P_{laser} \propto 1/n_0}$

To increase the energy gain in a plasma module
Decrease the density and increase the laser power

PW level
1-10 cm long plasma



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Energy Limitations

- Electron energy gain $= L_{acc} \times E_{acc}$
- Diffraction (b) $\quad b = 2Z_R = \frac{2\pi\omega_0^2}{\lambda}$ $\quad \boldsymbol{b \approx 230\ \mu\mathrm{m}}$
- Depletion (L_{DP}) $\quad E_{plasma}^2 L_{dp} = E_{Laser}^2 L$

$$L_{dp} \propto \frac{\lambda_p^3}{\lambda_0^2} \begin{cases} 2a_0^{-2}; & a_0 \ll 1 \\ 1; & a_0 \gg 1 \end{cases}$$

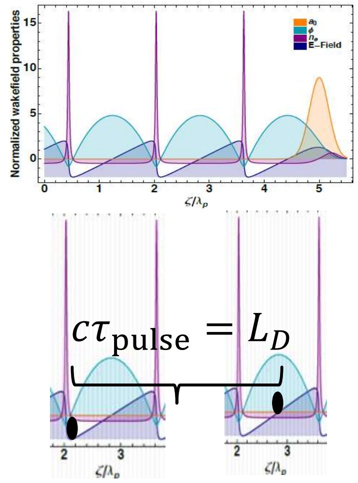
$\boldsymbol{L_{dp} \approx 80\ \mu\mathrm{m}}$

- Electron dephasing (L_D) $\quad L_D \sim \frac{\lambda_p^3}{\lambda_L^2} \propto \tau_{pulse}^3$

Depends on the pulse duration
$(c\tau_{pulse} = \lambda_p/2)$

5 fs $\rightarrow n_e = 8x10^{19} \rightarrow$ $\boldsymbol{L_D \approx 80\ \mu\mathrm{m}}$

26 fs $\rightarrow n_e = 5x10^{18} \rightarrow$ $\boldsymbol{L_D \approx 5\ \mathrm{mm}}$



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Injection mechanisms

- **Injector is of prime importance**
  - Determines the performances of the overall accelerator : charge, energy spread, emittance
- **Better to decouple the injection mechanism from the acceleration mechanism**
  - Indivudual adjustment of parameters, stability, control
- **External injection**
  - Fine definition of beams delivered by conventional photo-injectors
  - Issues: to achieve an ultra-short bunch $< \lambda_p/4 \sim 10\mu m$ (30 fs)
    possible solution : longer bunch injection, further self-compressed and accelerated in the plasma wakefield, but limited to low charges (1-2 pC)
  - Synchronization between laser and injected beam
- **Internal injection**
  - Various mechanisms more or less complex to implement
  - Issues: to achieve high charge > 100 pC, and low energy spread
    $\Rightarrow$ the trapping of e- by the plasma wave should be highly localized

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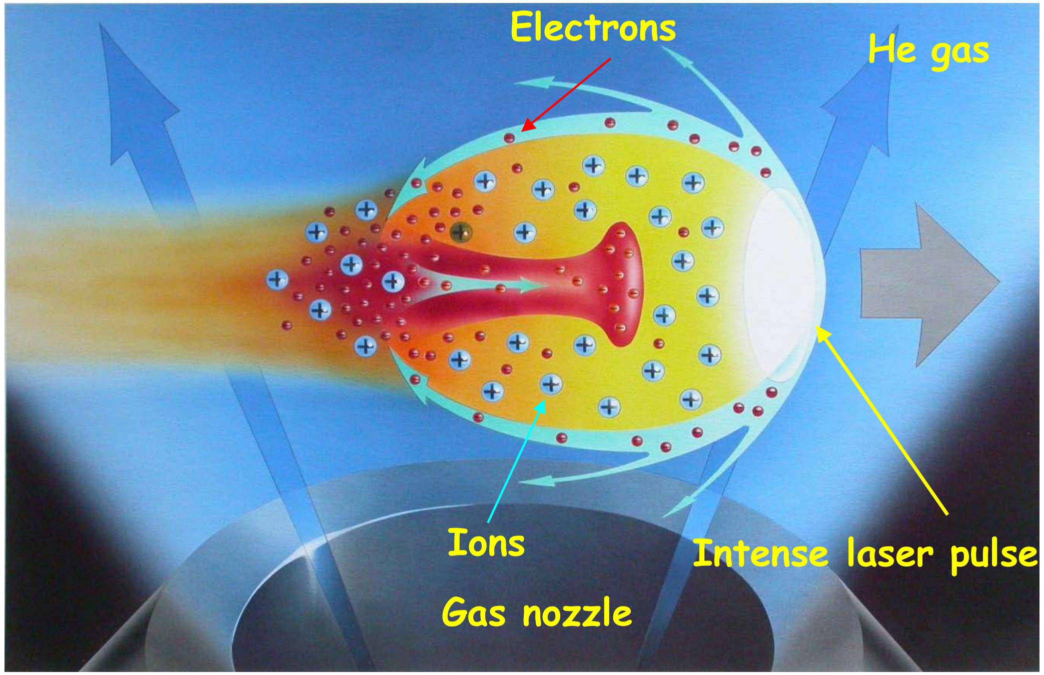
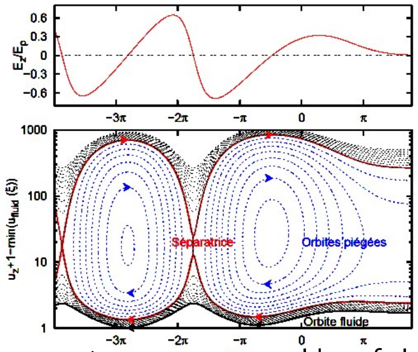
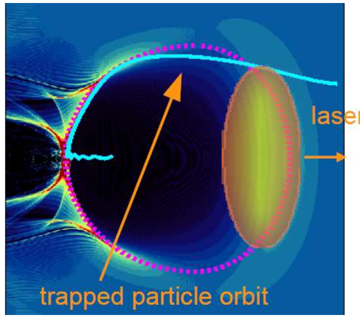
Injection mechanisms

1. Self-injection (so-called bubble or blow out regime): needs strong wakefield to trap the cold plasma e-





Vph ≈ Vg   cold e- of plasma



- On-axis or off-axis injection
- Non-linear regime
- Self-guiding

⇒ Uneasy to control

S. Bulanov et al., PRE 58, R5257 (1998)
C.G.R. Geddes et al., PRL 100, 215004 (2008)

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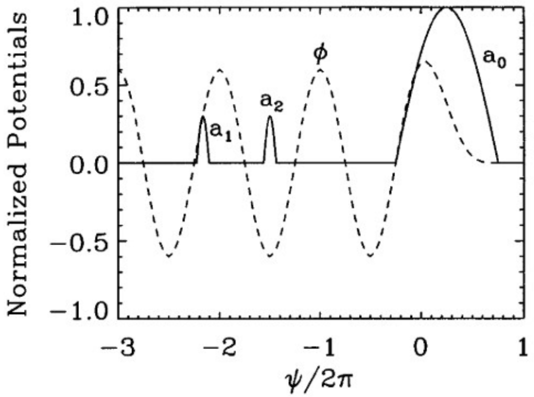
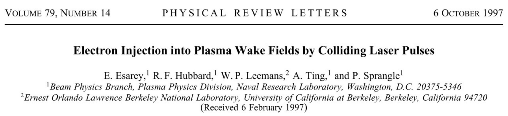
Injection mechanisms

2. Counterpropagating Pulses

- Excite plasma wave below the self-injection threshold
- Counter-propagating injection pulse: to generate a beating with main pulse → triggers the injection



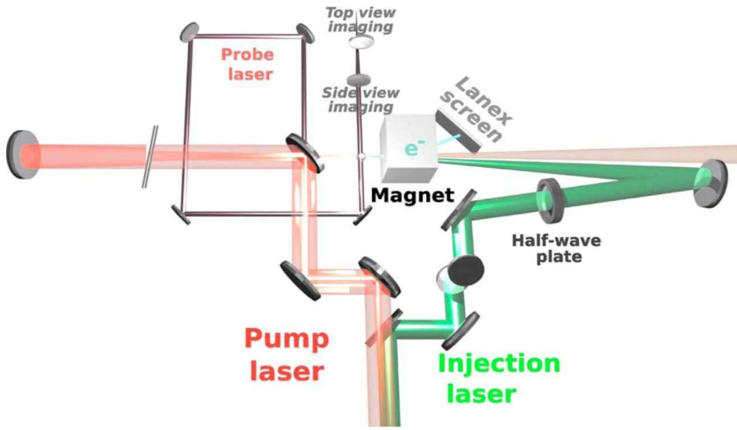


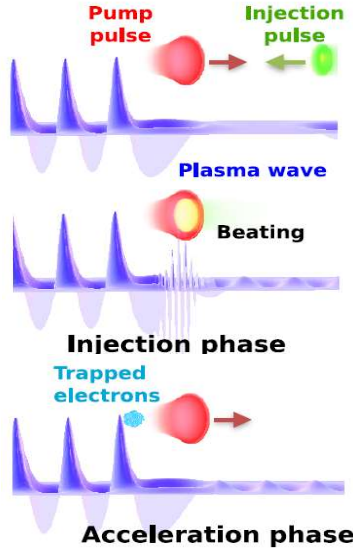
VOLUME 79, NUMBER 14 PHYSICAL REVIEW LETTERS 6 OCTOBER 1997

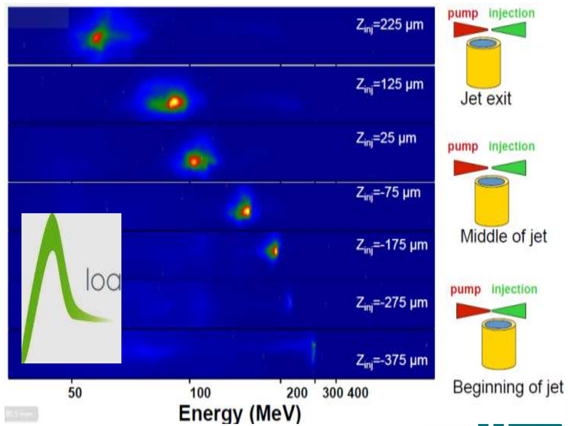
Electron Injection into Plasma Wake Fields by Colliding Laser Pulses

E. Esarey,[1] R. F. Hubbard,[1] W. P. Leemans,[2] A. Ting,[1] and P. Sprangle[1]
[1]Beam Physics Branch, Plasma Physics Division, Naval Research Laboratory, Washington, D.C. 20375-5346
[2]Ernest Orlando Lawrence Berkeley National Laboratory, University of California at Berkeley, Berkeley, California 94720

(Received 6 February 1997)







Faure et al, Nature 444 (2006)

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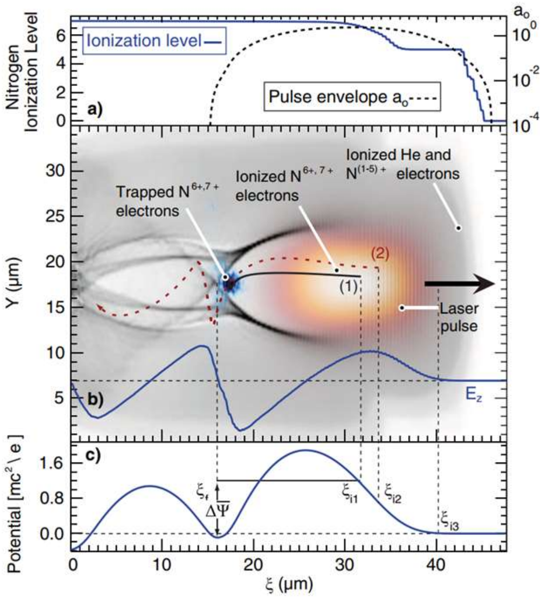
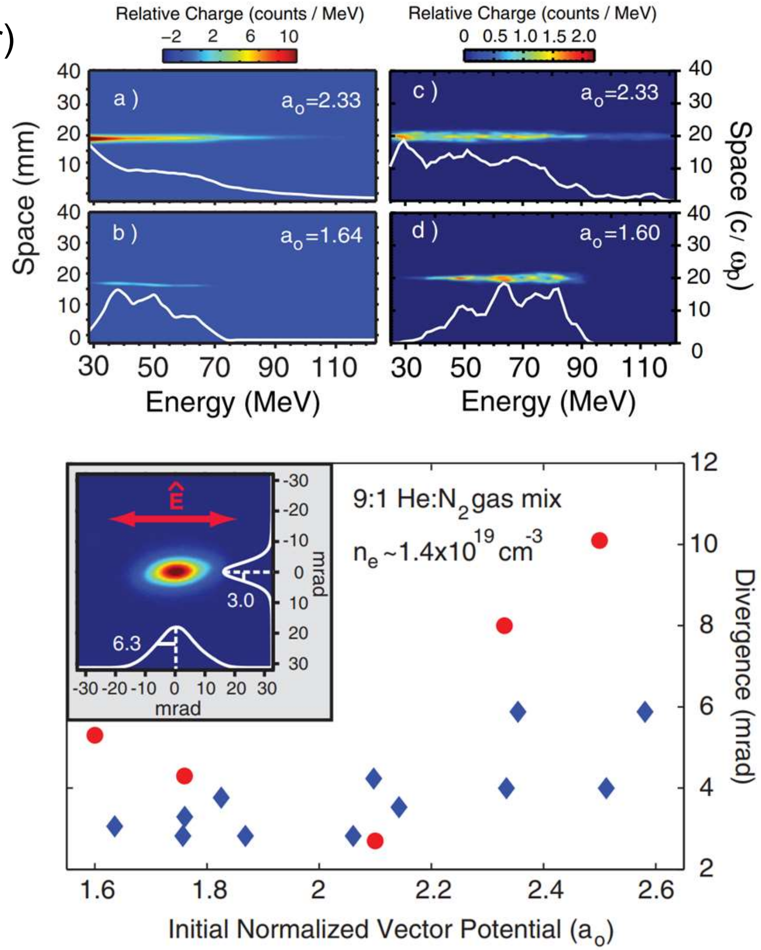
Injection mechanisms

3. Ionization-induced injection

- Ionization of inner shells of high Z atom (N,Kr,Ar) at the peak intensity of the laser pulse
- e- injected at the proper phase for trapping and acceleration to high energies
- Potential for high charge > 100 pC but high E_spread





Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes

A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, and C. Joshi
Phys. Rev. Lett. **104**, 025003 – Published 15 January 2010

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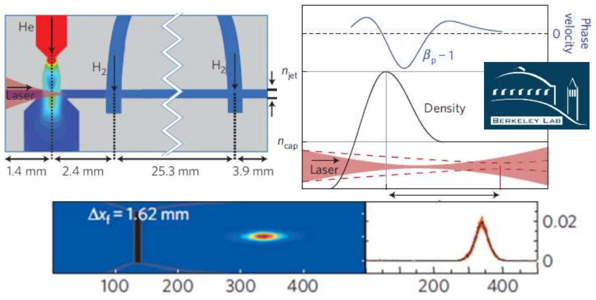
Injection mechanisms

4. Density transition injection

- **soft gradient** $L_{grad} >> \lambda_p$

$\rightarrow$ slows down the plasma wave

A.J. Gonsalves et al, Nature Physics (2011)



$$\frac{v_p}{c} = \left(1 + \frac{\zeta}{k_p}\frac{dk_p}{dz}\right)^{-1}$$

$$dk_p/dz = (k_p/2n_e)(dn_e/dz)$$

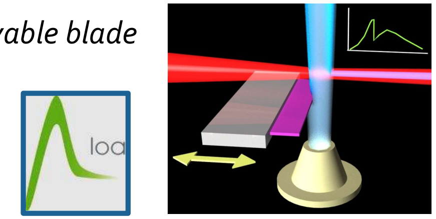
- **sharp density ramp** $L_{grad} \leq \lambda_p$

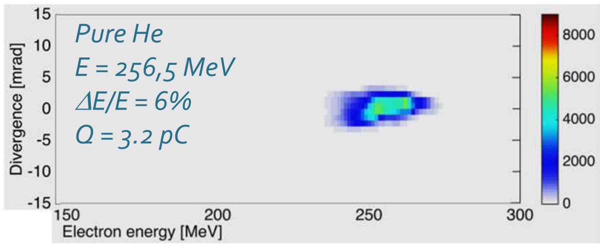
$\rightarrow$ Increase of the bubble size places e- at the right phase

$\rightarrow$ Localize injection $\rightarrow$ reduce E spread

E. Guillaume et al, Physical Review Letters (2015)

movable blade

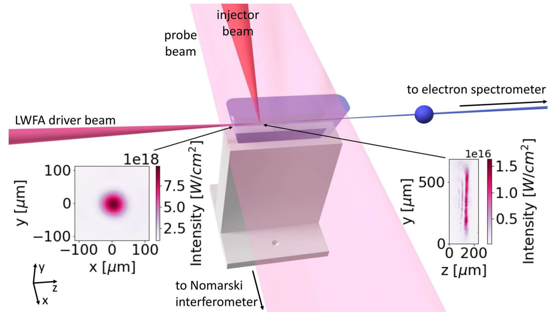


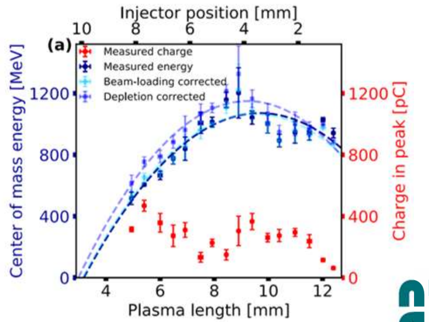


- **Optically-induced shock injection**

$L_{grad} \leq \lambda_p$

K. v. Grafenstein et al, Scientific Reports (2023)





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„Bubble acceleration“ principle

Characteristics:

- **High efficiency (~20%)**
- **Quasi-monoenergetic electron spectrum (ΔE/E ~ 3-5%)**
- **Low normalized emittance (few mm•mrad)**
- **Large accelerating fields (100GV/m – 1TV/m)**
- **Very short acceleration distance (100μm – 1mm)**

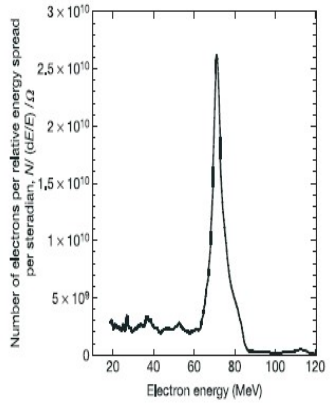
Requirements:

- **Relativistic laser intensities 10^{18}-10^{19} W/cm^2**

C.G.R. Geddes et al.,
Nature 431, 538, (2004)

S.P.D. Mangles et al.,
Nature 431, 535, (2004)

J. Faure et al.,
Nature 431, 541, (2004)



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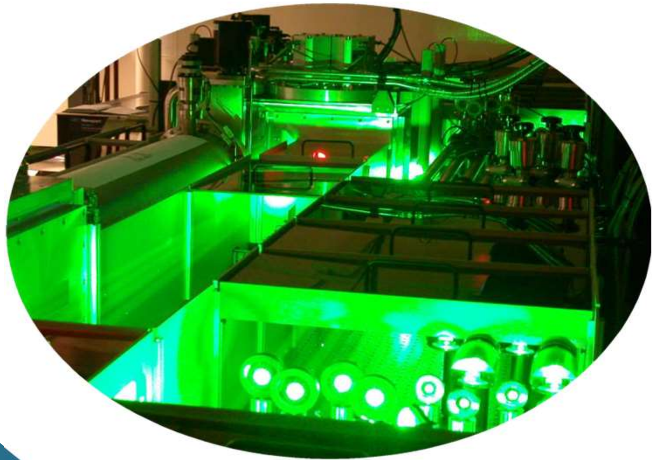
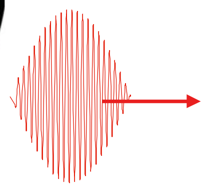
GeV: channeling over cm-scale

- Increasing beam energy requires increased dephasing length and power:

Capillary $$\Delta W[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$$

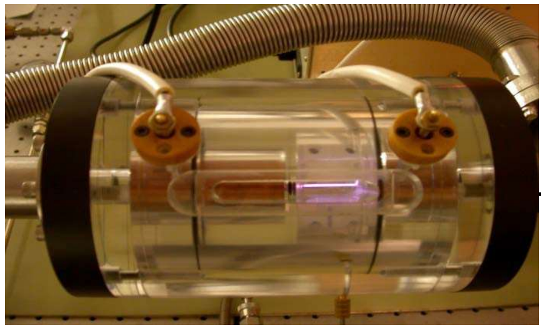
- Scalings indicate cm-scale channel at ~ 10^{18} $\mathrm{cm^{-3}}$ and ~50 TW laser for GeV
- Laser heated plasma channel formation is inefficient at low density
- Use capillary plasma channels for cm-scale, low density plasma channels





Laser: 40-100 TW, 40 fs 10 Hz

Plasma channel technology: Capillary



3 cm

1 GeV

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LETTERS

GeV electron beams from a centimetre-scale accelerator

Published online: 24 September 2006; doi:10.1038/nphys418 G

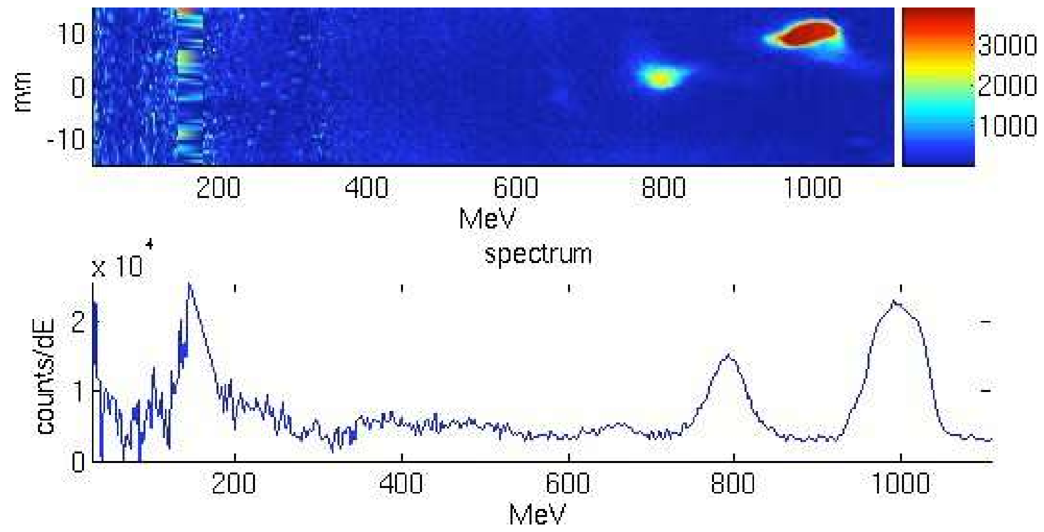
W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1],
E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

Laser → → **1 GeV electrons**

1.5 J, 38 TW,
40 fs, a = 1.5

Plasma filled capillary
Density: $4\times10^{18}/cm^3$

Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Charge: > 30.0 pC



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1.0 GeV Beam Generation

312 μm diameter and 33 mm length capillary

Laser: 1500(±15%) mJ/pulse

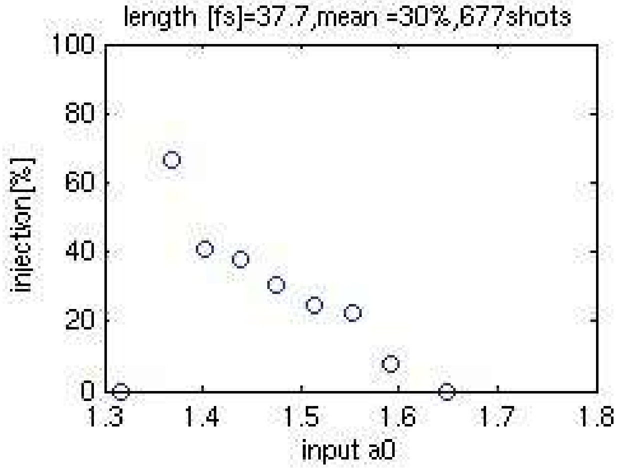
Density: $4 \times 10^{18}/cm^3$

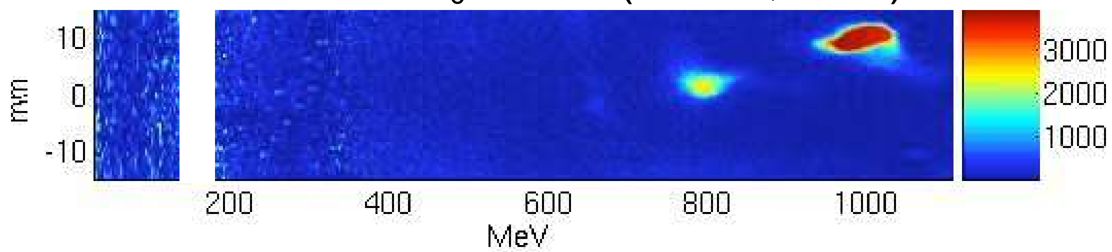
Injection threshold: a_0 ~ 1.35 (~35TW, 38fs)

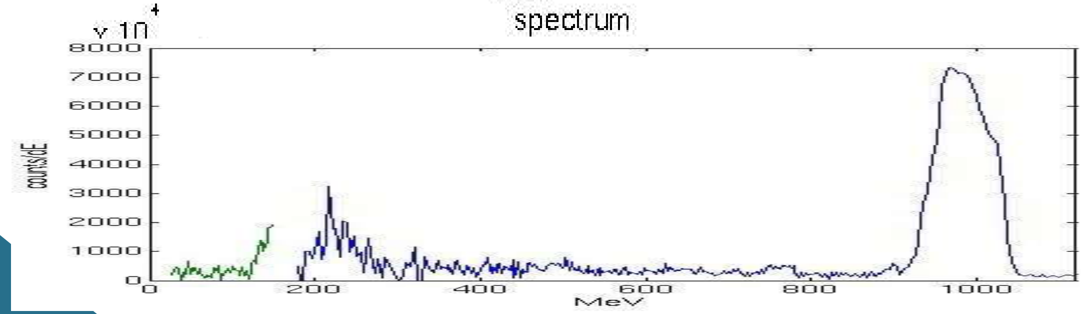
Less injection at higher power

Relativistic effect, self-modulation

1 GeV beam: a_0 ~ 1.46 (40 TW, 37 fs)







Peak energy: 1000 MeV
Divergence(rms): 2.0 mrad
Energy spread (rms): 2.5%
Resolution: 2.4%
Charge: > 30.0 pC

Less stable operation

Laser power fluctuation, discharge timing, pointing stability

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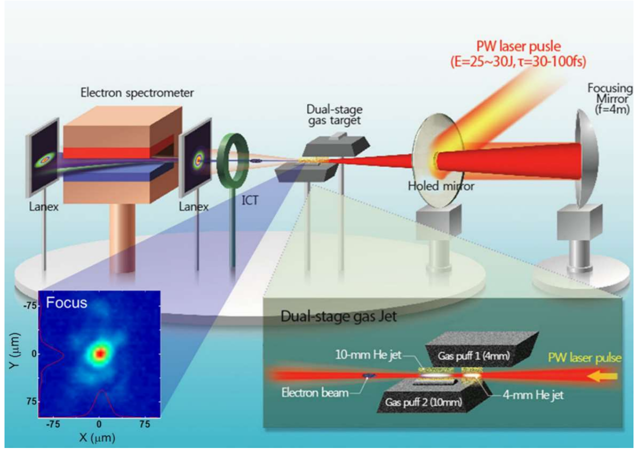
Multi-GeV Beam Generation

PRL 111, 165002 (2013) PHYSICAL REVIEW LETTERS week ending 18 OCTOBER 2013

Enhancement of Electron Energy to the Multi-GeV Regime by a Dual-Stage Laser-Wakefield Accelerator Pumped by Petawatt Laser Pulses

Hyung Taek Kim,[1,2] Ki Hong Pae,[1] Hyuk Jin Cha,[1] I Jong Kim,[1,2] Tae Jun Yu,[1,2] Jae Hee Sung,[1,2] Seong Ku Lee,[1,2] Tae Moon Jeong,[1,2,†] and Jongmin Lee[1,*]
[1]Advanced Photonics Research Institute, GIST, Gwangju 500-712, Korea
[2]Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 500-712, Korea
(Received 17 July 2013; published 15 October 2013)



PHYSICS OF PLASMAS 22, 056703 (2015)

Generation and pointing stabilization of multi-GeV electron beams from a laser plasma accelerator driven in a pre-formed plasma waveguide[a)]

A. J. Gonsalves,[1] K. Nakamura,[1] J. Daniels,[1] H.-S. Mao,[1] C. Benedetti,[1] C. B. Schroeder,[1] Cs. Tóth,[1] J. van Tilborg,[1] D. E. Mittelberger,[1,2] S. S. Bulanov,[1] J.-L. Vay,[1] C. G. R. Geddes,[1] E. Esarey,[1] and W. P. Leemans[1,2,b) c)]
[1]Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[2]Department of Physics, University of California, Berkeley, California 94720, USA

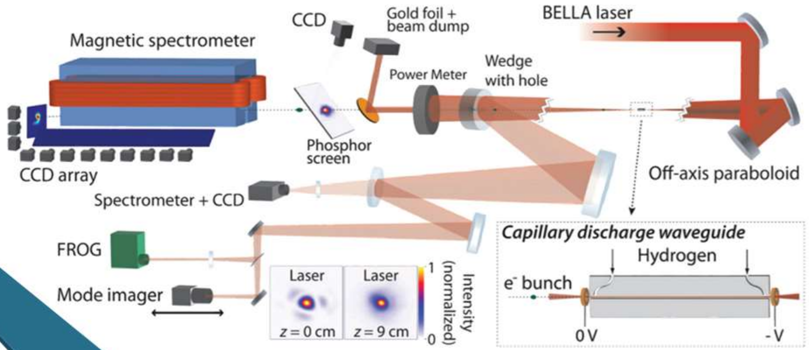


FIG. 1. Schematic of the experimental setup showing the target (inset) and diagnostics of the laser and electron beam. Typical laser spatial profiles with input laser pulse energy 16.6 J are shown at focus ($z = 0$) and at the exit of the capillary ($z = 9$ cm) for density 8×10^{17} cm^{-3}. The width of each image is 500 μm. The Airy ring observed in the image of the laser at focus is both due to the input mode and the hole in the first wedge.

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

A. J. Gonsalves, K. Nakamura, J. Daniels, C. Benedetti, C. Pieronek, T. C. H. de Raadt, S. Steinke, J. H. Bin, S. S. Bulanov, J. van Tilborg, C. G. R. Geddes, C. B. Schroeder, Cs. Tóth, E. Esarey, K. Swanson, L. Fan-Chiang, G. Bagdasarov, N. Bobrova, V. Gasilov, G. Korn, P. Sasorov, and W. P. Leemans
Phys. Rev. Lett. **122**, 084801 – Published 25 February 2019

0.85 PW

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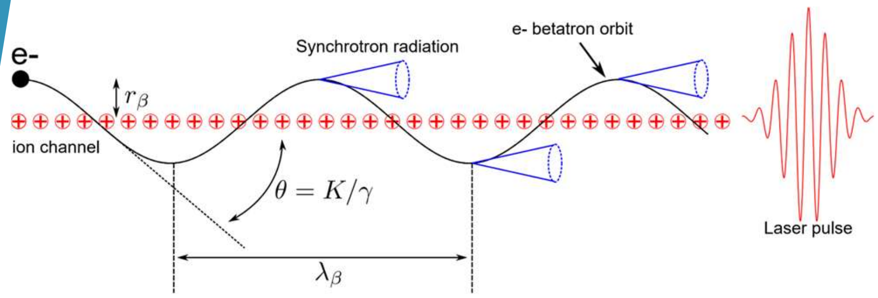
LWFA X-ray source: Betatron Radiation



SCALING LAWS

- Betatron frequency: $\omega_\beta = \omega_p / \sqrt{2\gamma}$
- Transverse momentum: $a_\beta \propto \sqrt{\gamma n_e} r_\beta$
- Divergence: $\vartheta = a_\beta / \gamma$
- Critical photon energy: $E_c \propto \gamma^2 n_e r_\beta$
- Efficiency: $N_{phot/cycle} = \alpha a_\beta$

- Wavelength:

$$\lambda_h = \frac{\lambda_\beta}{h 2\gamma_e^2}\left(1 + \frac{a_\beta^2}{2} + (\gamma_e \varphi)^2\right) = \frac{\sqrt{3}\pi c}{h \omega_p \gamma_e^{3/2}}\left(1 + \frac{a_\beta^2}{2} + (\gamma_e \varphi)^2\right)$$

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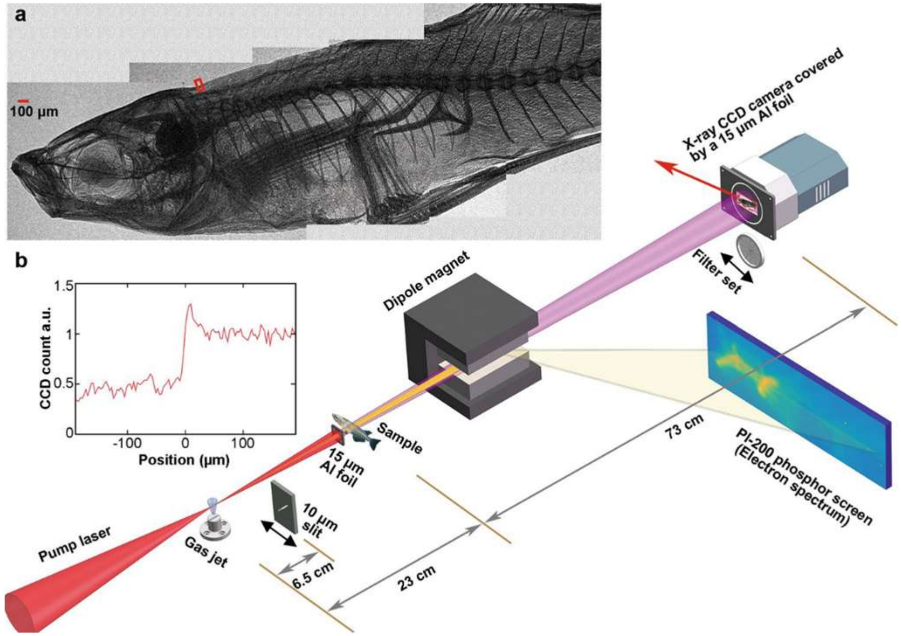
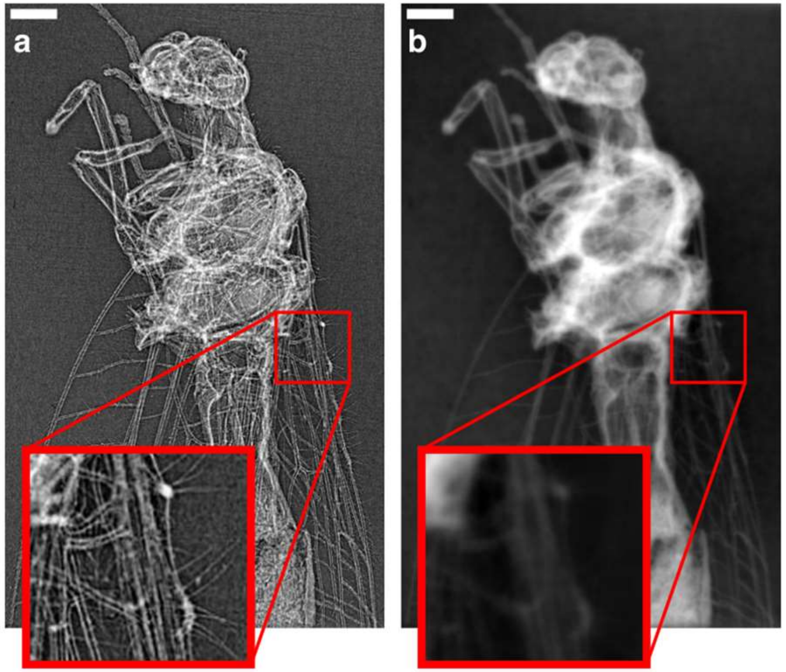


Scientific Reports **volume 9**, Article number: 7796 (2019)



Nature Communications **volume 6**, Article number: 7568 (2015)

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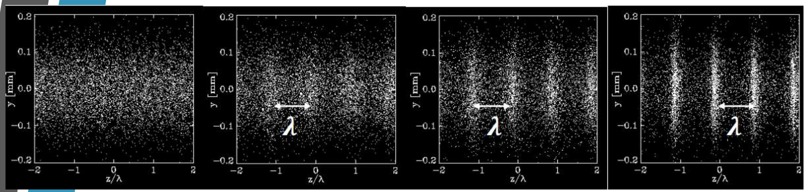
LWFA X-ray source: Free electron laser



Linear in no. of electrons/bunch

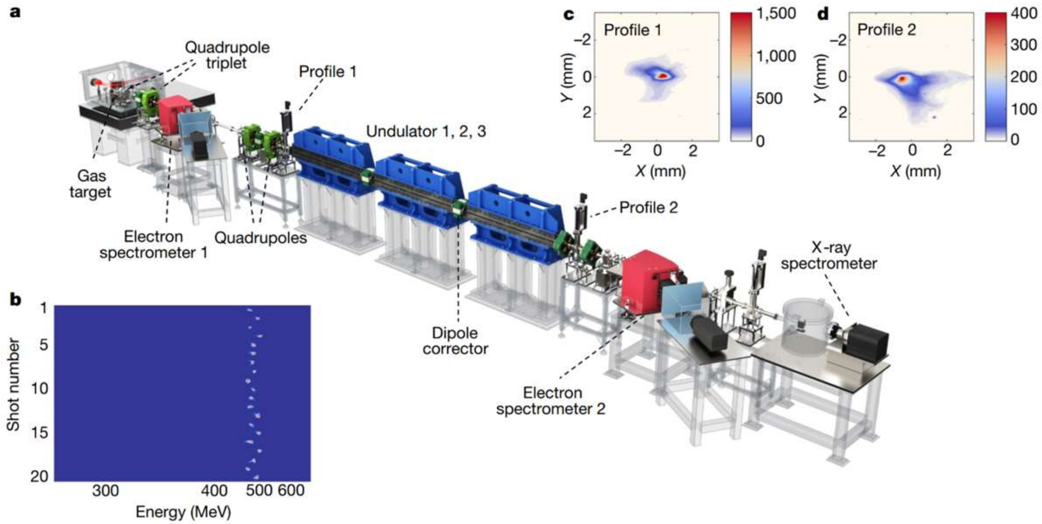
$$N_{ph} \sim N_e \pi\alpha \frac{K^2}{1+K^2/2}$$

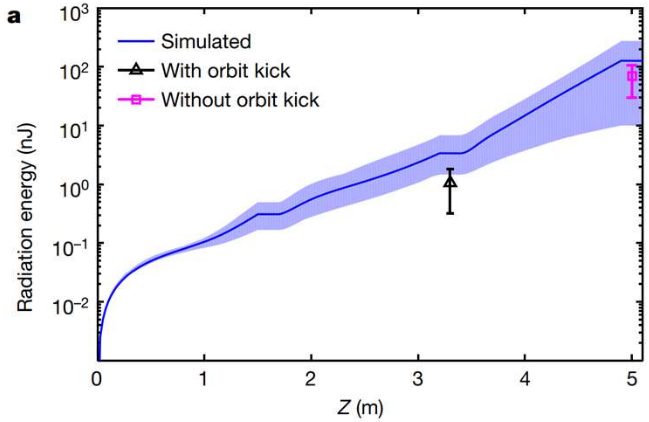
Incoherent emission

Quadratic in no. of electrons/bunch

$$N_{ph} \sim N_e^2 \pi\alpha \frac{K^2}{1+K^2/2}$$

Fully coherent emission





Nature volume 595, pages516–520 (2021)

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Future TeV Collider-Staging

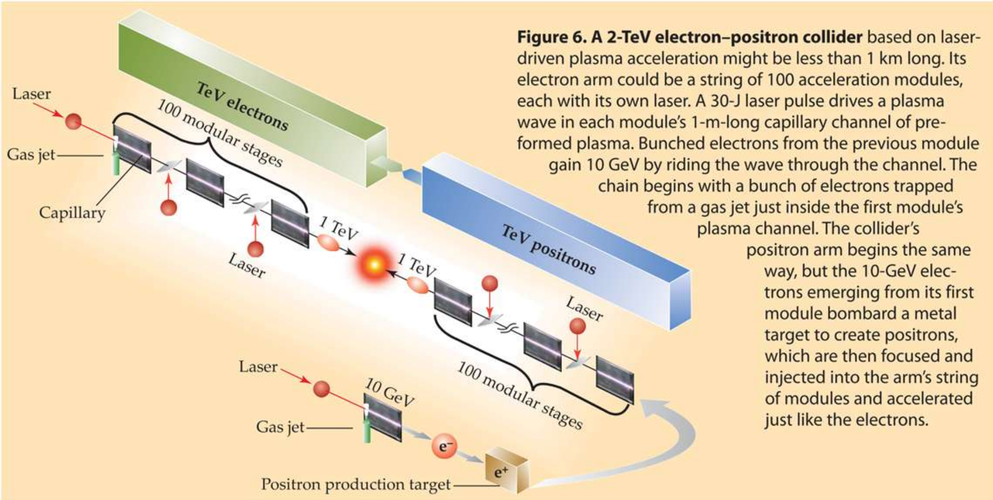
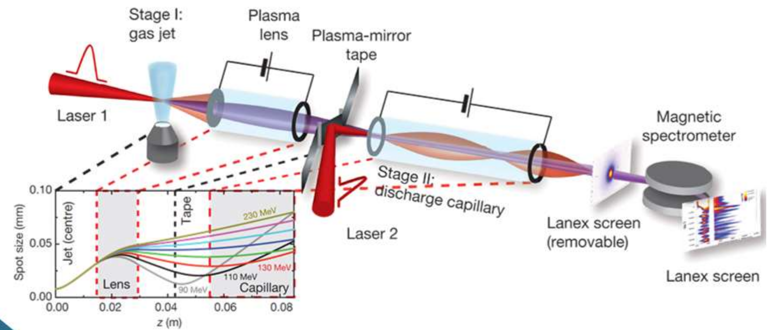
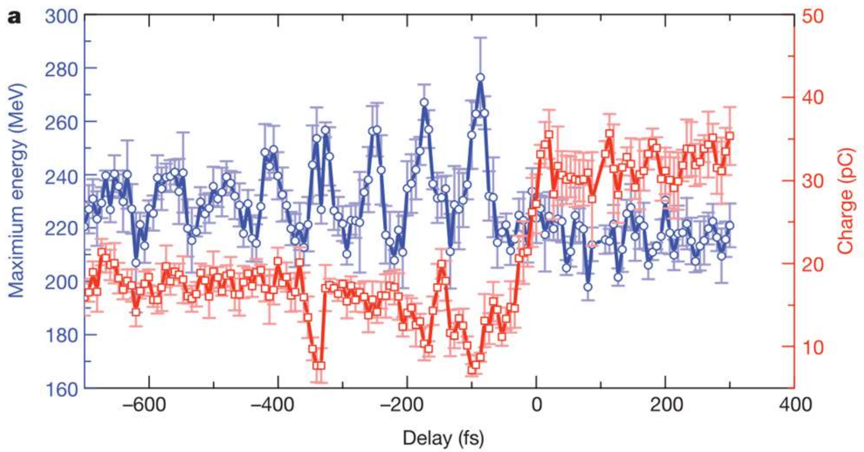


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

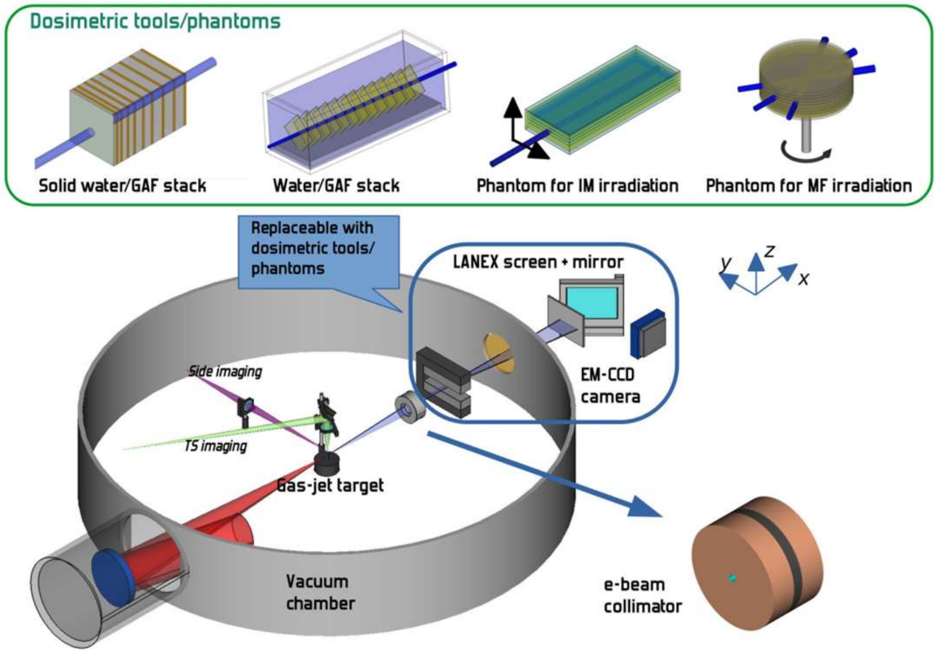
Physics Today March 2009; page 44-49

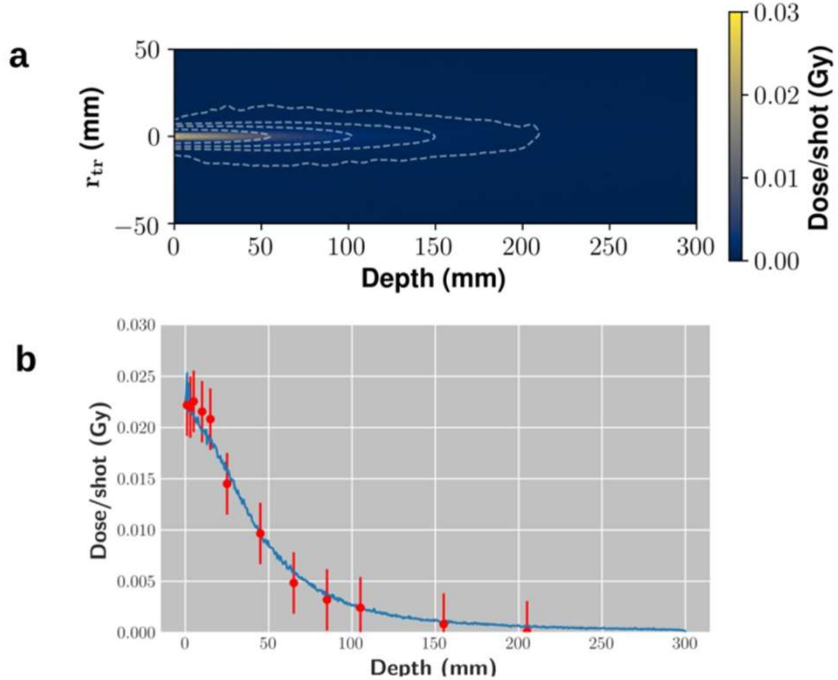


Nature volume 530, pages190–193 (2016)



Radiotherapy





Scientific Reports volume 10, Article number: 17307 (2020)

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Thanks For Your Attention!!

Questions?

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