Laser-driven Plasma Accelerator and Application

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05.07.2023

Topics in relativistic laser-plasma physics

- Introduction of plasma physics
- Laser wakefield accelerator (LWFA)
- Relativistic optics
- Application
  - X-ray imaging
  - Free electron laser

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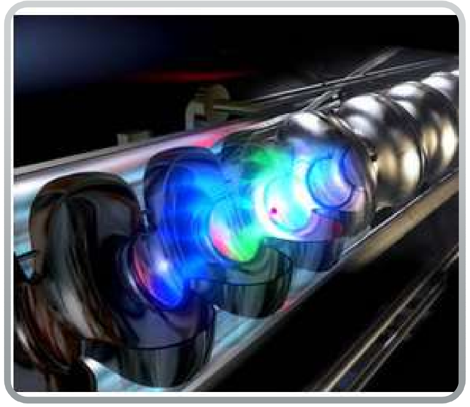
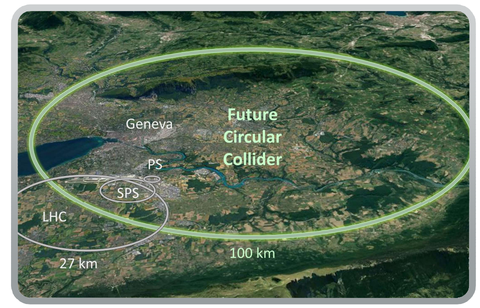
Conventional accelerators

- Accelerating fields of 10_s MV/m due to material breakdown
- Colossus infrastructure
- CERN: $8 billion to construct and $1 billion pro year to maintain





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Limitations of Classical RF accelerators: 1 TeV electron

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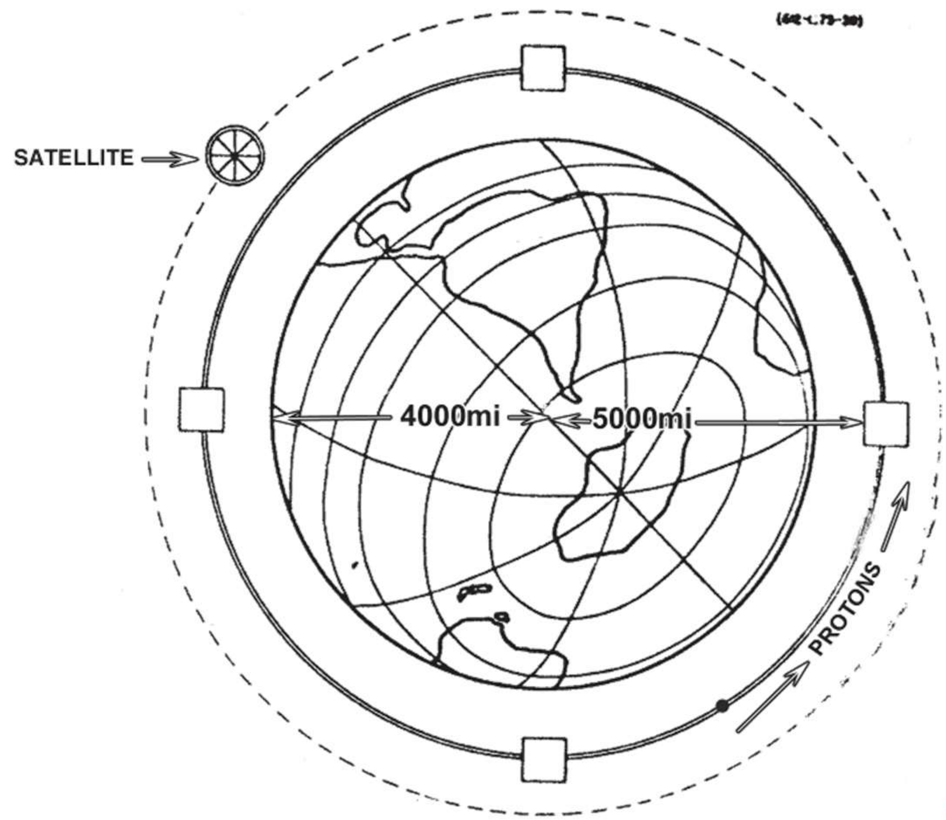
Fermi's Ultimate Accelerator

- To get PeV proton
- Preliminary design…8000 km, 20,000 gauss, 1600 km above the surface of earth
- "What we can learn impossible to guess…main element surprise…some things look for but see others…Look for multiple production…antinucleons…strange particles…puzzle of long lifetimes…large angular momentum?…double formation? (now called associated production) At present more probable…"
- Cost (in 1954): 170 B$ (LHC: 8 B$ in 2010)
- Estimated completion date: 1994



Orear, Jay. Enrico Fermi - The Master Scientist. 2004

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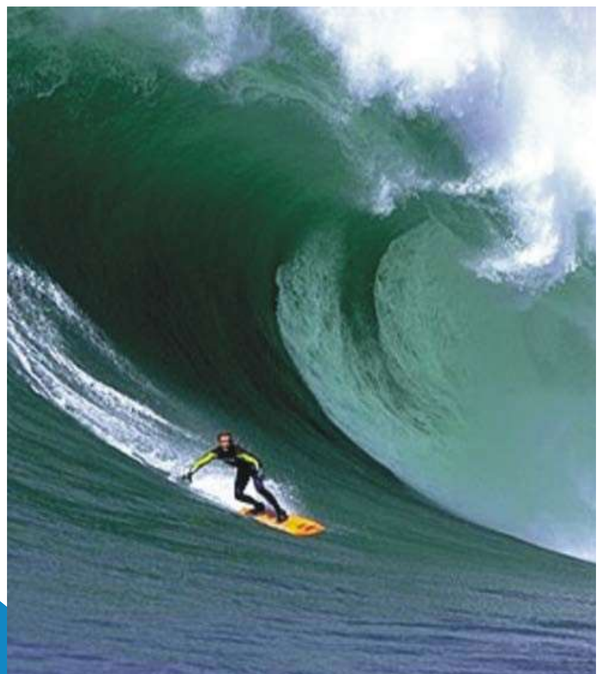
VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

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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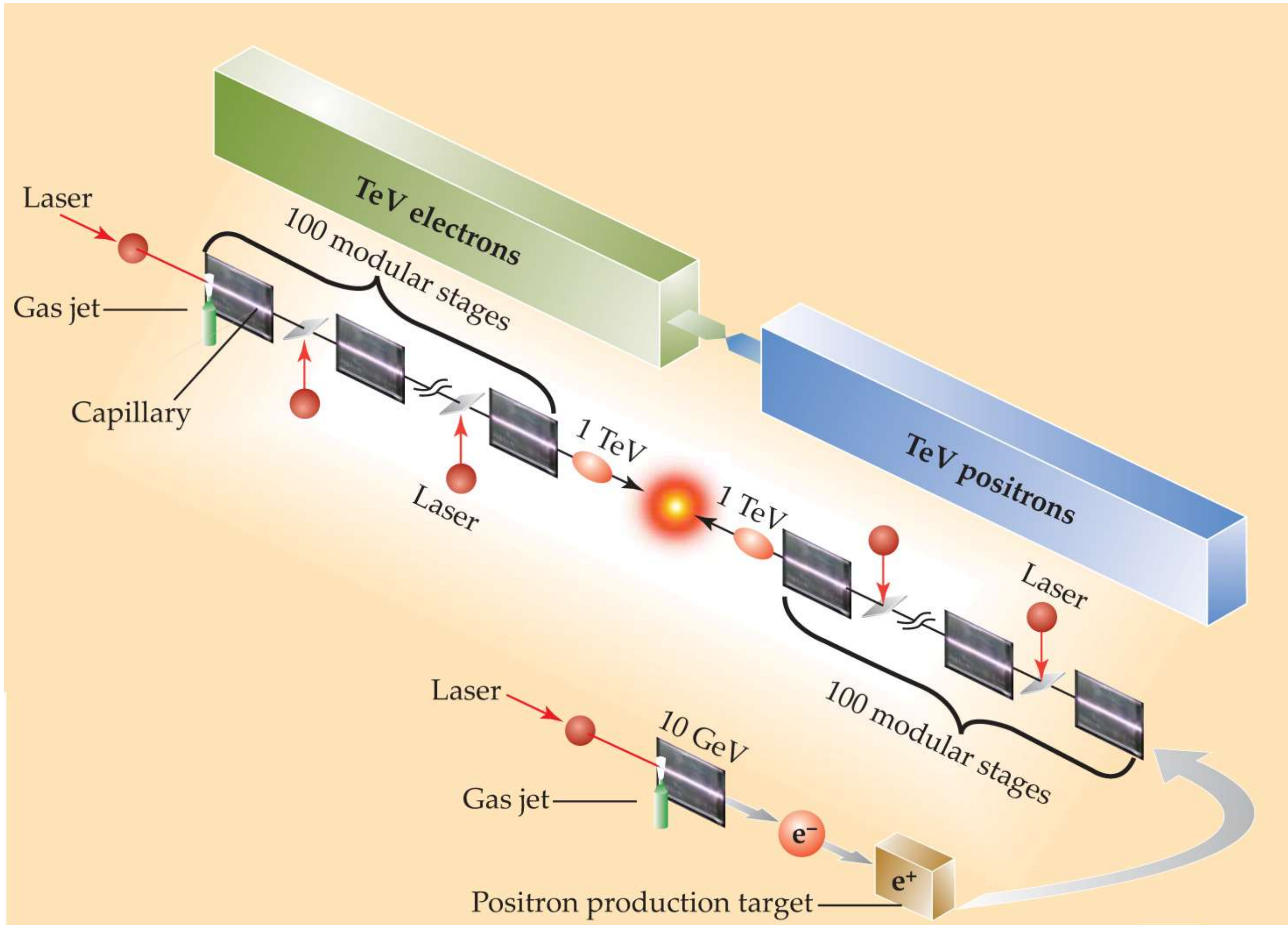

Physics Today **62**, 3, 44 (2009); https://doi.org/10.1063/1.3099645

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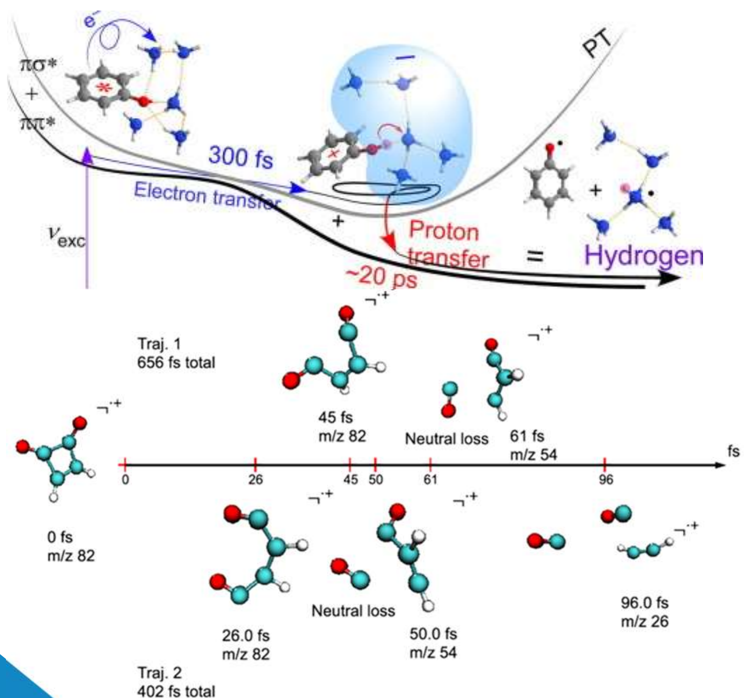
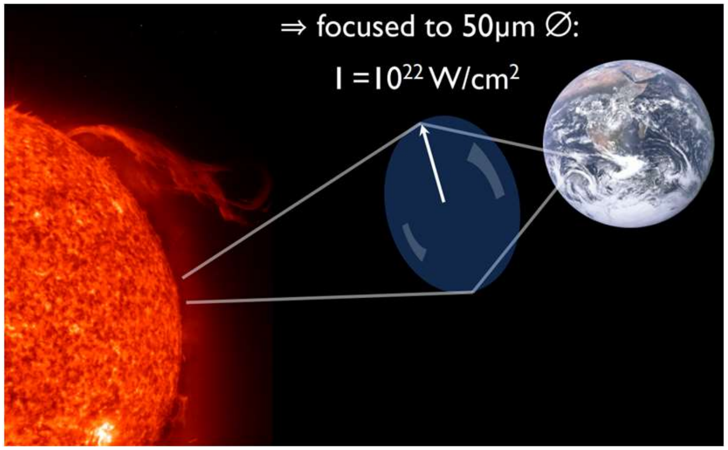
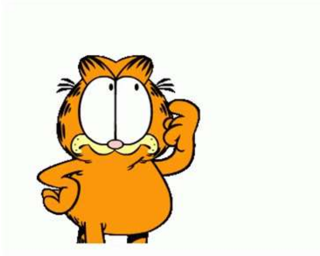
What kind of laser are we talking about?

Very short (~fs)



Very strong





Total power of sun on earth: 1.73×10^{17} W

$$\frac{1.73 \times 10^{17}\ \mathrm{W}}{\pi \times (25\ \mu m)^2} \sim 8.8 \times 10^{21}\ \frac{W}{cm^2}$$

https://doi.org/10.1016/j.chemphys.2018.08.004

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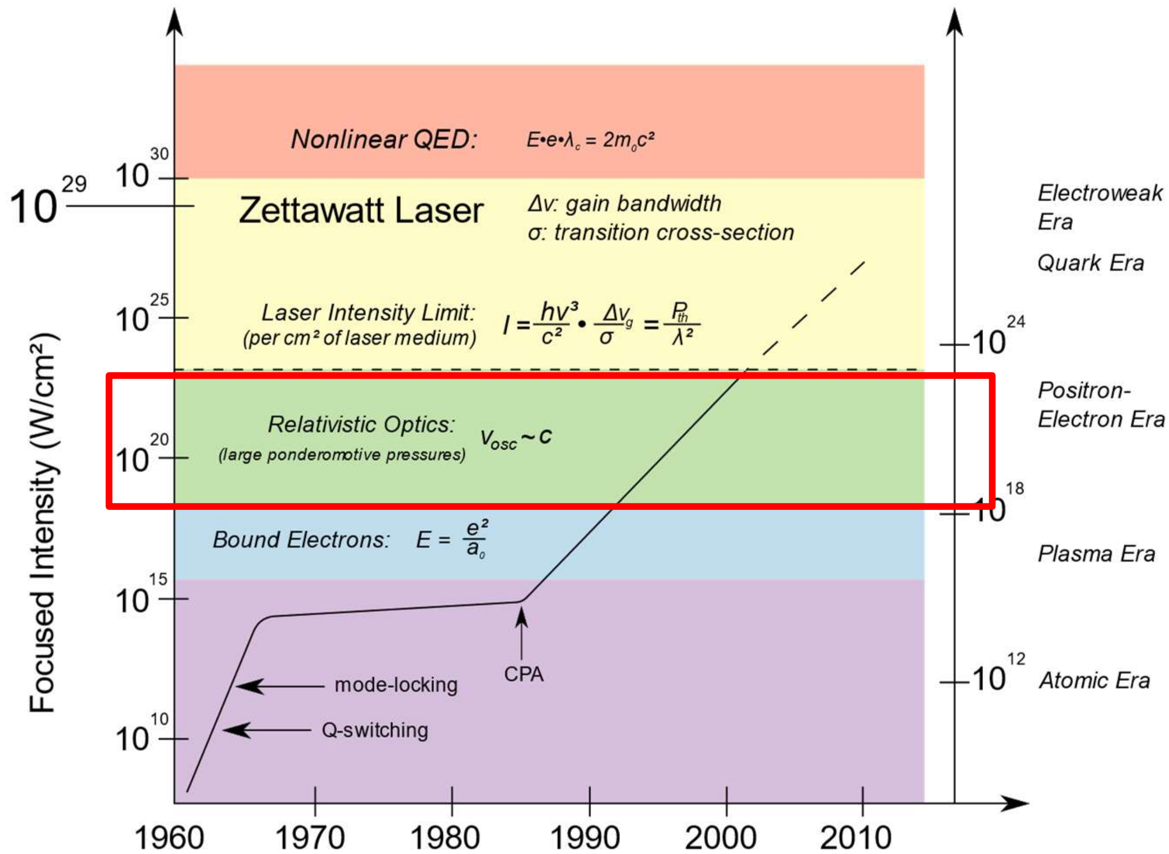
Introduction: What happens to the matter when the E field intensity increases?



NCU 100TW Laser System

beam line	first	second	third
pulse energy	3.3 J	450 mJ	200 mJ
central wavelength	810 nm	805 nm	870–920 nm
bandwidth (FWHM)	35 nm	34 nm	35 nm
duration (FWHM)	30 fs	34 fs	38 fs
peak power	110 TW	13 TW	5 TW
energy fluctuation	1.1%	1.8%	2.6%
focusability (M^2)	1.2	1.1	1.3
enclosed energy	77%	81%	72%
pointing fluctuation	4.5 μrad	4.8 μrad	4.7 μrad
temporal contrast at -100 ps	4×10^{-10}	2×10^{-9}	2×10^{-9}

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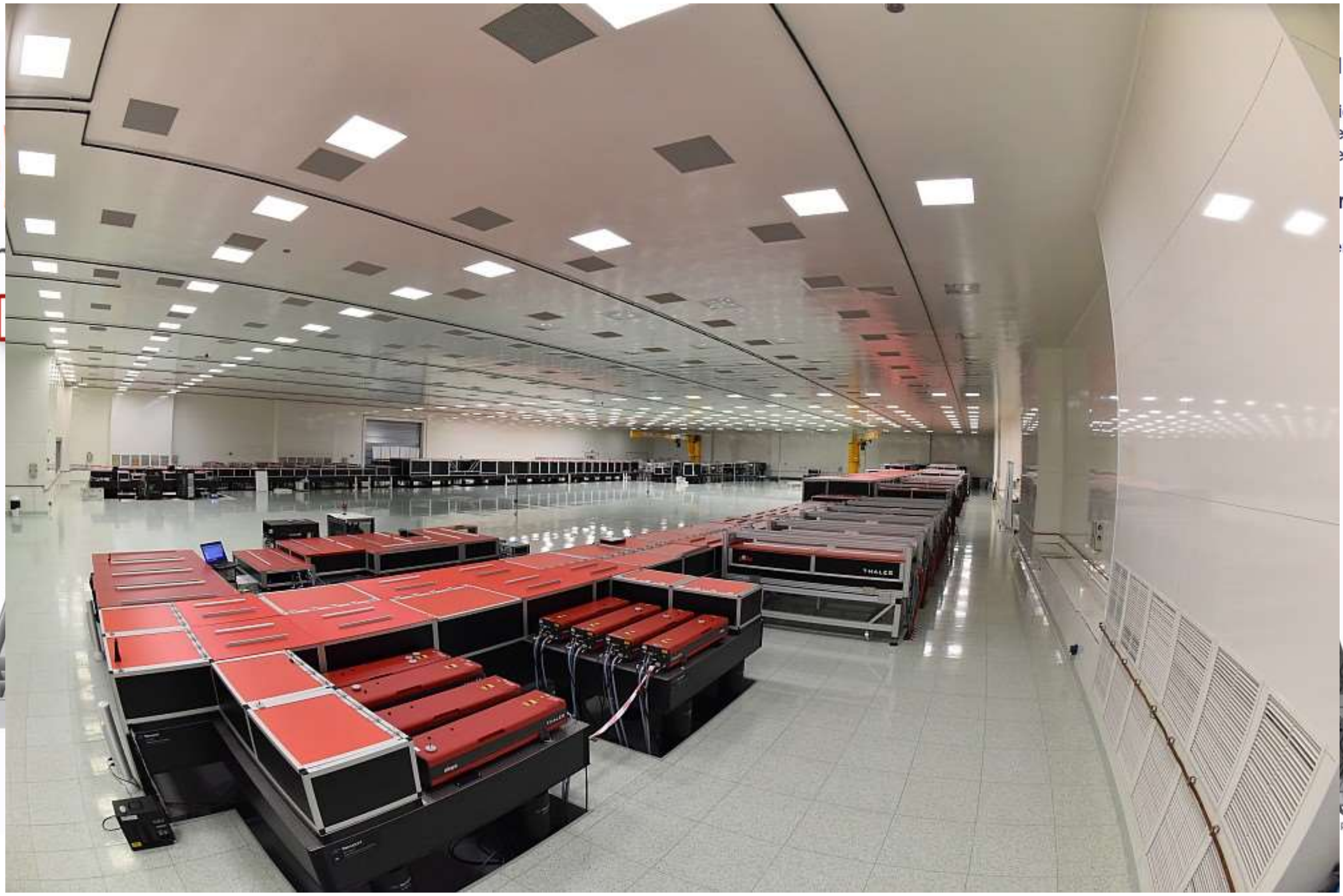
ELI-NP



Vulcan OPCPA

All Optical Parametric Amplification allows for Ultra-broad Bandwidth

Vulcan OPcpa PEtawatt Laser

	Vulcan Long Pulse	Vulcan Short Pulse	VOPPEL
Pulse Length	3 ns	500 fs	< 30 fs
Spectral Bandwidth	-	5nm	160 nm
Final Beam Size	96 mm	600 mm	200 mm
Energy on Target	250 J	500 J	30 J
Final Beam Shape	Round	Round	Round
Rep. Rate	20 min	20 min	20 min*

*To be decreased to 5 min air-cooled amplifier

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What is plasma?

- Composition: ionized gas, ion and free electron
- Plasma is electrically conducting
- Weak coupling between pairs of particles, but strong collective interactions:
  - Debye shielding
  - electron plasma oscillations

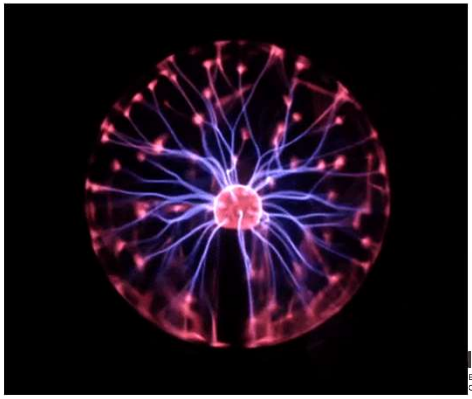
$$\lambda_{Ds} \equiv \left(\frac{\varepsilon_0 K T_e}{n e^2} \right)^{1/2} \qquad \omega_p \equiv \left(\frac{n e^2}{\varepsilon_0 m} \right)^{1/2}$$

- Hierarchy of length scales, expressed in terms of fundamental plasma parameter

  $\Lambda \equiv \frac{4\pi}{3} {\lambda_D}^3 n$= # of particles in a Debye sphere

- Dispersive for electromagnetic wave

  Critical density n_{crit}: $\omega_p = \omega_0$



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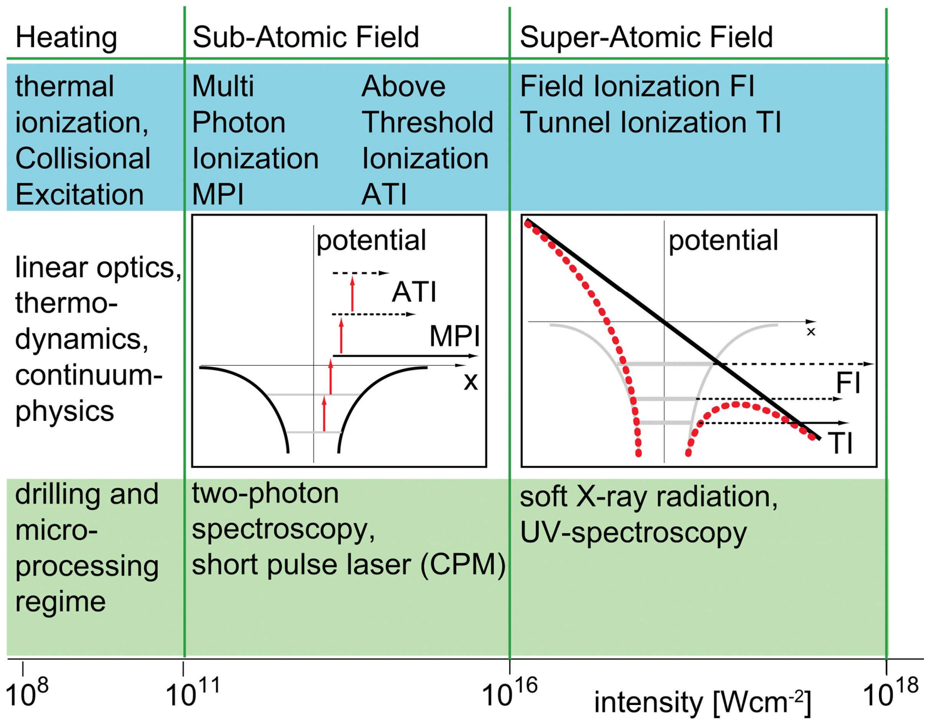
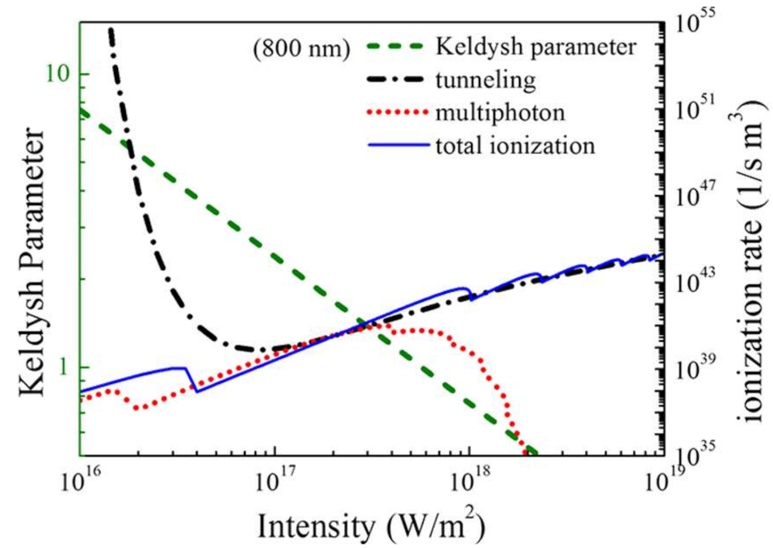
Ionization by laser



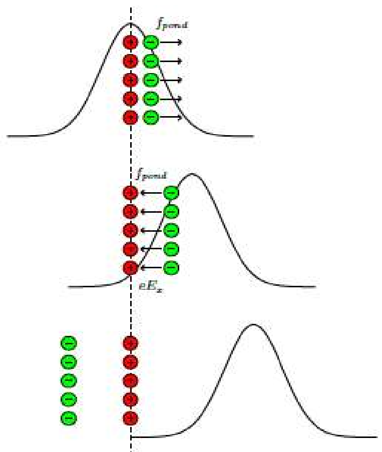


Journal of Laser Applications **25**, 012006 (2013)
DOI: 10.5772/65637

Keldysh parameter:

$$\gamma = \frac{\sqrt{2mE_{ion}}}{eE_L/\omega}$$

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:

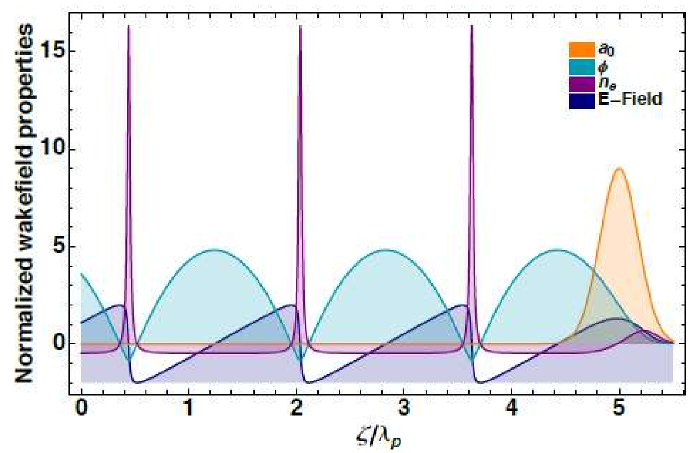
$$a_0 = \frac{eE}{m\omega c} = 1 \Leftrightarrow I = 10^{18} W cm^{-2}$$

Ponderomotive force:

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

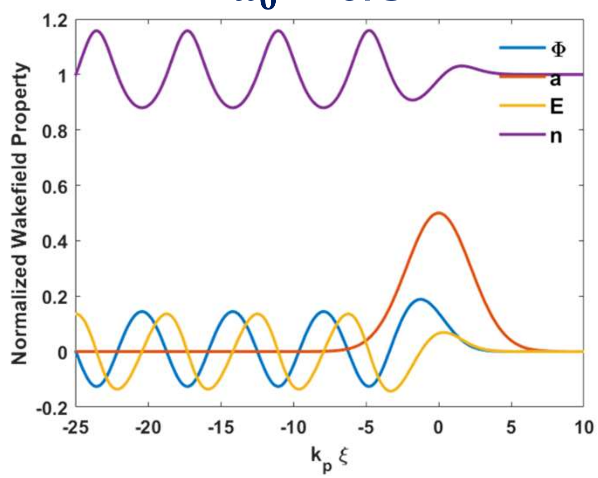
Resonant Excitation:

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

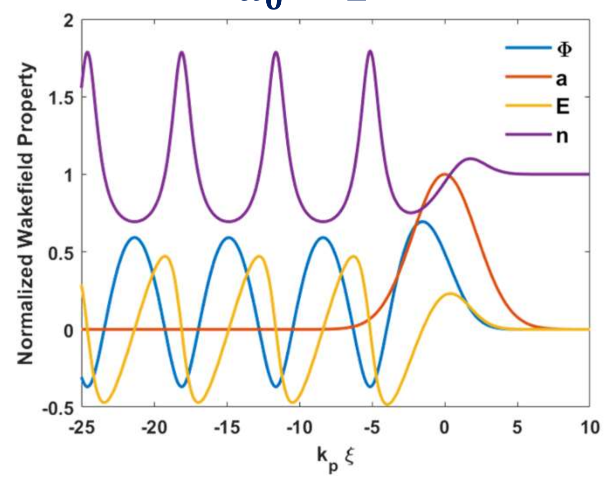


1D description, linear and non-linear plasma waves

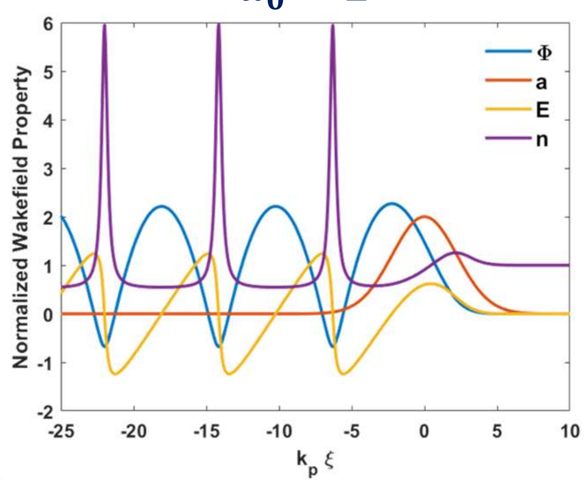
$a_0 = 0.5$



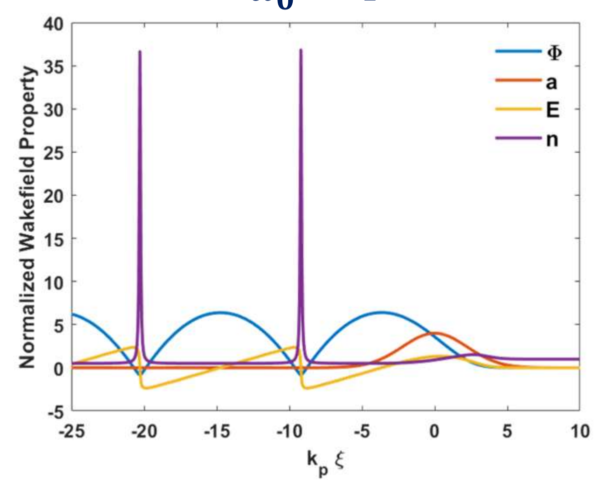
$a_0 = 1$



$a_0 = 2$



$a_0 = 4$



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Strength of Wakefield

Single electron ⇨ plasma (n_{crit} =10^{21} cm^{-3} @800nm)

- In plasma, laser interaction generates additional

  E-fields (due to the separation of electrons from ions)

  B-fields (due to laser-driven electron currents)

- They are quasi-stationary and of the same order as laser fields:

  - ❑ $E_L \approx 3 \times 10^{12}\ \text{V/m} \cdot a_0$
  - ❑ $B_L \approx 10^{8}\ \text{Gauss} \cdot a_0$

- Plasma is governed by **collective oscillatory electron motion**

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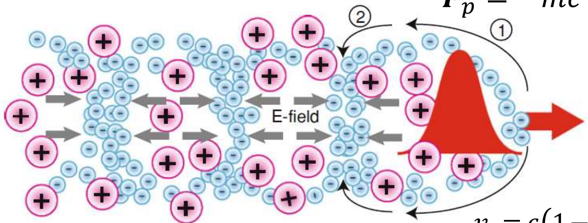
T. Tajima & J.M. Dawson,
Phys. Rev. Letter 43, 267 (1979)

Wakefield excitation

Laser field (vector potential a)

$\boldsymbol{F}_p = -mc^2 \boldsymbol{\nabla}(a^2/2)$



$v_g = c\left(1-\omega_p^2/\omega_L^2\right)^{1/2}$

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

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p^2\right)\frac{\delta n}{n_0} = \nabla^2 \frac{a^2(\xi)}{2}$$

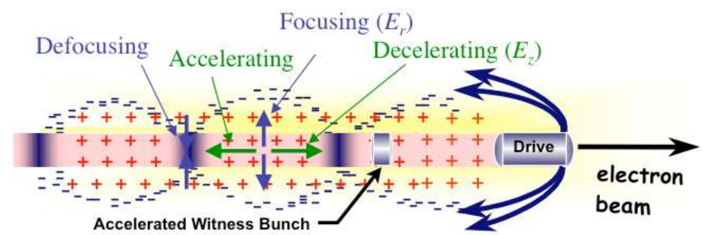
Plasma wave forced density oscillation — Ponderomotive Force

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* $\omega_p = (4\pi e^2 n_0/m_e)^{1/2}$

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

$$wave\ number\ k_p = \omega_p/c$$

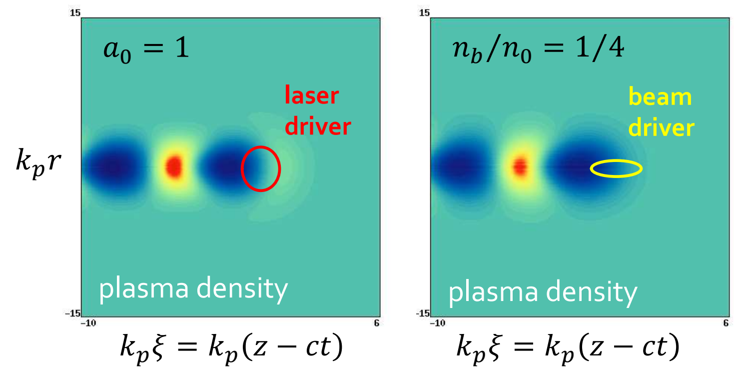
Particle beam field



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

$$\left(\frac{\partial^2}{\partial \xi^2} + k_p^2\right)\frac{\delta n}{n_0} = -{k_p}^2\frac{n_b}{n_0}$$

Space charge force



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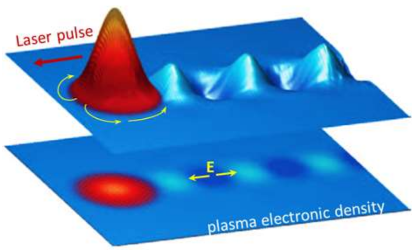
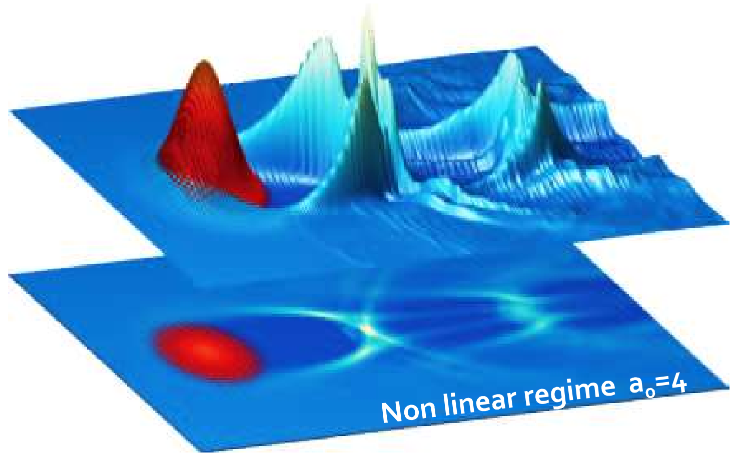
3D non-linear regime (bubble regime)



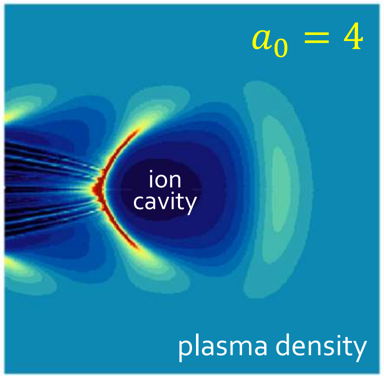
Quasi-linear regime a_0=0.5



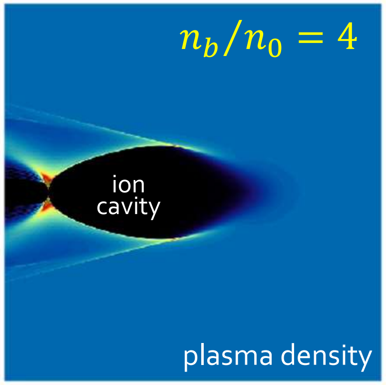
- Ponderomotive forces of laser larger than space charge restoring force of the ions

⇒ All electrons of the plasma are expelled

⇒ ionic cavity ⇒ linear fields



driver = laser



driver = e-beam

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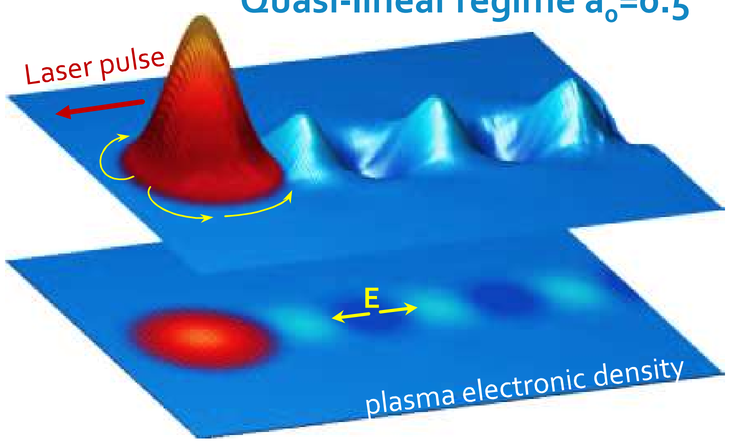
Characteristic scales of LWFA

Quasi-linear regime a_0=0.5



Plasma wavelength

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

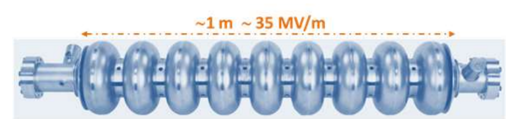
- for ~ 10^{18} cm^{-3} → λ_p ~ 30 μm
- LWFA produce ultrashort bunches

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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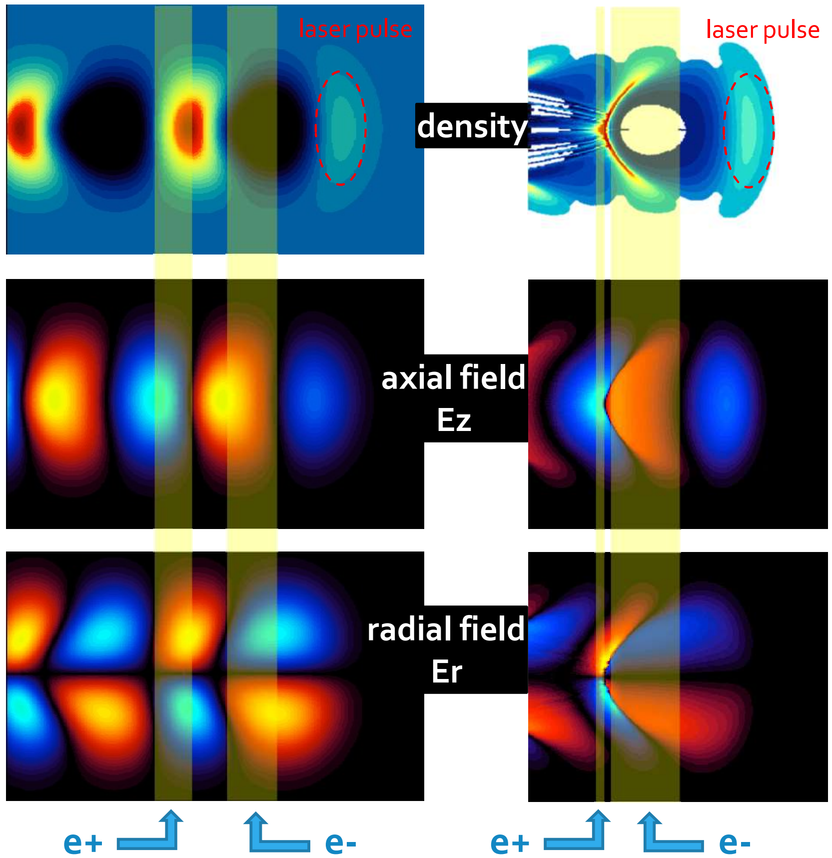
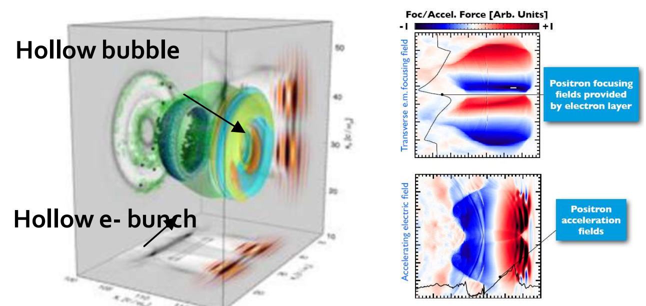
Useable phase range (accelerating & focusing)

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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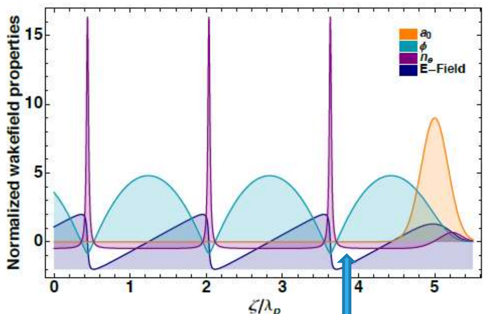
Injection in Wakefield

$a_0 \sim 1$

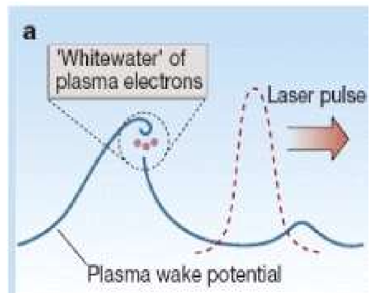
$c\tau_{pulse} \sim \lambda_p$



External Injection

$a_0 > 1$

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



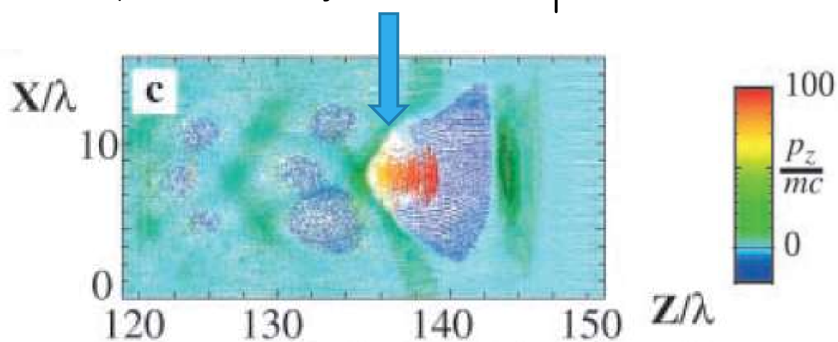
Wavebreaking

Self-injection

$a_0 \gg 1$

$c\tau_{pulse} < \lambda_p$

Wave breaks at first oscillation. No plasma wave



Bubble acceleration principle

Characteristics:

- **High efficiency (~20%)**
- **Quasi-monoenergetic electron spectrum ($\Delta E/E$ ~ as low as 0.2 %)**
- **Low normalized emittance (few mm•mrad)**
- **Large accelerating fields (100GV/m – 1TV/m)**
- **Very short acceleration distance (100μm – 1mm)**

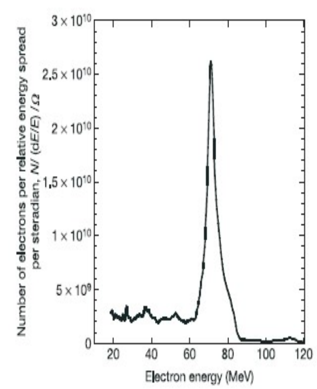
Requirements:

- **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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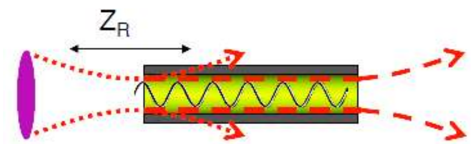
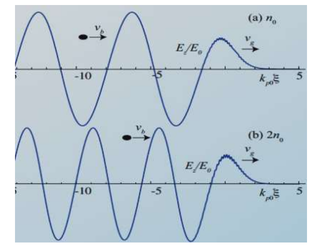
Energy gain limitations

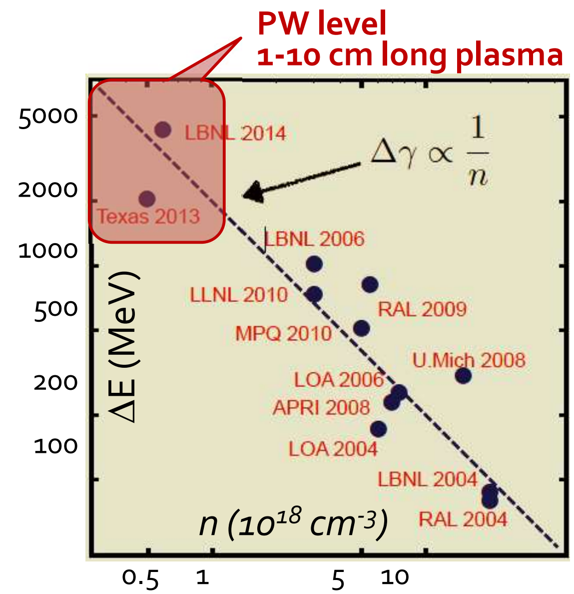
- ❑ Laser **Diffraction** ~ Rayleigh range
  - Controlled by relativistic self-guiding, pre-formed plasma channel, capillary guiding…



- ❑ 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

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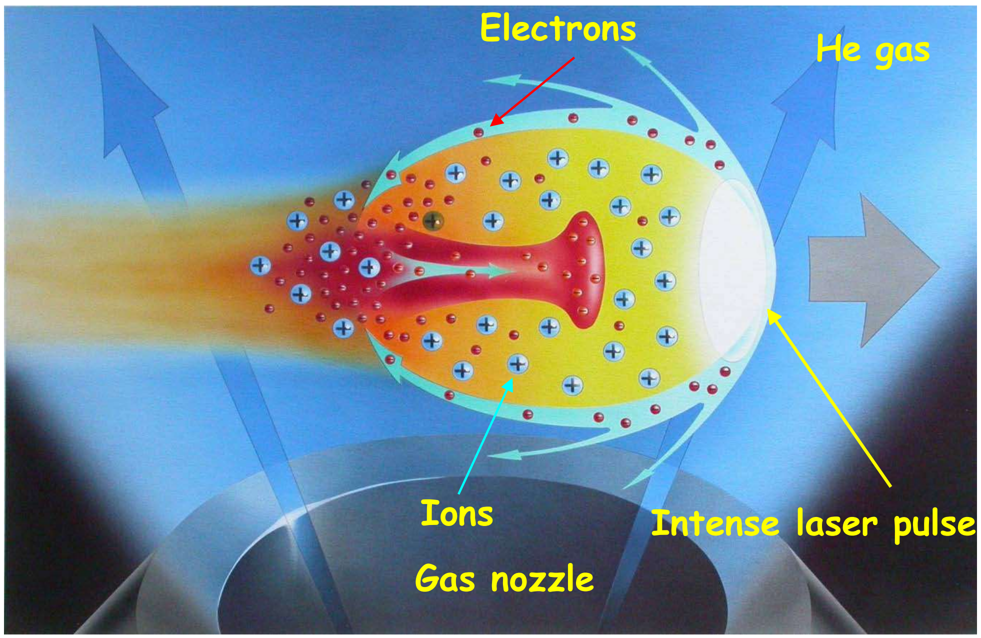
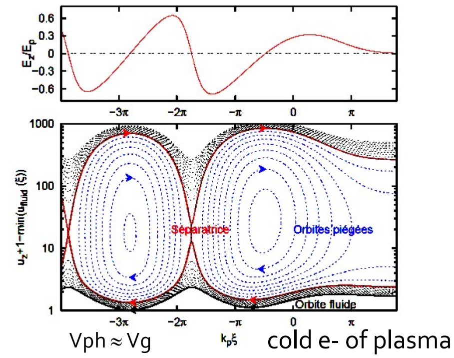
Injection mechanisms

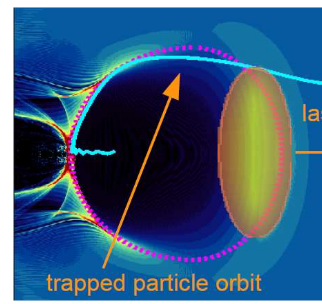
- **Injector is of prime importance**
  - Determines the performances of the overall accelerator : charge, energy spread, emittance
- **Better to decouple the injection mechanism from the acceleration mechanism**
  - Indivudual adjustment of parameters, stability, control
- **External injection**
  - Fine definition of beams delivered by conventional photo-injectors
  - Issues: to achieve an ultra-short bunch < $\lambda_p/4$ ~10µm (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

Injection mechanisms

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







- 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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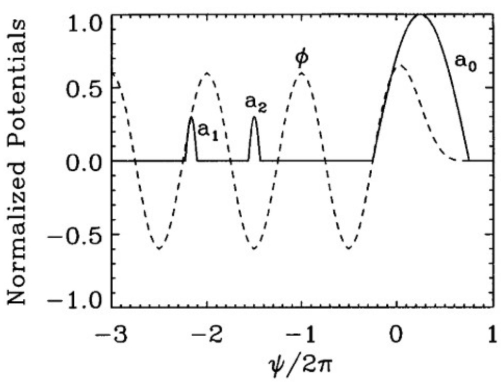
Injection mechanisms

2. Counterpropagating Pulses

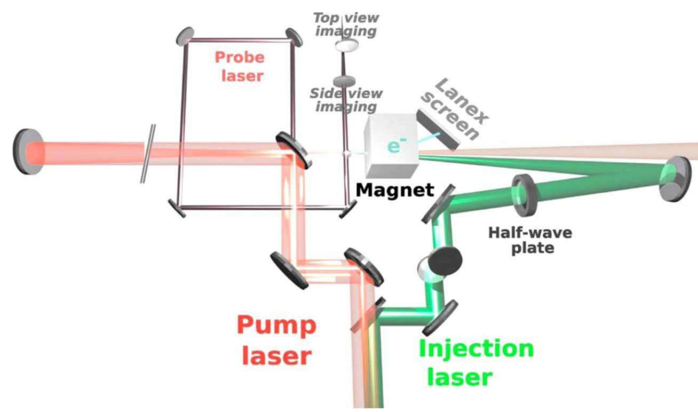
- Excite plasma wave below the self-injection threshold
- Counter-propagating injection pulse: to generate a beating with main pulse → triggers the injection

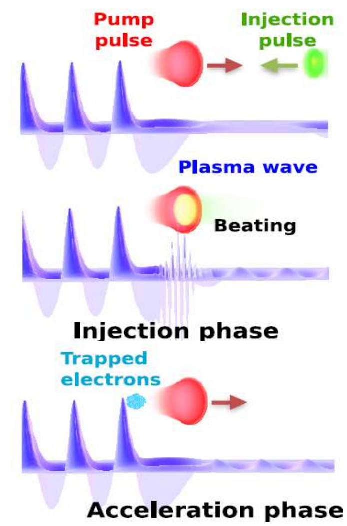


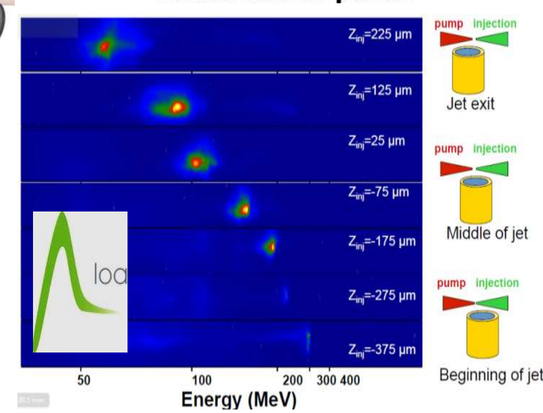
Volume 79, Number 14 PHYSICAL REVIEW LETTERS 6 October 1997

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)





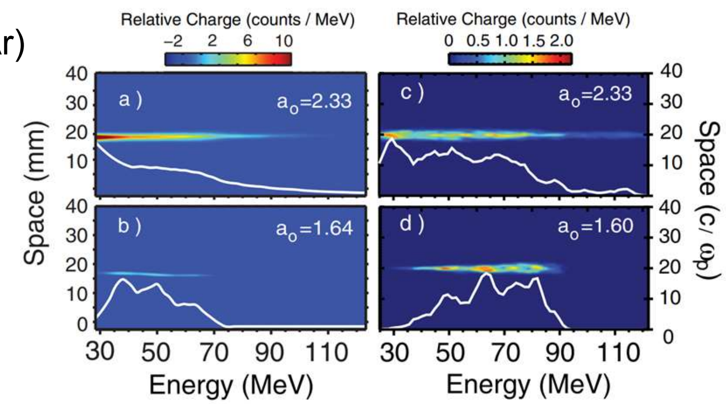


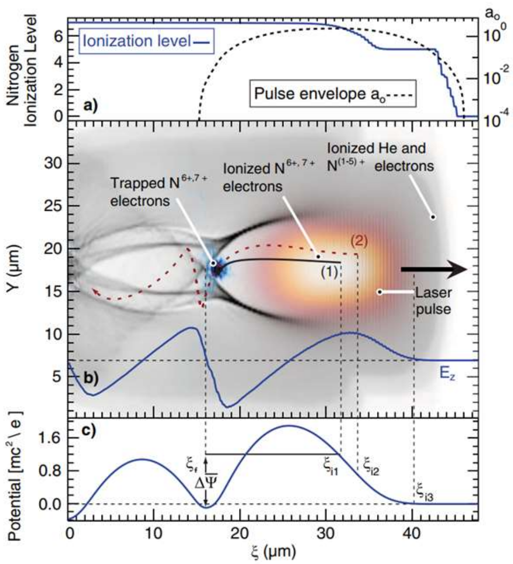
Faure et al, Nature 444 (2006)

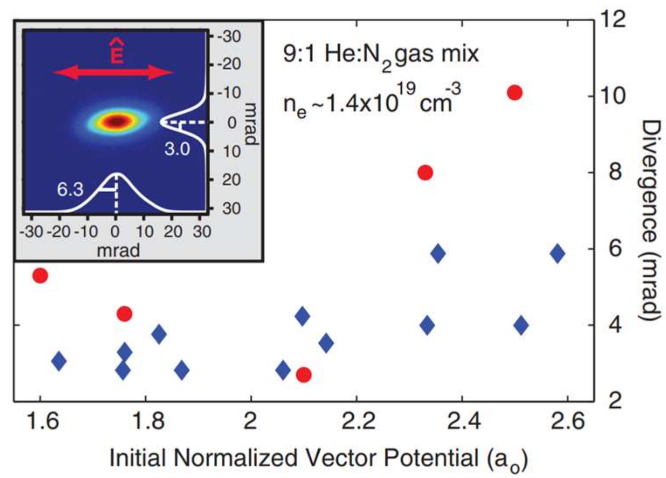
Injection mechanisms

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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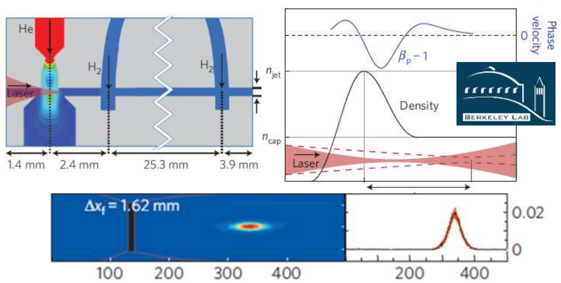
Injection mechanisms

4. Downramp injection

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

$\rightarrow$ slows down the plasma wave

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



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

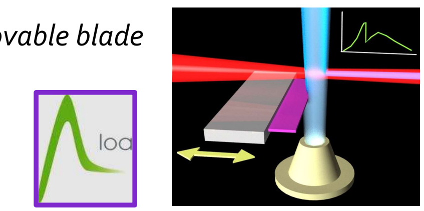
$$dk_p/dz = (k_p/2n_e)(dn_e/dz)$$

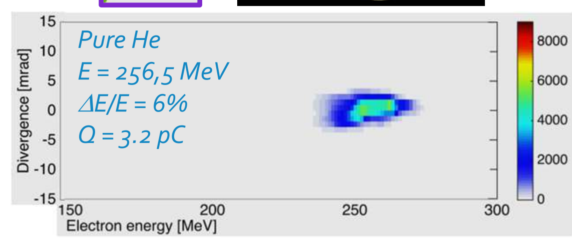
- **sharp density ramp** $L_{grad} \leq \lambda_p$

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

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

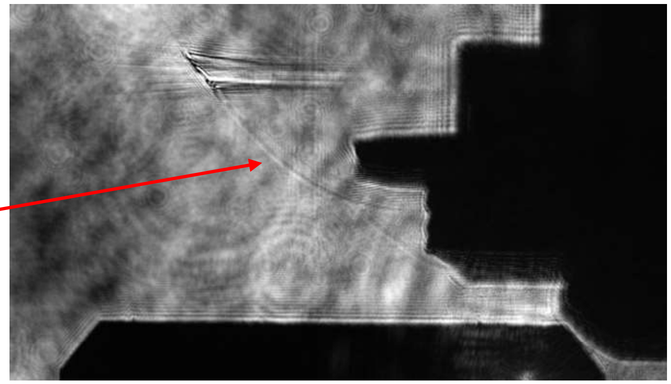
movable blade

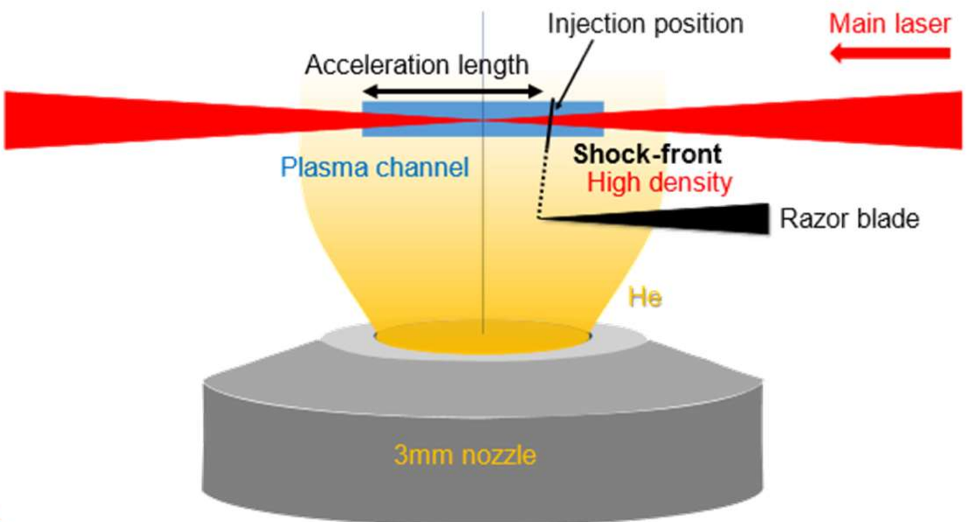


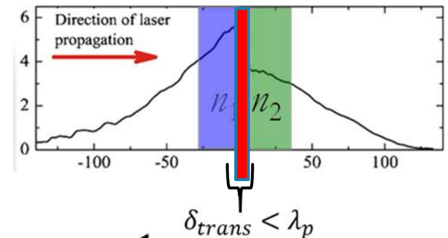


Principle of shock-front injection

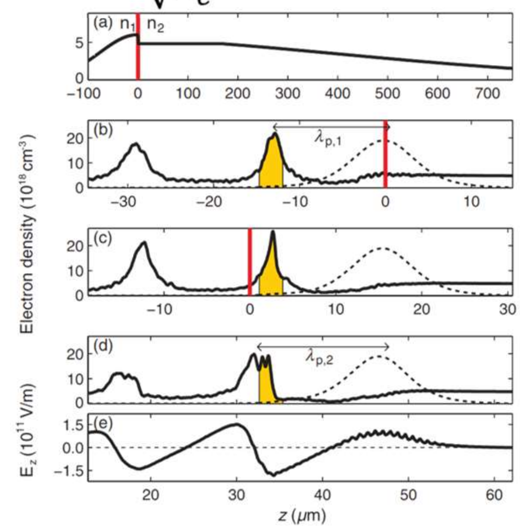
Shock wave





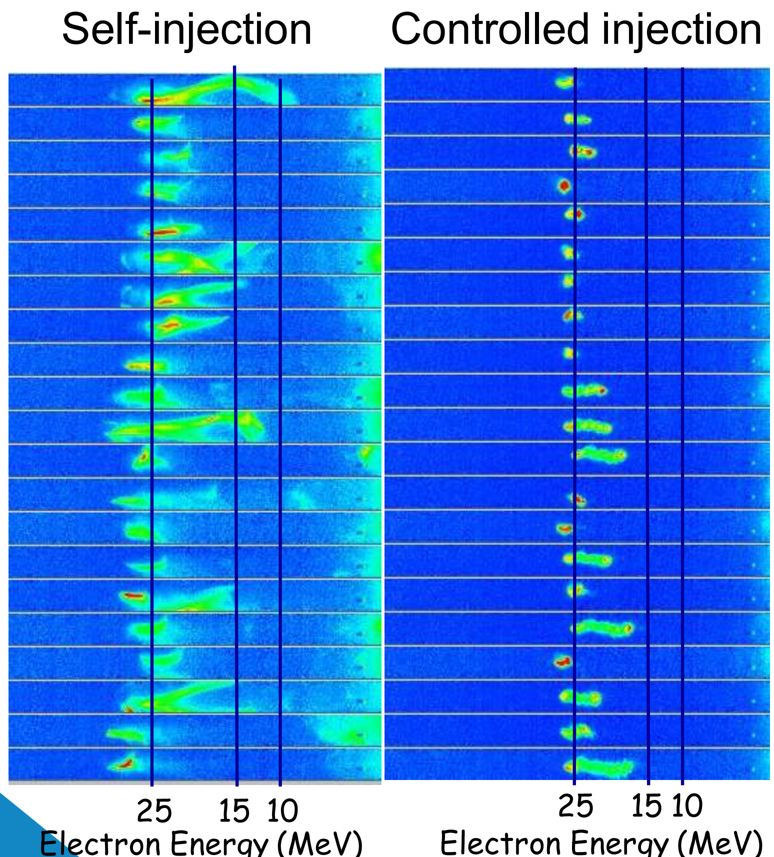


$$\lambda_p \propto \frac{1}{\sqrt{n_e}} \Longrightarrow \lambda_{p,1} < \lambda_{p,2}$$



Phys. Rev. Lett. 110, 185006 (2013)
Phys. Rev ST- Acc and beams 13,091201 (2010)

Improved electron spectra



Comparing the two good runs with injection by transverse wave-breaking and by sharp density transition

	Self-injection		Sharp density transition	
Peak energy	25.1	8.0 MeV	27.6	3.9 MeV
Mean energy spread	8.5 % (RMS)		2.6 % (RMS)	
Peak charge	3.8	3.8 pC	2.9	1.9 pC
Divergence	11.0	2.9 mrad	11.0	1.7 mrad
Pointing	3.8 mrad (RMS)		3.8 mrad (RMS)	

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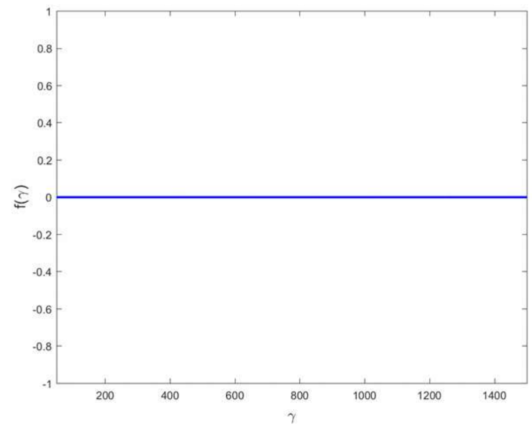
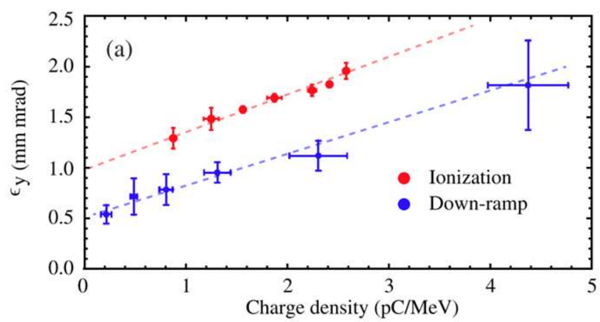
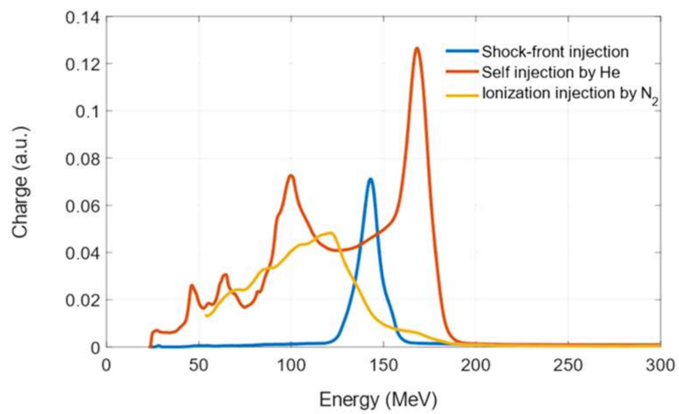
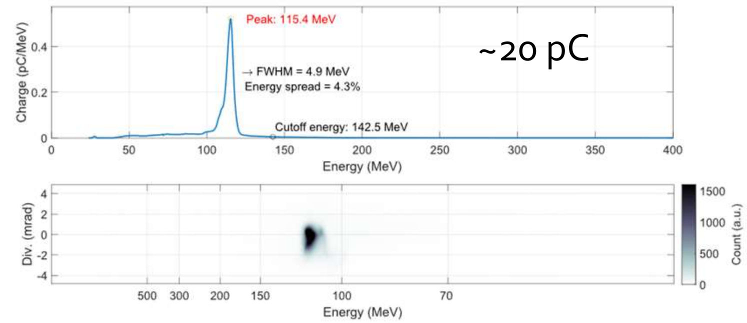




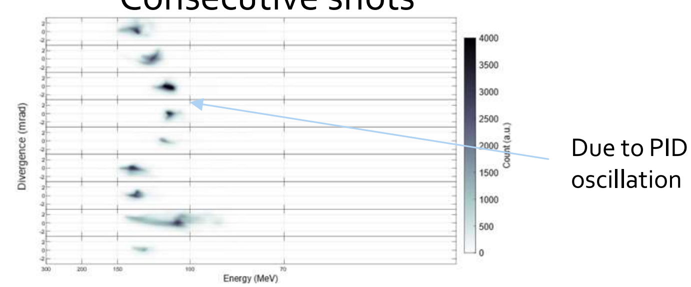
Properties of Shock-front Injection

Comparison of injection mechanism by NCU 100TW laser system





Consecutive shots



Injection method	Electron density (cm^{-3})
Ionization injection (N_2)	2.0×10^{18} (neutral)
Self-injection (He)	$8.5 \times 10^{18} - 1.0 \times 10^{19}$
Shock-front injection (He)	3.7×10^{18}

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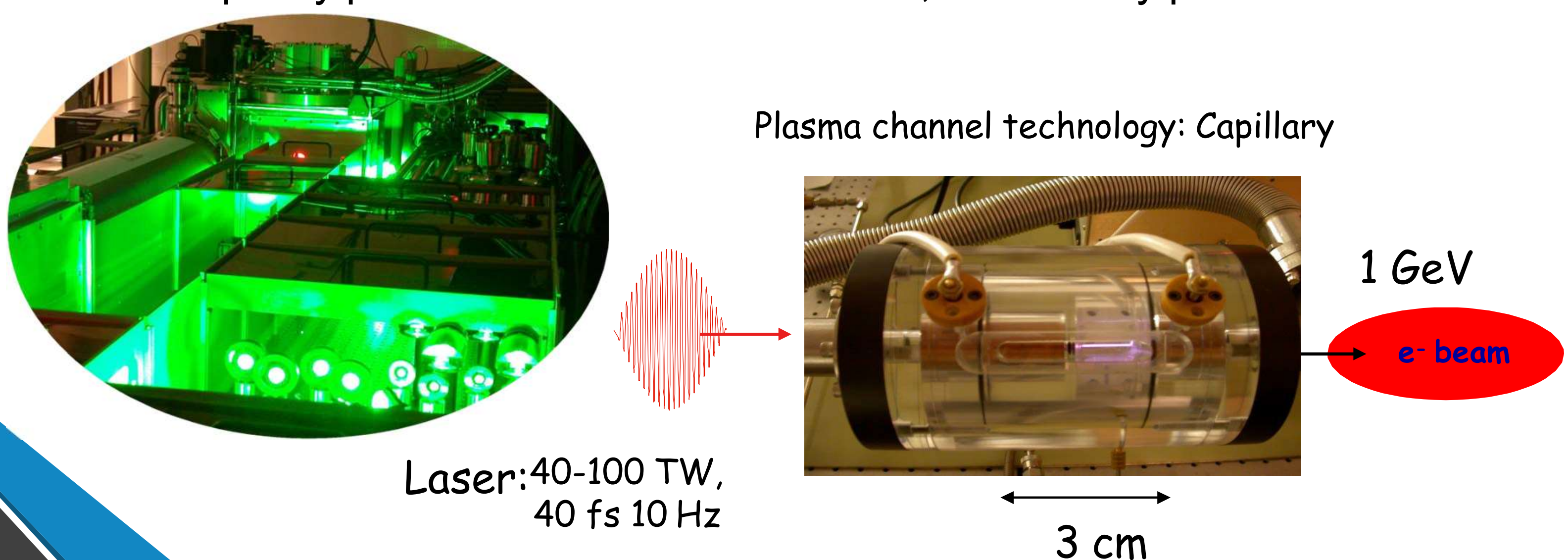
GeV: channeling over cm-scale

- 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} 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



0.5 GeV Beam Generation

225 μm diameter and 33 mm length capillary

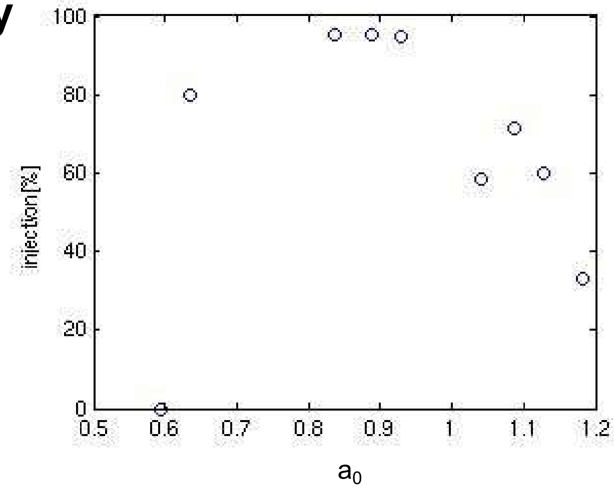
Density: 3.2-3.8x10^{18}/cm^3

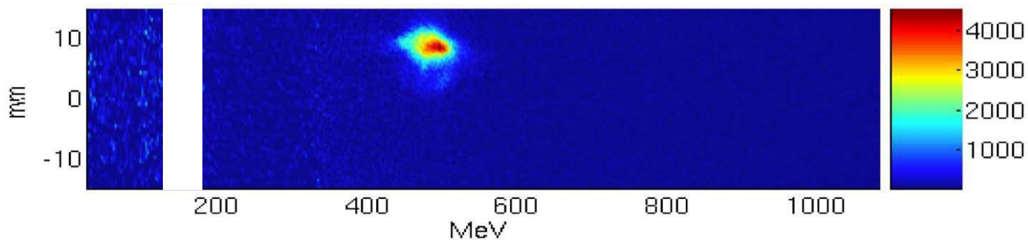
Laser: 950(±15%) mJ/pulse (compression scan)

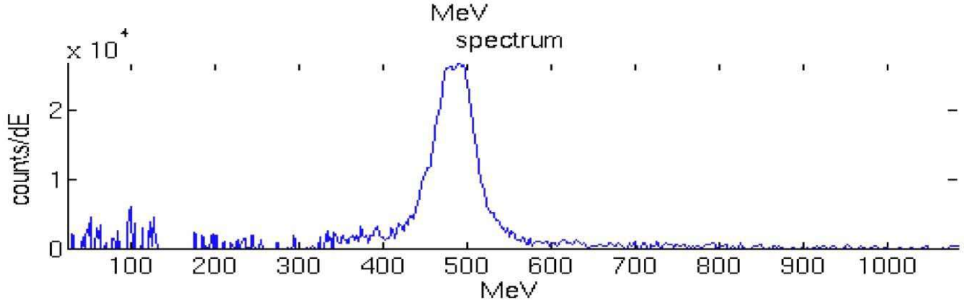
Injection threshold: a_0 ~ 0.65 (~9TW, 105fs)

Less injection at higher power

- Relativistic effects
- Self-modulation







Stable operation

500 MeV Mono-energetic beams:

a_0 ~ 0.75 (11 TW, 75 fs)

Peak energy: 490 MeV
Divergence(rms): 1.6 mrad
Energy spread (rms): 5.6%
Resolution: 1.1%
Charge: ~50 pC

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LETTERS

GeV electron beams from a centimetre-scale accelerator

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]

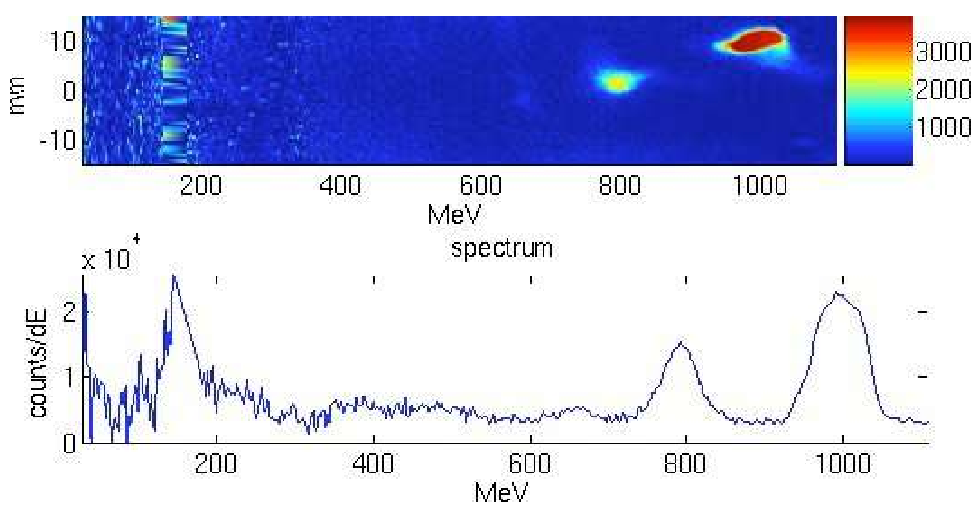
Published online: 24 September 2006;
doi:10.1038/nphys418 G

Laser → Plasma filled capillary → **1 GeV electrons**

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

Plasma filled capillary
Density: $4x10^{18}/cm^3$

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



1.0 GeV Beam Generation

312 μm diameter and 33 mm length capillary

Laser: 1500(±15%) mJ/pulse

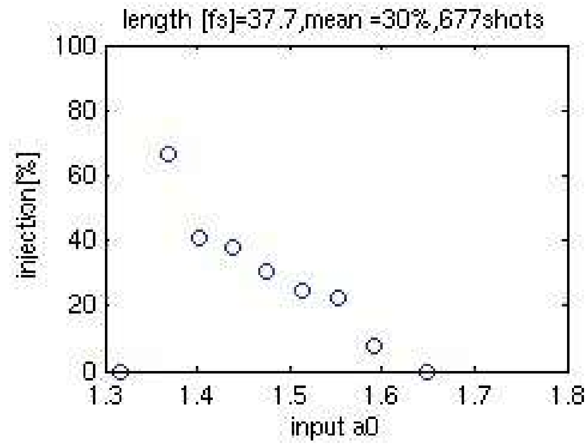
Density: $4 \times 10^{18}/cm^3$

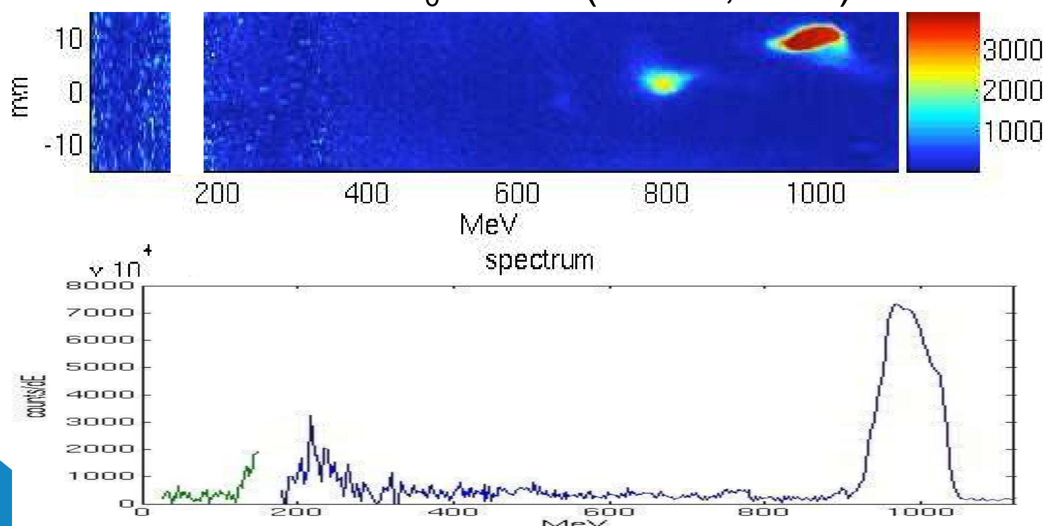
Injection threshold: a_0 ~ 1.35 (~35TW, 38fs)

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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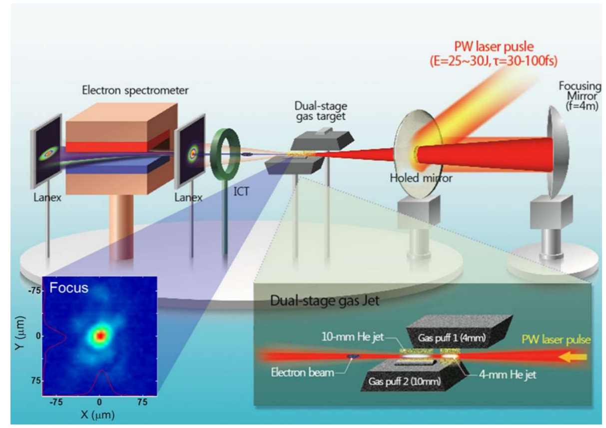
Multi-GeV Beam Generation

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,[1,2] 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*

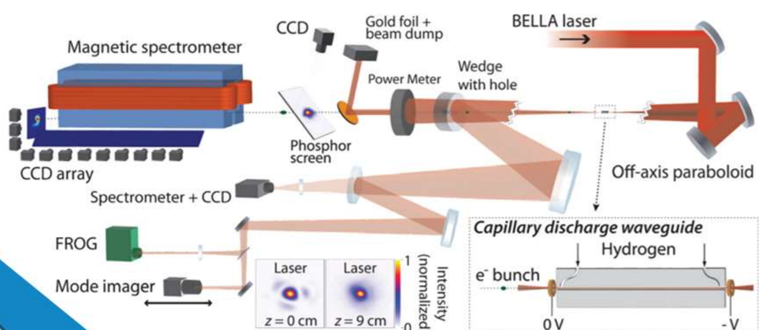


FIG. 1. Schematic of the experimental setup showing the target (inset) and diagnostics of the laser and electron beam. Typical laser spatial profiles with input laser pulse energy 16.6 J are shown at focus ($z = 0$) and at the exit of the capillary ($z = 9$ cm) for density 8×10^{17} cm^{-3}. The width 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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Propagation of non-relativistic laser light in plasma

$$\omega^2 = \omega^2 + c^2 k^2$$

- Index of refraction: $\omega/k = c/n_R$

$$n_R = \sqrt{1 - \frac{{\omega_p}^2}{\omega^2}} = \sqrt{1 - \frac{N_e}{N_c}} \qquad \omega_p = \sqrt{\frac{4\pi N_e e^2}{m_e}}$$

- Critical density:

$$N_c = \frac{m_e \omega^2}{4\pi e^2} \qquad N_c = 1.1 \times 10^{21}\ cm^{-3} / {\lambda_{\mu m}}^2$$

- Criteria of overdense ($n_e > N_c$) and underdense ($n_e < N_c$) plasmas
- Index of refraction in plasma is smaller than 1 !

$$n_R < 1$$

- No problem with relativity!
- Group velocity ($\frac{\partial \omega}{\partial k}$): $v_g = c n_R$

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Relativistic non-linear optics

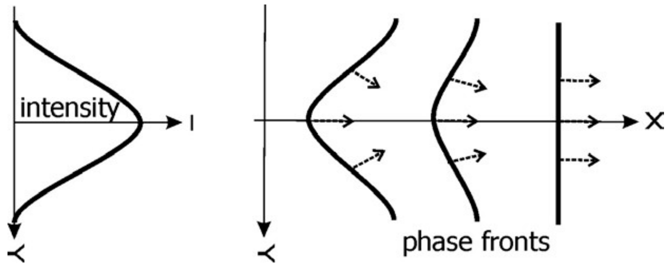
$$\omega^2 = \omega_p{}^2 + c^2 k^2$$

$$\omega_p{}^2 = 4\pi e^2 n_e / m\langle\gamma\rangle$$

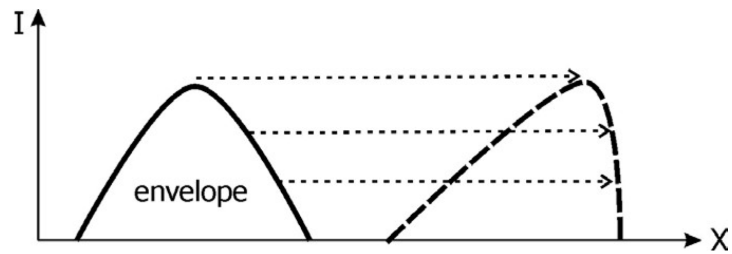
$$\gamma = 1 \Big/ \sqrt{1 - \frac{v^2}{c^2}}$$

$$n_R = \sqrt{1 - \frac{\omega_p{}^2}{\omega^2}}$$

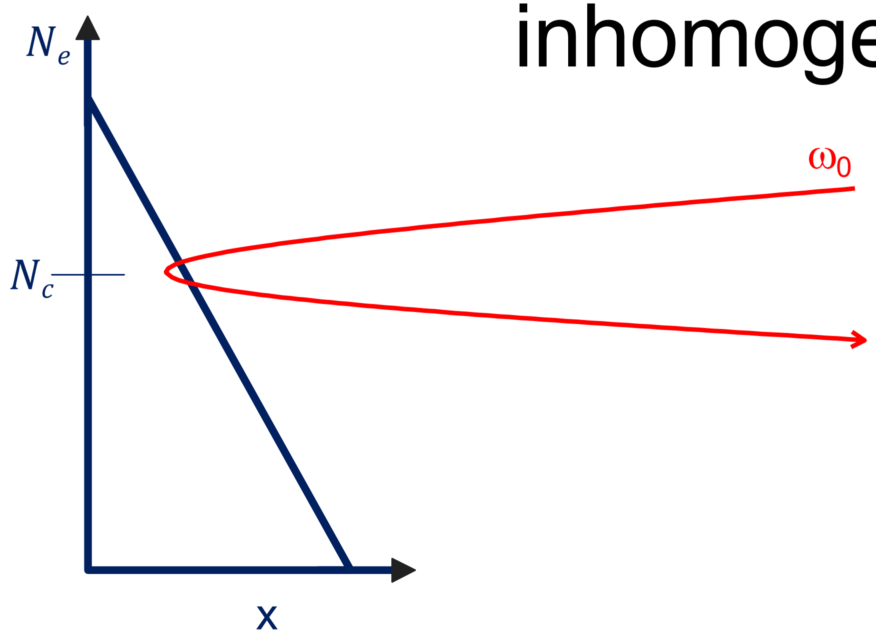
Self-focusing: $v_{ph} = c/n_R$



Profile steepening: $v_g = cn_R$



Propagation of non-relativistic laser light in inhomogeneous plasma



$$\vec{A}(r,t) = \mathrm{Re}\{\vec{A}_0 e^{i(\vec{k}\cdot\vec{r}-\omega t)}\}$$

$$\omega/_k = c/_{n_R}$$

- Reflection from the critical density (by perpendicular incidence)
- No significant penetration into the overdense region (just evanescent wave)
- Reflection from lower densities ($N_c cos^2\alpha$) by oblique incidence (α)

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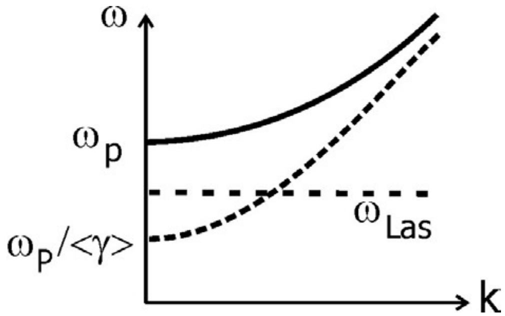
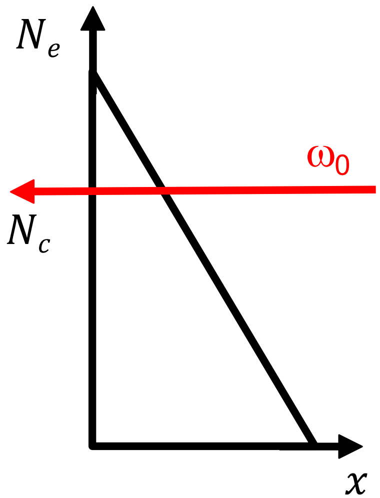
Relativistic non-linear optics

Induced transparency:





$$\omega^2 = \omega_p{}^2 + c^2k^2$$

$$\omega_p{}^2 = 4\pi e^2 n_e / m\langle\gamma\rangle$$

$$\gamma = 1 \Big/ \sqrt{1 - \frac{v^2}{c^2}}$$

$$n_R = \sqrt{1 - \frac{\omega_p{}^2}{\omega^2}}$$

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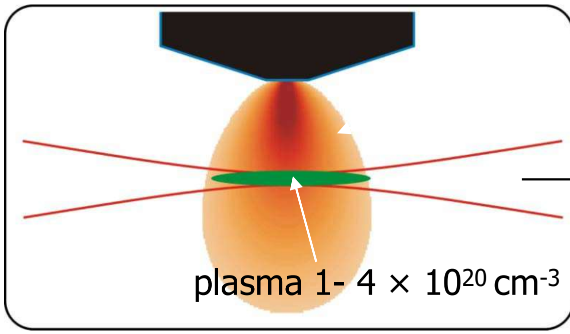
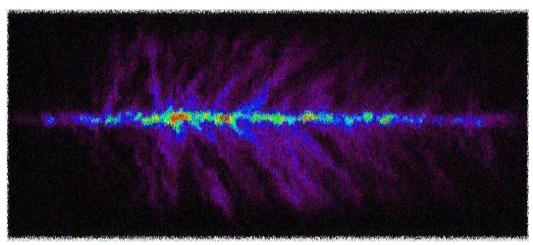
Plasma channels and electron beams observed

C. Gahn et al. PRL 83, 4772 (1999)

laser

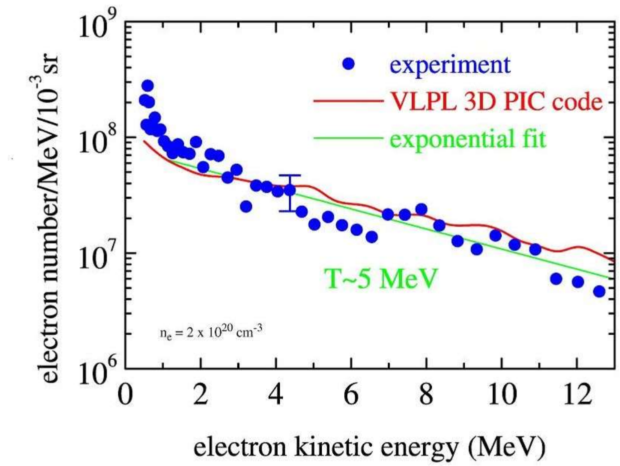
6×10^{19} W/cm^2





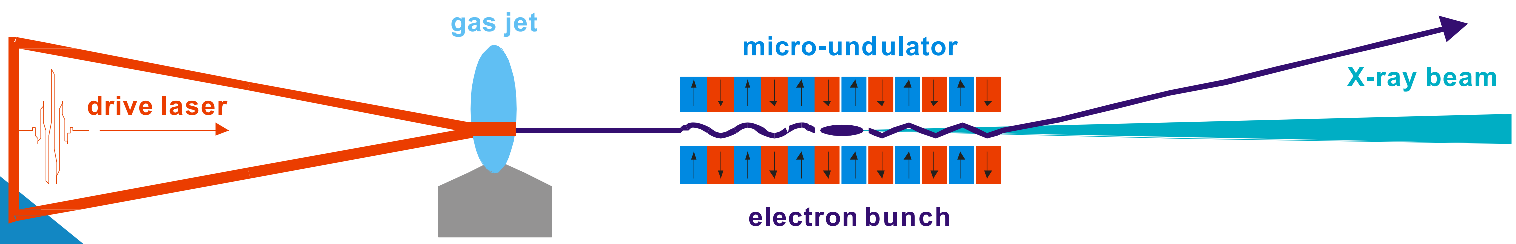
observed channel

electron spectrum



Application: Laser-driven X-ray sources

- K_α line radiation from laser produced plasma
- Bremsstrahlung from accelerated particles
- Transverse betatron oscillation of electrons in the „Bubble“
- Undulator, Table Top - Free Electron Laser



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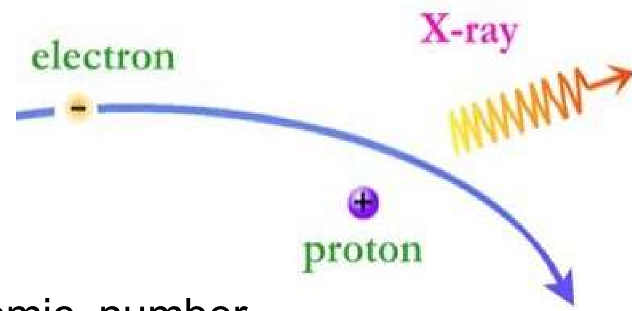
K_α line radiation and Bremsstrahlung

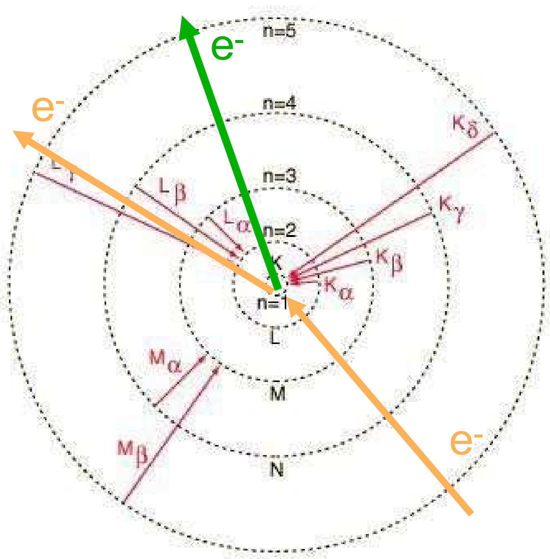
K_α radiation

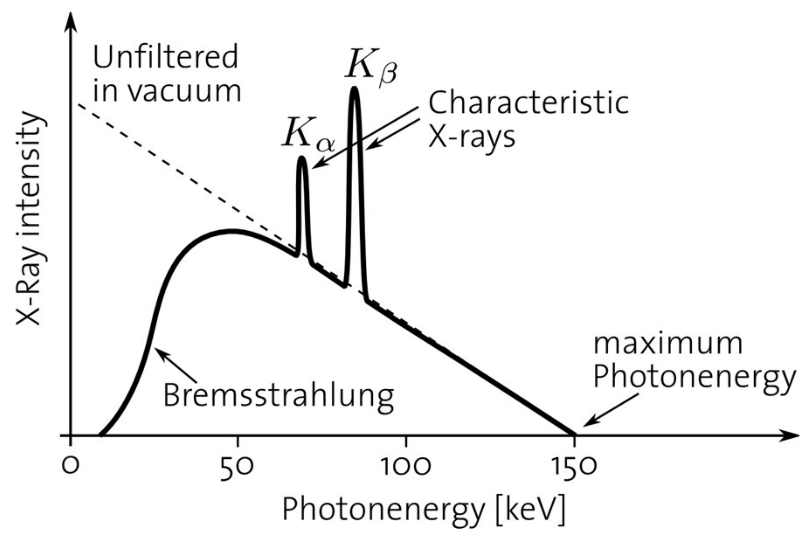
- Line emission → monochromatic
- Incoherent
- Duration can be few 100 fs
- 1-10 keV photon energy

Bremsstrahlung

- Broad spectrum
- Incoherent
- Intensive
- ~ Z^2 Z :atomic number







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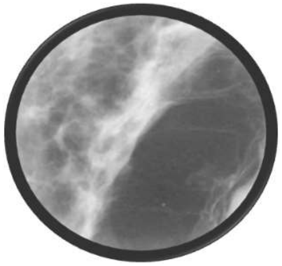
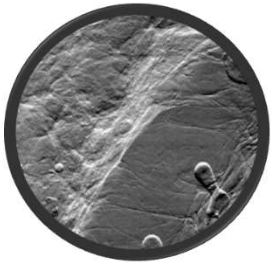
Imaging

- Application of bright X-Rays:
  - Small angle X-ray scattering
  - Phase Contrast Imaging
  - Ultrafast science
  - Biomolecular Imaging

- Requirements:
  - High energy (10-160 keV)
  - Spatial coherent X-Ray beams
  - Small emittance



X-ray absorption radiography image



X-ray phase contrast image

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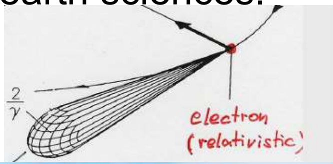
Synchrotron radiation light source

- **Synchrotron radiation** emitted from accelerated charged particles can produce very intense radiation at X-ray frequencies
- The last decades, vast increase in the use of synchrony radiation **for photon science**. Some uses: material sciences; life sciences; earth sciences.



Radiation from ultra-relativistic electrons: forward direction.

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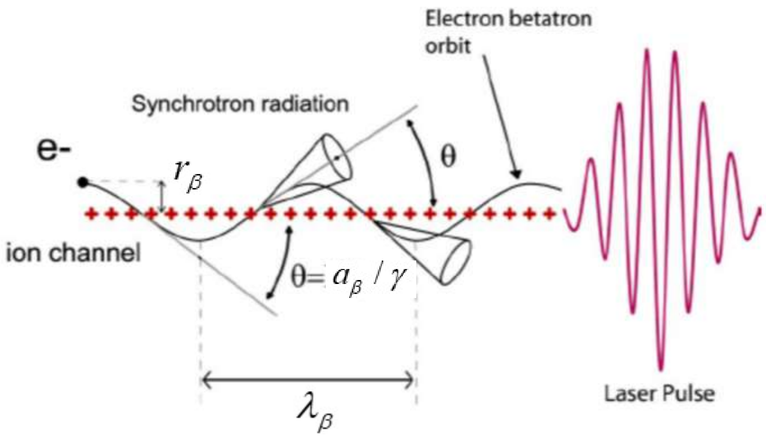
Introduction of Betatron Radiation



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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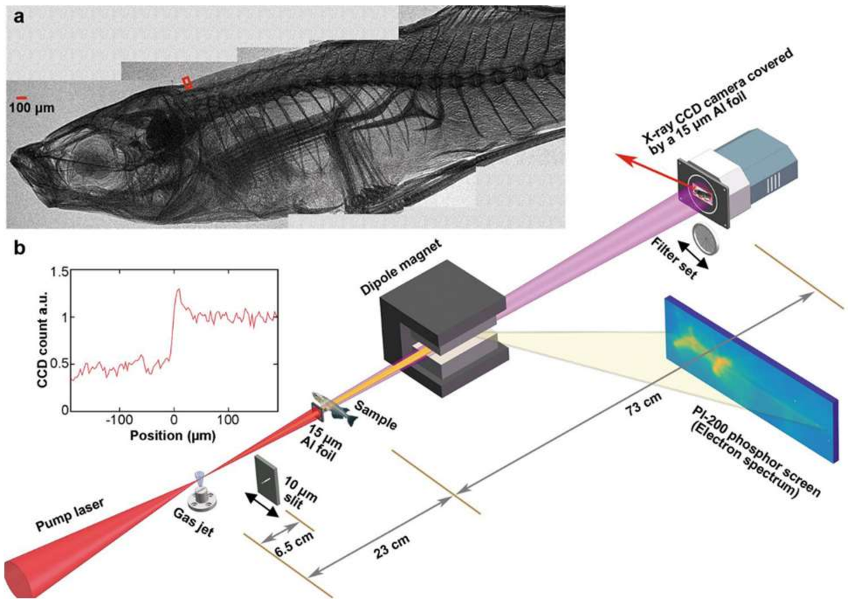
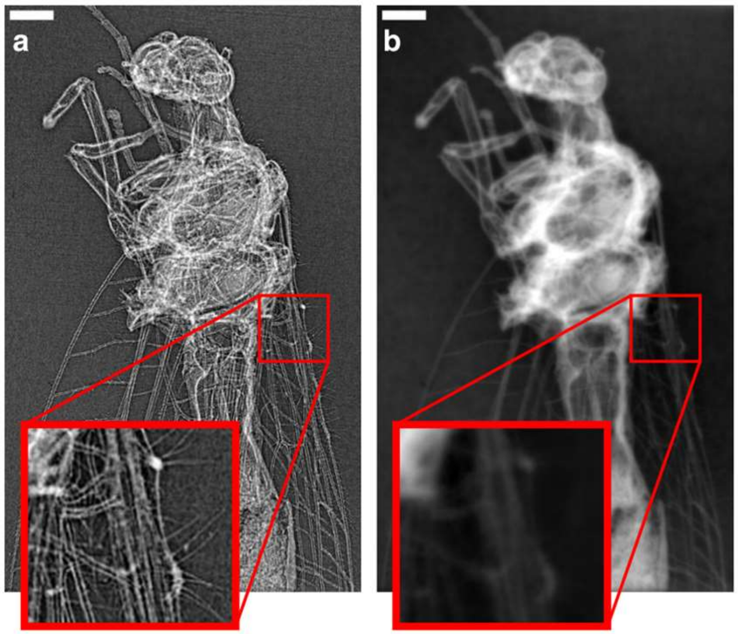


Scientific Reports **volume 9**, Article number: 7796 (2019)



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

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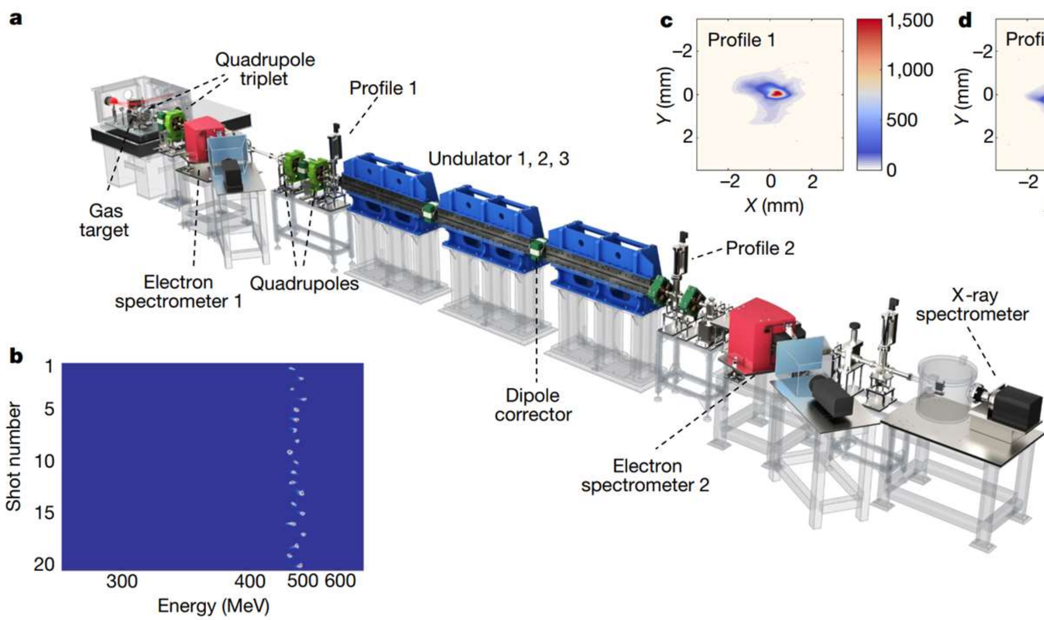
Free Electron Laser



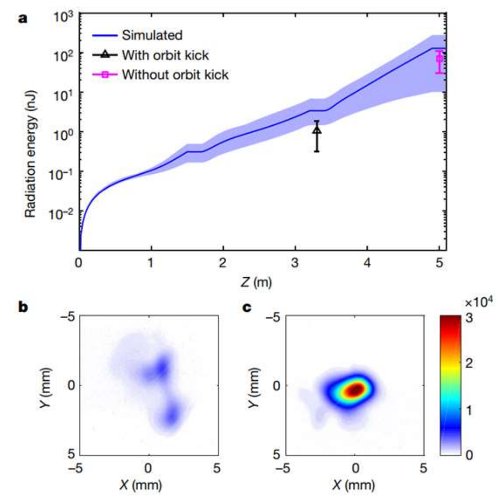


Fig. 3 | Undulator radiation measurement at 27 nm. a, Measured radiation energy with (black) and without (magenta) the orbit kick and the simulated energy along the undulator. Error bars represent the r.m.s. statistical uncertainty in the measured energy averaged over 20 shots. **b**, **c**, Corresponding transverse-beam patterns of the radiation measured with (**b**) and without (**c**) the orbit kick. The scale bar is normalized.

Nature **volume 595**, pages516–520 (2021)

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