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Laser applications for accelerators:

Introduction to the frontiers

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Contents

- Advanced accelerator concepts
- Laser accelerators
  - Lawson–Woodward theorem
  - Electron acceleration
    - *Vacuum accelerators and ponderomotive force*
    - *Plasma accelerators*
    - *Laser driven meta structures*
    - *Inverse free electron lasers*
  - Ion accelerations
- Application
  - Table top Thomson scattering source
  - Table top free electron lasers
    - *Laser-laser concept*
    - *Laser undulator*
  - Mini colliders concept

Contents

- Need for advanced accelerator concepts
- Laser accelerators
  - Lawson–Woodward theorem
  - Electron acceleration
    - *Vacuum accelerators*
    - *Plasma accelerators*
    - *Laser driven dielectric structures*
    - *Inverse free electron lasers*
  - Ion accelerations
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  - Table top free electron lasers
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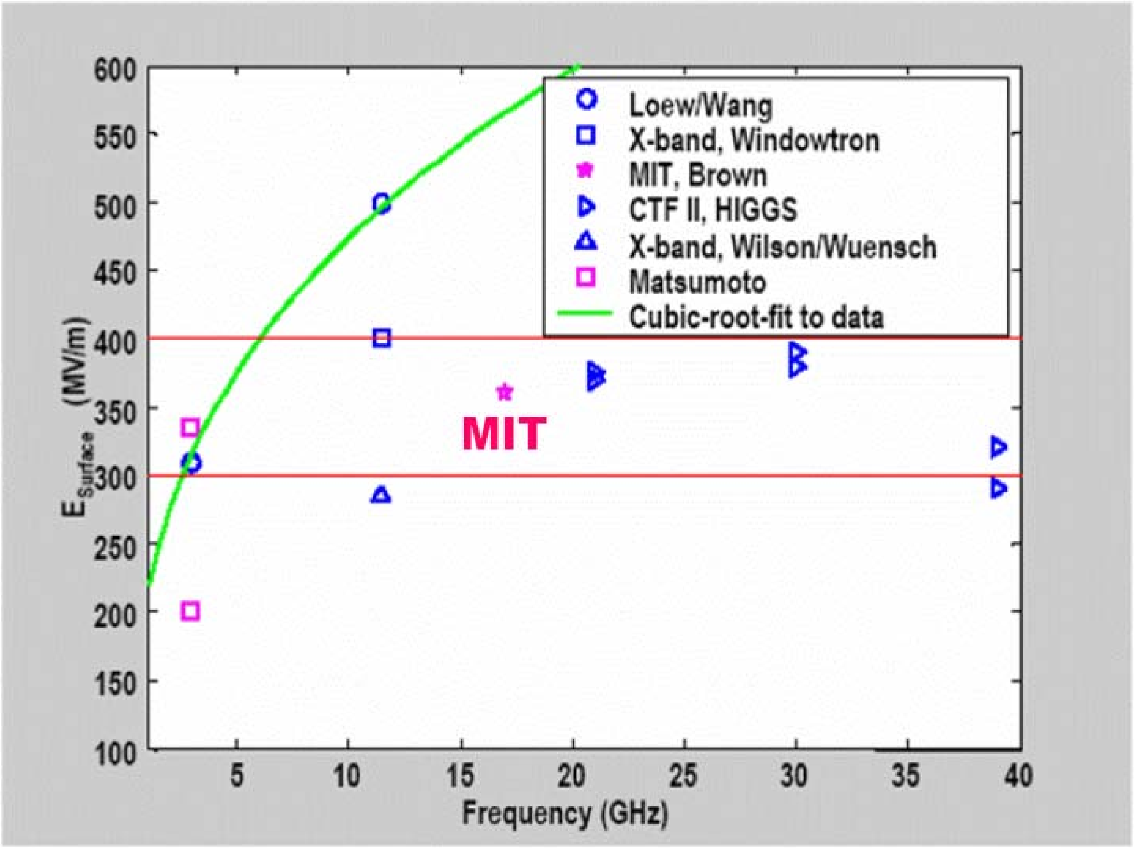
Why do we need advanced concepts



- Cost, and science
- Traditional accelerators:
  - gradient: <100 MV/m limited by material break down
  - Thus large facilities
- To shrink the facility one needs higher gradient:
  - Higher frequency to avoid break down L band (1.3 GHz)→S Band (3 GHz) →X band(11 GHz), Ku band (15 GHz)
  - How about optical frequency (~100 THz)
  - How about no material or material already broken?

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Laser concept: Current high intensity laser parameters

Written the laser field in term so the vector potential **A**

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{c\partial t}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

Define the normalized vector potential as

$$\mathbf{a} = \frac{e\mathbf{A}}{m_e c^2}$$

And the **laser strength parameter** is given by

$$a_0 = \left(\frac{2e^2 \lambda_0^2 I}{\pi m_e^2 c^5} \right)^{1/2} \cong 0.855 \times 10^{-9} I^{1/2} \left[\mathrm{W/cm^2} \right] \lambda_0 [\mu\mathrm{m}]$$

I: laser peak intensity, λ is the wavelength

The amplitude of the transverse electric field of linearly polarized laser is

$$E_L [\mathrm{TV/m}] = \frac{m_e c^2 k}{e} a_0 \cong 3.21 \frac{a_0}{\lambda[\mu\mathrm{m}]} \cong 2.7 \times 10^{-9} I^{1/2} \left[\mathrm{W/cm^2} \right]$$

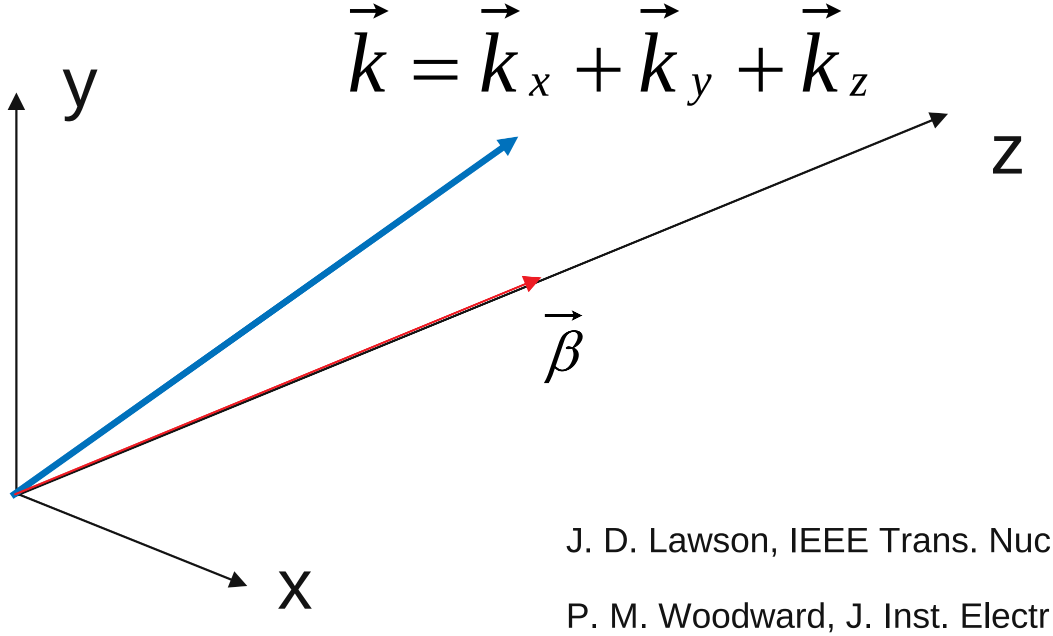
At $I = 1 \times 10^{18}$ W/cm^2, $E_L = 2.7$ TV/m

E. Esary, LBNL Report, LBNL-53510, 2003

Lawson–Woodward theorem

There is no net energy gain for an electron when interacting with a laser field

- Laser field in vacuum, no boundaries or walls
- The electron is highly relativistic, $\beta \to 1$
- No static E or B field in presence
- Region of interaction is infinite



$$\vec{k} = \vec{k}_x + \vec{k}_y + \vec{k}_z$$

J. D. Lawson, IEEE Trans. Nucl. Sci. NS-26, 4217 (1979).

P. M. Woodward, J. Inst. Electr. Eng. **93**, 1554 (1947).

Lawson–Woodward theorem

An electron propagating in z is accelerated by $E_{z,}$ and in vacuum this is

$$E_z = \frac{1}{2\pi}\int dk_x \int dk_y \hat{E}_z(k_x,k_y)\exp\left[i(k_x x + k_y y + k_z z - \omega t)\right]$$

In vacuum, one has

$$k_z = \sqrt{(\omega/c)^2 - k_x^2 - k_y^2}, \quad k = \omega/c$$

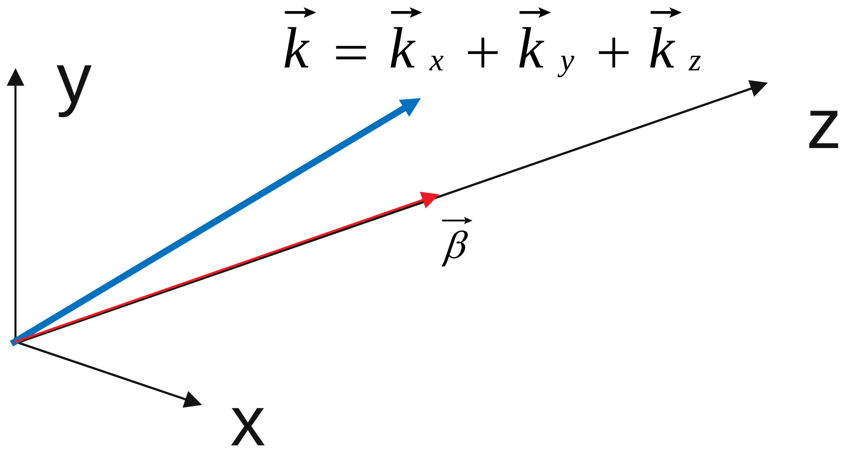
Field in Fourier space

$$\hat{E}_z = -\frac{1}{k_z}\left(k_x\hat{E}_x + k_y\hat{E}_y\right) \longleftarrow \nabla\cdot\vec{E} = 0 \Rightarrow k_z\hat{E}_z + k_x\hat{E}_x + k_y\hat{E}_y = 0$$

Assuming linear polarization along x, and the electron propagate along z with x=y=0, thus

$$\hat{E}_z = -\frac{1}{k_z}\left(k_x\hat{E}_x + k_y\hat{E}_y\right) = -\frac{k_x}{k_z}\hat{E}_x$$

$$\exp\left[i(k_x x + k_y y + k_z z - \omega t)\right] = \exp\left[i(k_z z - \omega t)\right]$$



$$\vec{k} = \vec{k}_x + \vec{k}_y + \vec{k}_z$$

E. Esarey et al., Phys. Rev. E 52, 5443 (1995).

Lawson–Woodward theorem

Assuming linear polarization along x, and the electron propagate along z with x=y=0, thus the energy gain is

$$\Delta U = q\int E_z dz = \frac{q}{2\pi}\int dk_x \int dk_y \frac{k_x}{k_z}\hat{E}_x(k_x,k_y)\int dz\exp[i(k_z z-\omega t)]$$

If there is no boundary and the integration for z is on infinity

$$\int_{-\infty}^{\infty} dz\exp[i(k_z z-\omega t)] = \delta(k_z - k)$$

$$k_z z-\omega t = k_z z - kct = (k_z - k)z$$

$$\Rightarrow \Delta U = q\int_{-\infty}^{\infty} E_z dz = \frac{q}{2\pi}\int dk_x \int dk_y \frac{k_x}{k_z}\hat{E}_x(k_x,k_y)\delta(k_z - k)$$

Clearly, $\delta(k_z-k)\neq 0$ only when $k_z=k$, then $k_x=0$. Thus under this condition

$$\Rightarrow \Delta U = q\int_{-\infty}^{\infty} E_z dz = 0$$

E. Esarey et al., Phys. Rev. E 52, 5443 (1995).

Lawson–Woodward theorem

$$\Delta U = q\int E_z dz = \frac{q}{2\pi}\int dk_x \int dk_y \frac{k_x}{k_z}\hat{E}_x(k_x,k_y)\int dz \exp[i(k_z z-\omega t)]$$

Now, terminating the field at z=0, now we have a gain dependent on the phase of the laser

$$\Delta U = \frac{q}{2\pi}\int dk_x \int dk_y \frac{k_x}{k_z}\hat{E}_x(k_x,k_y)\int_{-\infty}^{0} \exp[i(k_z z-\omega t)]dz$$

It is clear one has to break the Lawson-Woodward theorem for energy gain.

How?

E. Esarey et al., Phys. Rev. E 52, 5443 (1995).

Break the Lawson-Woodward spell in semi vacuum

- For a Gaussian beam propagating along ***z***’, and electron propagating along ***z***

$$E_\perp(x',y',z',t)=\frac{E_0}{\sqrt{1+\left(z'/z_0\right)^2}}\exp\left[-\frac{x'^2+y'^2}{w(z')^2}\right]\exp\left\{i\left[\omega t-kz'-\eta(z')-\frac{kx'^2}{2R(z')}-\varphi\right]\right\}$$

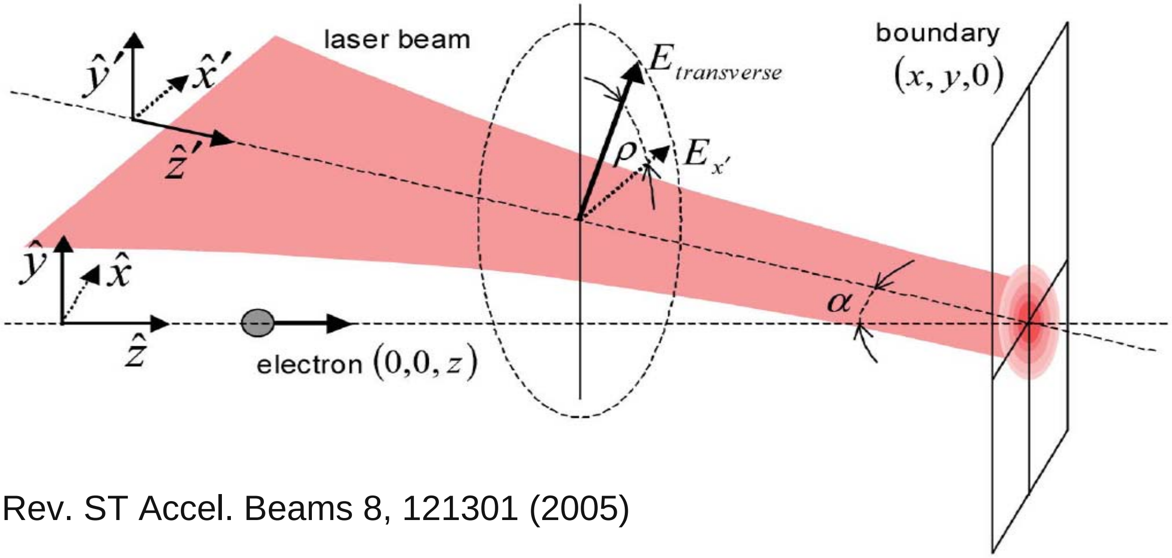
$$z_0=\pi\frac{w_0^2}{\lambda},\; w(z')=w_0\left[1+\left(z'/z_0\right)^2\right],\; R(z')=z\left[1+\left(z'/z_0\right)^2\right],\; \eta(z')=\tan^{-1}\left(z'/z_0\right)$$

- The field along ***z’*** is, obtained from Gauss’s law, $\nabla\cdot\vec{E}=0$

$$E_{z'}(x',z')=-2x'\left[\frac{1}{w(z')^2}+\frac{ik}{2R(z')}\right]E_{x'}(z')$$

- The field along ***z***

$$E_z(z)=E_{z'}\cos\alpha+E_{x'}\sin\alpha$$



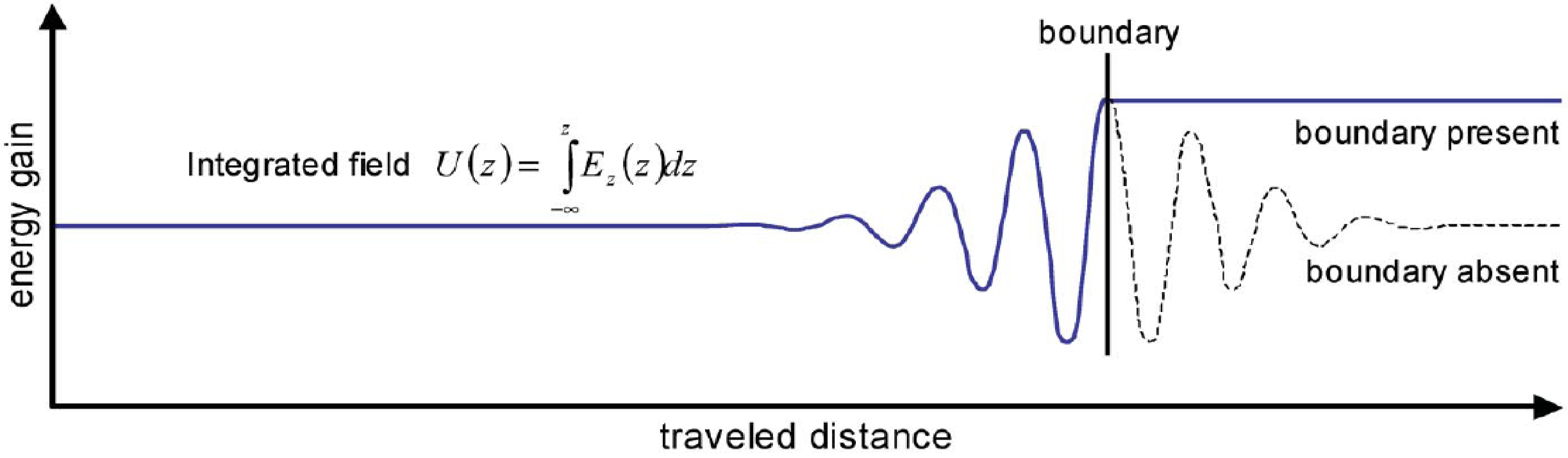
T. PLETTNER et al., PRL 95, 134801 (2005); Phys. Rev. ST Accel. Beams 8, 121301 (2005)

Semi Vacuum energy gain

- The energy gain of the electron

$$\Delta U = \int_{-\infty}^{0} qE_z(z)dz \sim \frac{\lambda e E_0}{\pi}\frac{\alpha}{\alpha^2 + 1/\gamma^2}\cos\rho\cos\varphi$$

Where ϕ is the phase of the laser



Semi vacuum: experiment

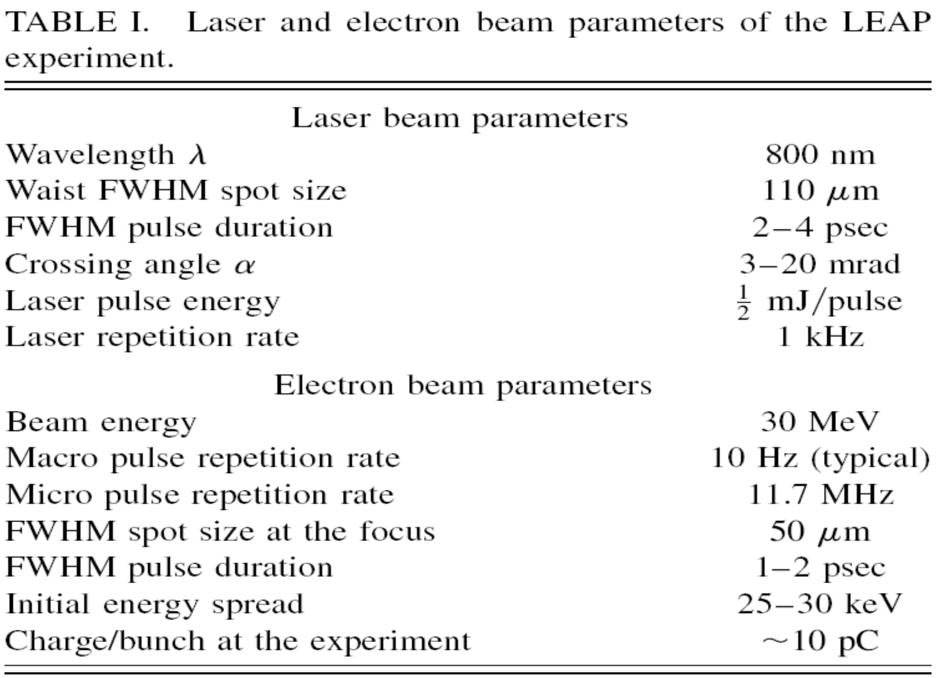
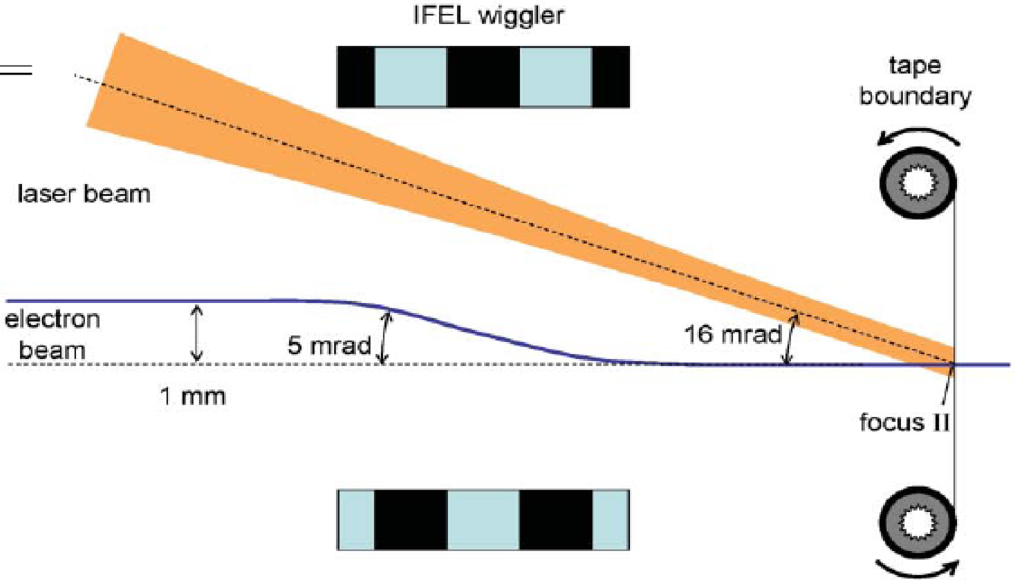


TABLE I. Laser and electron beam parameters of the LEAP experiment.

Laser beam parameters	
Wavelength λ	800 nm
Waist FWHM spot size	110 μm
FWHM pulse duration	2–4 psec
Crossing angle α	3–20 mrad
Laser pulse energy	$\frac{1}{2}$ mJ/pulse
Laser repetition rate	1 kHz
Electron beam parameters	
Beam energy	30 MeV
Macro pulse repetition rate	10 Hz (typical)
Micro pulse repetition rate	11.7 MHz
FWHM spot size at the focus	50 μm
FWHM pulse duration	1–2 psec
Initial energy spread	25–30 keV
Charge/bunch at the experiment	$\sim$10 pC

$$\Delta U \sim \cos\varphi$$

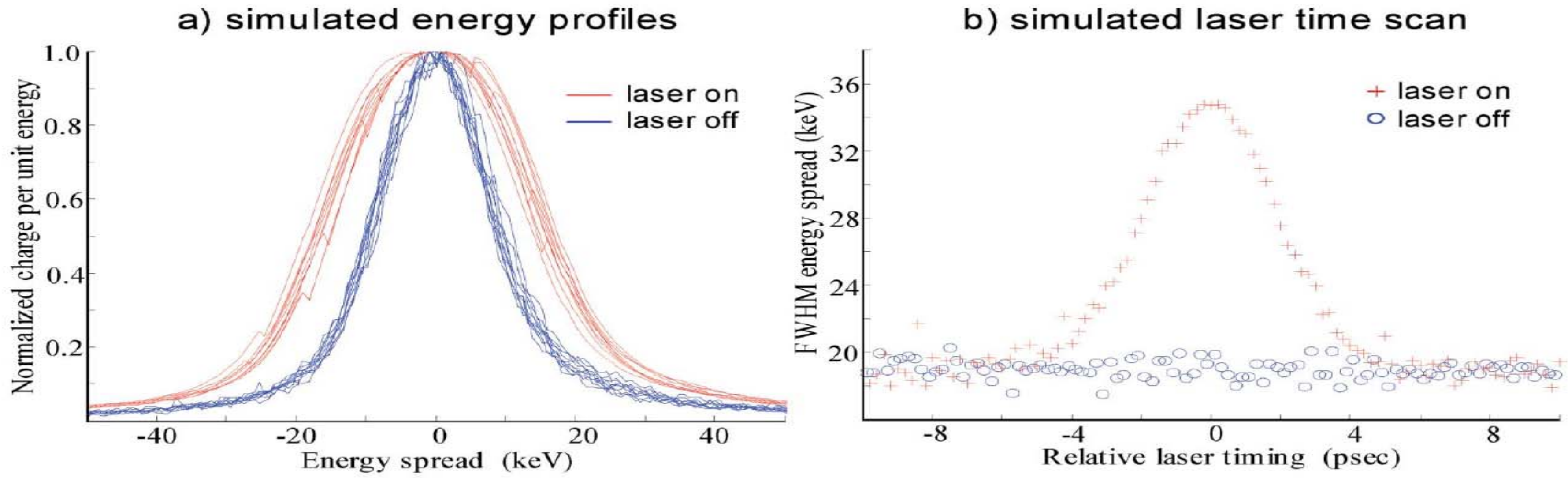
The gain is dependent on the phase, which normally we have no control, we only expect to a bigger energy spread.



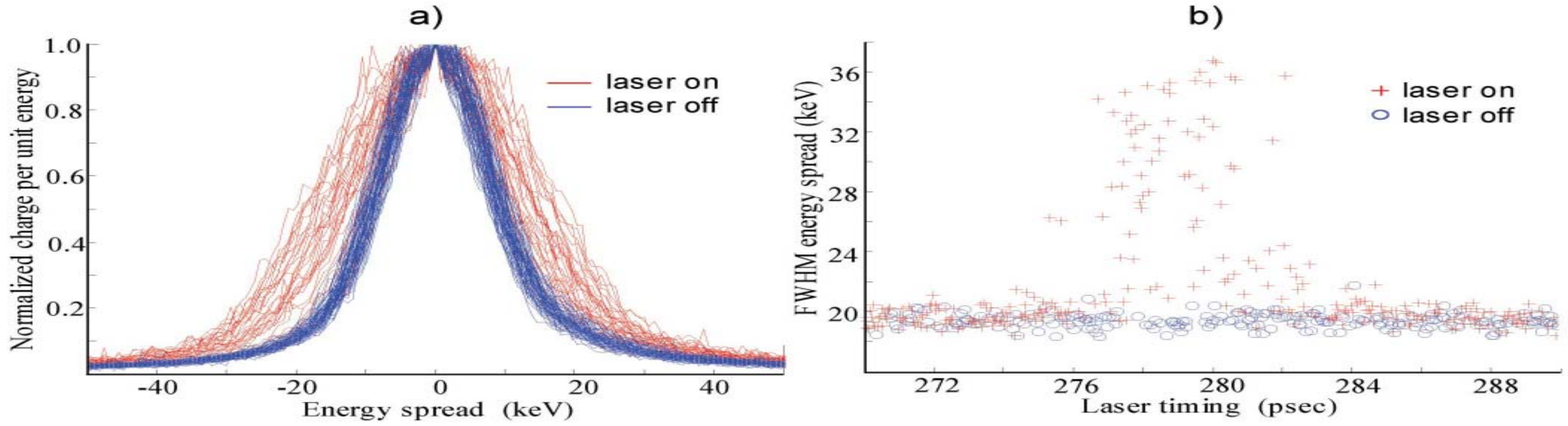
(b)

T. PLETTNER et al., PRL 95, 134801 (2005); Phys. Rev. ST Accel. Beams 8, 121301 (2005)

Semi vacuum: experiment


a) simulated energy profiles

b) simulated laser time scan


a)

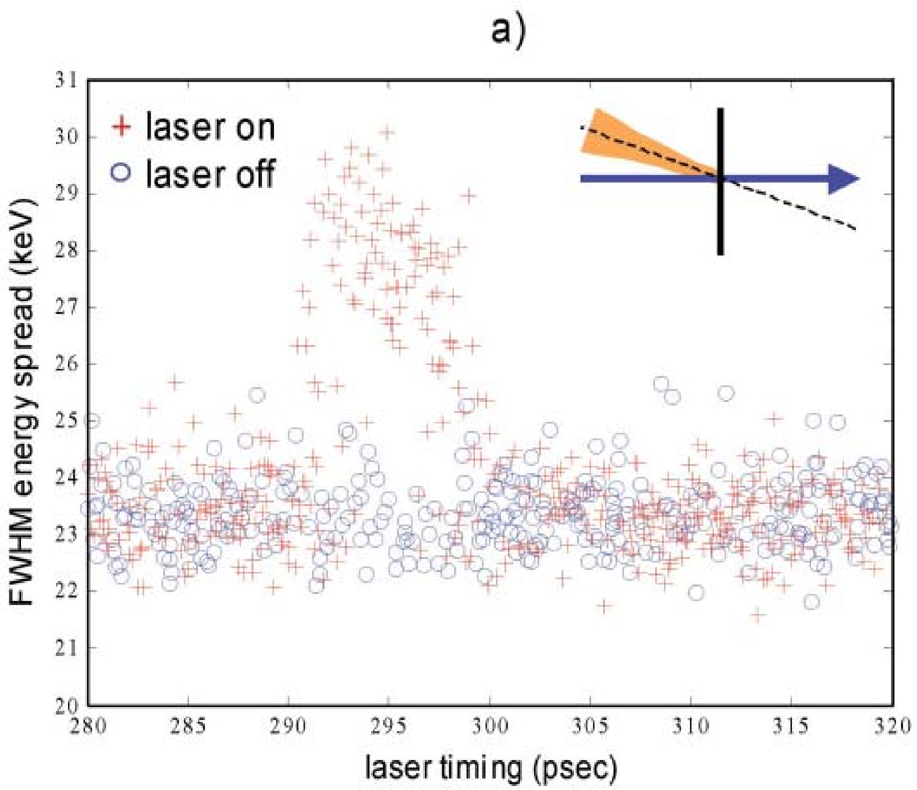
b)

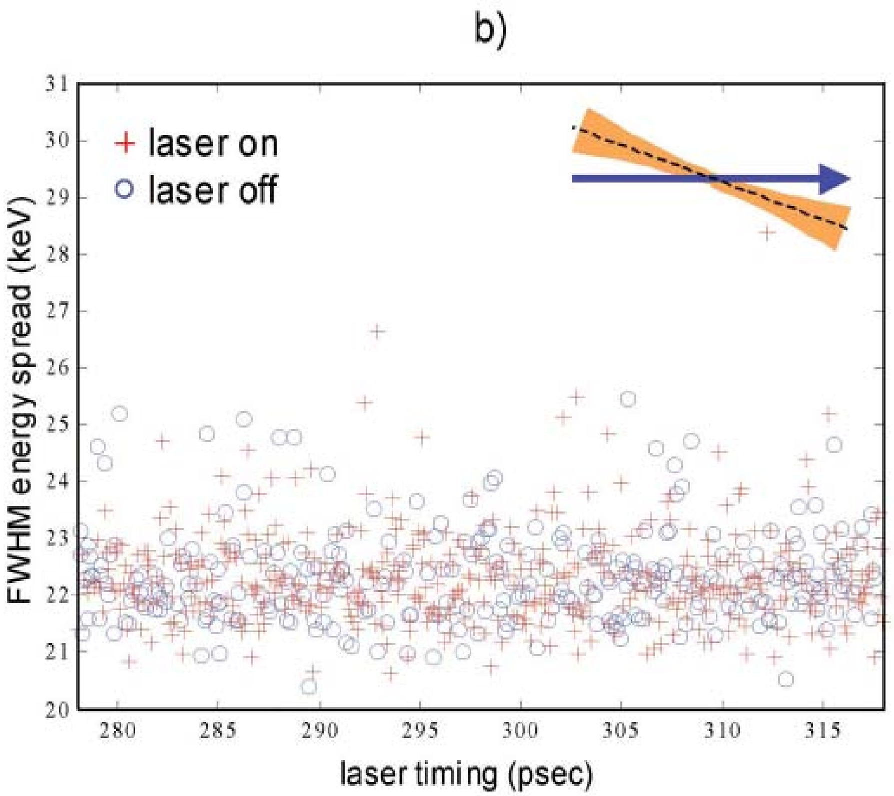
FIG. 8. (Color) (a) Experimentally observed laser-driven energy modulation near the condition of optimum temporal overlap. (b) Laser time scan showing the FWHM energy spread of the electron beam.

Energy gain:40 keV

T. PLETTNER et al., PRL 95, 134801 (2005); Phys. Rev. ST Accel. Beams 8, 121301 (2005)

Experiment results





T. PLETTNER et al., PRL 95, 134801 (2005); Phys. Rev. ST Accel. Beams 8, 121301 (2005)

Other way to break the spell of Lawson–Woodward theorem

- Tailoring laser beam spatial/temporal profile
  - High order Gaussian beam (E. Esarey et al., Phys. Rev. E 52, 5443 (1995))
  - Crossing beams (E. Esarey et al., Phys. Rev. E 52, 5443 (1995))
  - Beat wave (E. Esarey et al., Phys. Rev. E 52, 5443 (1995))
  - Bessel beam (Hafizi et al, Phys. Rev. E 55, 3539 - 3545 (1997))
  - With presence of B field, IFEL
  - Your own scheme
- Problems
  - No good control of laser-electron phase
  - Difficult to stage

Ponderomotive accelerator

Ponderomotive acceleration and scattering (F.V. Hartemann et al.,PR E,51,4833,1995)

- Considering a particle moving in a laser field

$$\boldsymbol{E}(\boldsymbol{r},t) = \boldsymbol{E}_0(\boldsymbol{r})\cos\omega t$$

$$\boldsymbol{B}(\boldsymbol{r},t) = \boldsymbol{B}_0(\boldsymbol{r})\sin\omega t$$

$$\boldsymbol{B}_0 = -\frac{1}{\omega}\nabla\times\boldsymbol{E}_0$$

$$m\dot{\boldsymbol{v}} = q\left[\boldsymbol{E}_0(\boldsymbol{r})\cos\omega t + \boldsymbol{v}\times\boldsymbol{B}_0(\boldsymbol{r})\sin\omega t\right]$$

- One can rewrite separate the coordinate and the velocity into slow and fast components

$$\boldsymbol{r} = \boldsymbol{R} + \rho(\boldsymbol{R},\boldsymbol{U}t,\tau)$$

$$\boldsymbol{v} = \boldsymbol{U} + \boldsymbol{u}(\boldsymbol{R},\boldsymbol{U}t,\tau)$$

Thus the time averaging $<\rho>=<\boldsymbol{u}>=0$, $\boldsymbol{R}$ and $\boldsymbol{U}$ represent the average particle position and velocity. Thus

$$\dot{\boldsymbol{u}} = \frac{q}{m}\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t \quad \Rightarrow \begin{cases} \boldsymbol{u} = \dfrac{q}{m\omega}\boldsymbol{E}_0(\boldsymbol{R})\sin\omega t \\ \rho = -\dfrac{q}{m\omega^2}\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t \end{cases}$$

- And averaging $\langle\dot{\boldsymbol{r}}\rangle = \boldsymbol{v}$ gives $\dot{\boldsymbol{R}} = \boldsymbol{U}$

Ponderomotive force of a laser field

- Now we have

$$\boldsymbol{E}_0(\boldsymbol{r}) = \boldsymbol{E}_0(\boldsymbol{R}+\rho) = \boldsymbol{E}_0(\boldsymbol{R}) + (\rho\cdot\nabla)\boldsymbol{E}_0(\boldsymbol{R})$$

$$\boldsymbol{B}_0(\boldsymbol{r}) = \boldsymbol{B}_0(\boldsymbol{R}+\rho) = \boldsymbol{B}_0(\boldsymbol{R}) + (\rho\cdot\nabla)\boldsymbol{B}_0(\boldsymbol{R})$$

$$\langle\dot{\boldsymbol{v}}\rangle = \langle\dot{U}\rangle = \frac{q}{m}\langle[\underline{\boldsymbol{E}_0(\boldsymbol{R})} + \underline{(\rho\cdot\nabla)\boldsymbol{E}_0(\boldsymbol{R})}]\cos\omega t + \underline{\boldsymbol{u}\times[\boldsymbol{B}_0(\boldsymbol{R})} + (\rho\cdot\nabla)\boldsymbol{B}_0(\boldsymbol{R})]\sin\omega t\rangle$$

- The averaging is over time, thus
  - Zero-th order $\quad \frac{q}{m}\langle\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t\rangle = 0$
  - First order $\quad \frac{q}{m}\langle(\rho\cdot\nabla)\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t + \boldsymbol{u}\times\boldsymbol{B}_0(\boldsymbol{R})\sin\omega t\rangle$
  - Use these conditions

$$\begin{cases} \boldsymbol{u} = \dfrac{q}{m\omega}\boldsymbol{E}_0(\boldsymbol{R})\sin\omega t \\ \rho = -\dfrac{q}{m\omega^2}\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t \\ \boldsymbol{B}_0 = -\dfrac{1}{\omega}\nabla\times\boldsymbol{E}_0 \end{cases}$$

Ponderomotive force of a laser field

$$\begin{cases} \boldsymbol{u} = \dfrac{q}{m\omega}\boldsymbol{E}_0(\boldsymbol{R})\sin\omega t \\ \boldsymbol{\rho} = -\dfrac{q}{m\omega^2}\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t \\ \boldsymbol{B}_0 = -\dfrac{1}{\omega}\nabla\times\boldsymbol{E}_0 \end{cases}$$

- Now we have on the first order

$$\dot{\boldsymbol{U}} = \frac{q}{m}\left\langle \boldsymbol{\rho}\cdot\nabla\boldsymbol{E}_0(\boldsymbol{R})\cos\omega t + \boldsymbol{u}\times\boldsymbol{B}_0(\boldsymbol{R})\sin\omega t\right\rangle$$

$$= -\frac{q^2}{m^2\omega^2}\left\langle \left[\boldsymbol{E}_0(\boldsymbol{R})\cdot\nabla\right]\boldsymbol{E}_0(\boldsymbol{R})\cos^2\omega t + \boldsymbol{E}_0(\boldsymbol{R})\times\left[\nabla\times\boldsymbol{E}_0(\boldsymbol{R})\right]\sin^2\omega t\right\rangle$$

$$= -\frac{1}{2}\frac{q^2}{m^2\omega^2}\left[\underline{(\boldsymbol{E}_0\cdot\nabla)\boldsymbol{E}_0 + \boldsymbol{E}_0\times(\nabla\times\boldsymbol{E}_0)}\right]$$

- From vector identity

$$\nabla(\boldsymbol{A}\cdot\boldsymbol{B}) = \boldsymbol{A}\times(\nabla\times\boldsymbol{B}) + \boldsymbol{B}\times(\nabla\times\boldsymbol{A}) + (\boldsymbol{A}\cdot\nabla)\boldsymbol{B} + (\boldsymbol{B}\cdot\nabla)\boldsymbol{A}$$

$$\Rightarrow \frac{1}{2}\nabla\left|\boldsymbol{E}_0\right|^2 = \underline{\boldsymbol{E}_0\times(\nabla\times\boldsymbol{E}_0) + (\boldsymbol{E}_0\cdot\nabla)\boldsymbol{E}_0}$$

- Hence the ponderomotive potential Φ_{pond} is thus defined

$$m\dot{\boldsymbol{U}} = -q\frac{1}{4}\frac{q}{m\omega^2}\nabla\left|\boldsymbol{E}_0\right|^2 = -q\nabla\Phi_{pond}$$

Ponderomotive acceleration

- The ponderomotive potential

$$\Phi_{pond} = \frac{1}{4}\frac{q}{m\omega^2}\left|\boldsymbol{E}_0\right|^2$$

$$= \frac{1}{4}\frac{mc^2}{q}a_0{}^2 \longleftarrow$$

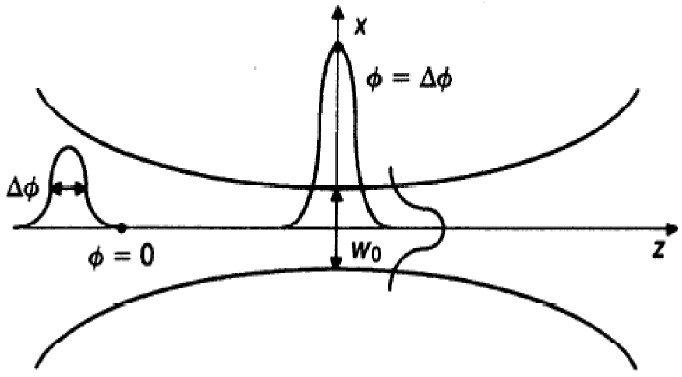
The laser strength parameter is

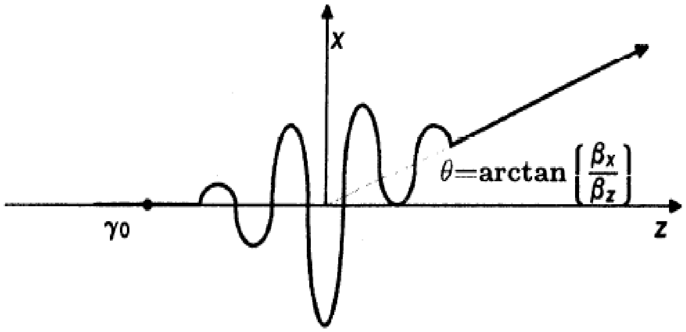
$$a_0 = \frac{q}{mc\omega}E_0$$

- The energy of the particle in the field is

$$q\Phi_{pond} = \frac{1}{4}mc^2 a_0{}^2$$

Ponderomotive acceleration





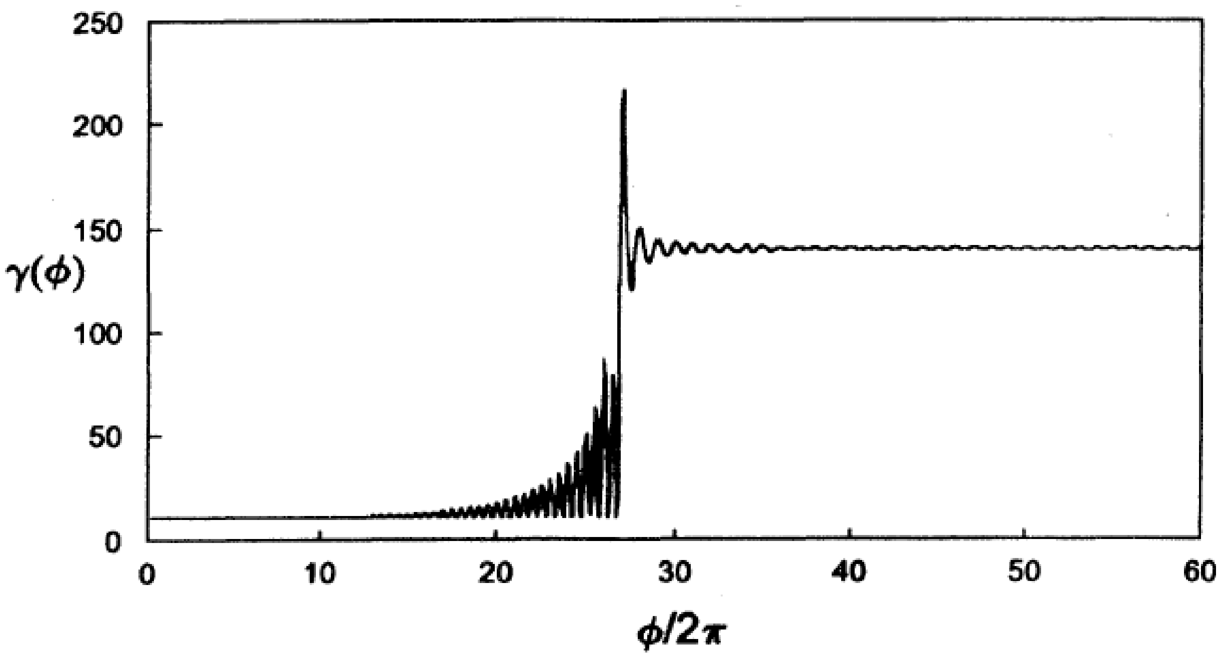


FIG. 10. Two-dimensional evolution of the electron normalized energy as a function of phase for $\alpha = 3.41$, $\lambda = 1$ μm, $\Delta\tau = 100$ fs, $w_0 = 20$ μm. The electron is injected at $z = -7.6$ mm with a normalized energy $\gamma_0 = 10$.

F.V. Hartemann et al.,PR E,51,4833,1995

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Laser Plasma Accelerator: the bubble regime

V. Malka et al., 'Principles and applications of compact laser–plasma accelerators' Nature Physics 4, 447 - 453 (2008)

- Laser plasma wake wave accelerator has a long way….
  - Proposed by T. Tajima and J. M. Dawson, PRL. 43, 267 (1979).
  - Demonstrated, A. Modena et al., Nature 377, 606 (1995)
- Revolution for high quality beams
  - Bubble regime proposed: A. Pukhov, Appl. Phys. B 74, 355 (2002)
  - Demonstration of high quality beams
    - *S.P.D. Mangles et al. Nature 431, 535 (2004)*
    - *C.G.R. Geddes et al. Nature 431, 538 (2004)*
    - *J. Faure et al. Nature 431, 541 (2004)*
  - Controlled injection using laser or density modulation
    - Faure *Nature* **444** 737 (2006)
    - *Hsieh et al., Phys. Rev. Lett.* ***96****, 095001 (2006)*

- plasma wake wave accelerator (beam driven)
  - Proposed by P. Chen, PRL. 54, 693 (1985).
- Revolution for high quality beams
  - Blow out regime (beam friven), J> Rosenzweig et. al., PRA. 44 R6189 (1991)
- Demonstration (energy gain of 2.7 GeV for 50 GeV beam)
  - M. Hogan et. Al. Phys. Rev. Lett. 95, 054802 (2005)

Laser plasma accelerato: Bubble regime explained

- High intensity laser pulse expels electrons from a ion/electron mixture to form a cavity, critical power for this to happen: self focusing

$$P > 17\frac{n_c}{n_e}GW$$

n_e n_c are the electron density of the plasma and critical density for the laser wavelength, $10^{21}/\text{cm}^3$ at 1 μm.

- The cavity has a static electric field that accelerates the beam

$$\boldsymbol{E}_B = \hat{\boldsymbol{r}}\nabla\phi(\boldsymbol{r}) = K\boldsymbol{r}$$

ϕ is the scalar potential of the wake wave

$K = m_e w_p^2/3e = 4.5\times10^{16}$ V/m^2.

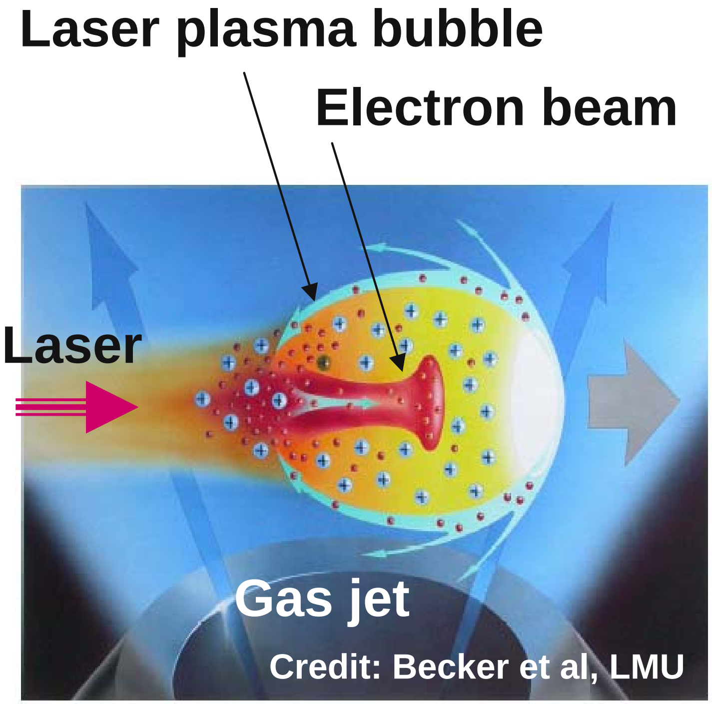
- If electrons are 'injected' into the bubble they can be accelerated, criteria

$$v > v_p \approx c\eta$$

Index of refraction

Plasma frequency

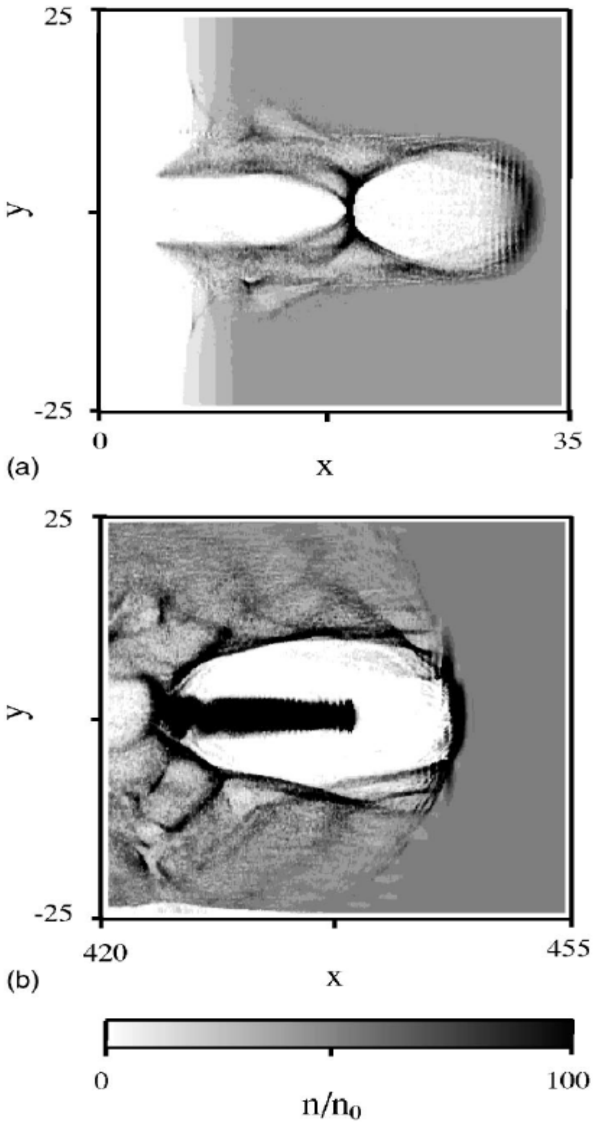
$$\eta = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2}, \quad \omega_p = \sqrt{\frac{4\pi n_e e^2}{\gamma m_e}}$$



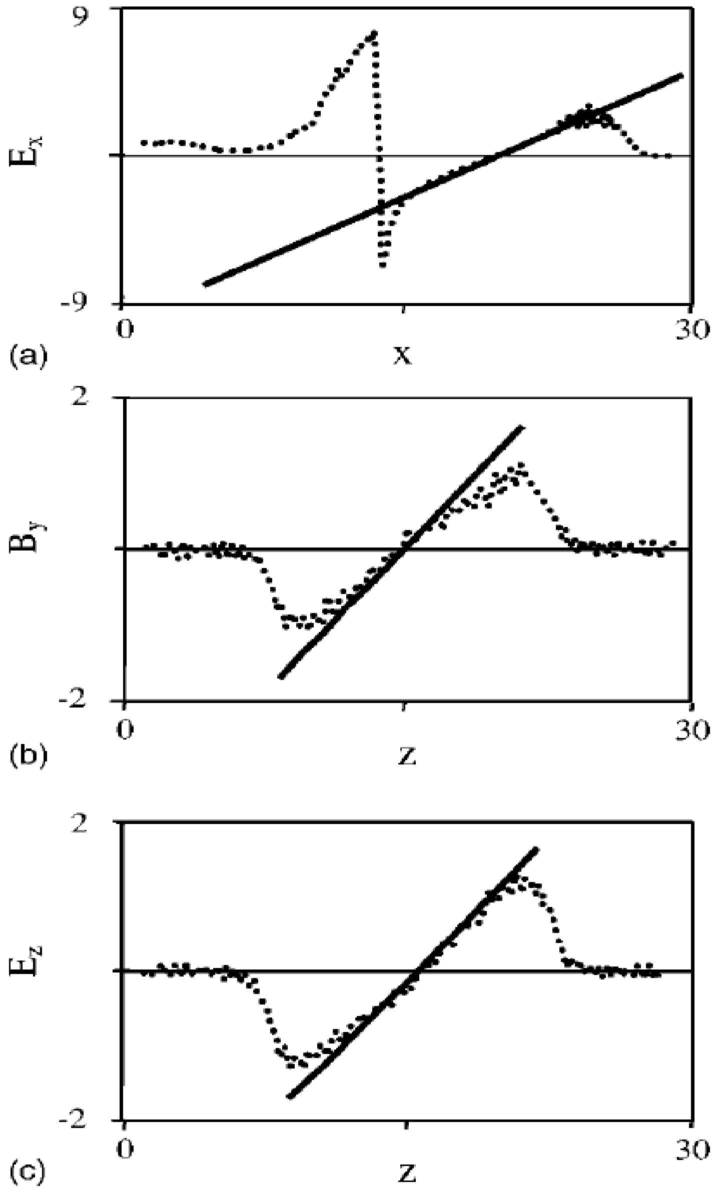
Credit: Becker et al, LMU

What does simulation say?

Density distributions

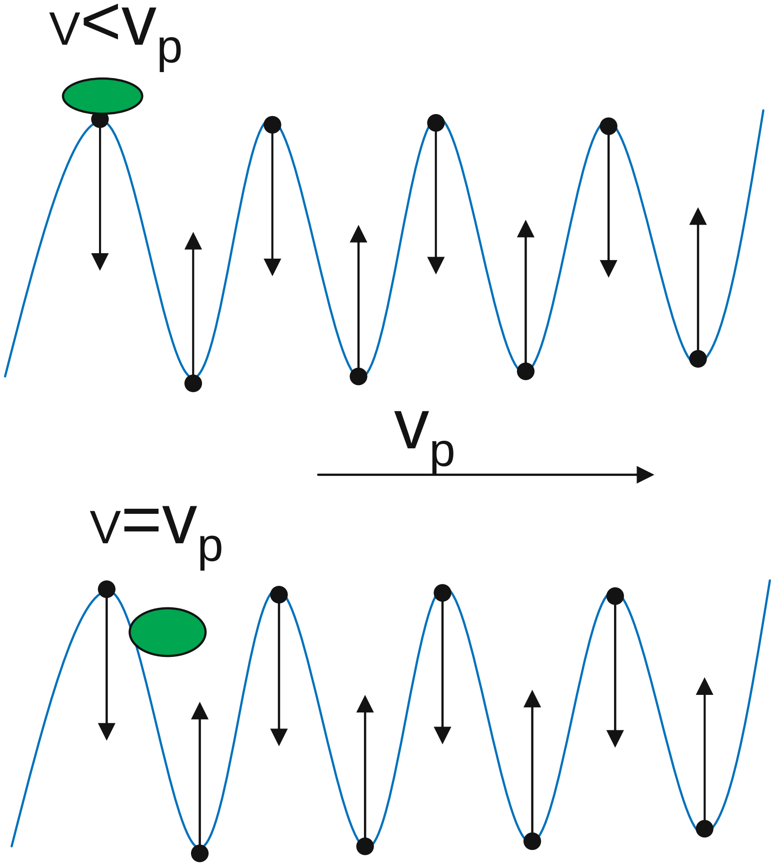


Field distributions in bubble

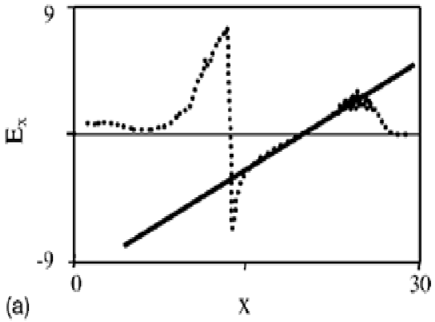


I. Kostyukov, Phys. Plasmas 11 5256 (2004)

Start to surf: Injection of electrons

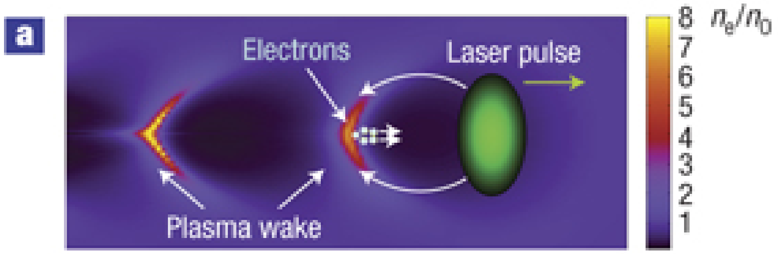


For injection to happen, the surfer has to be pushed off phase with wave. The way to do it for electrons, is 1) Disturb the field, 2) push the electrons

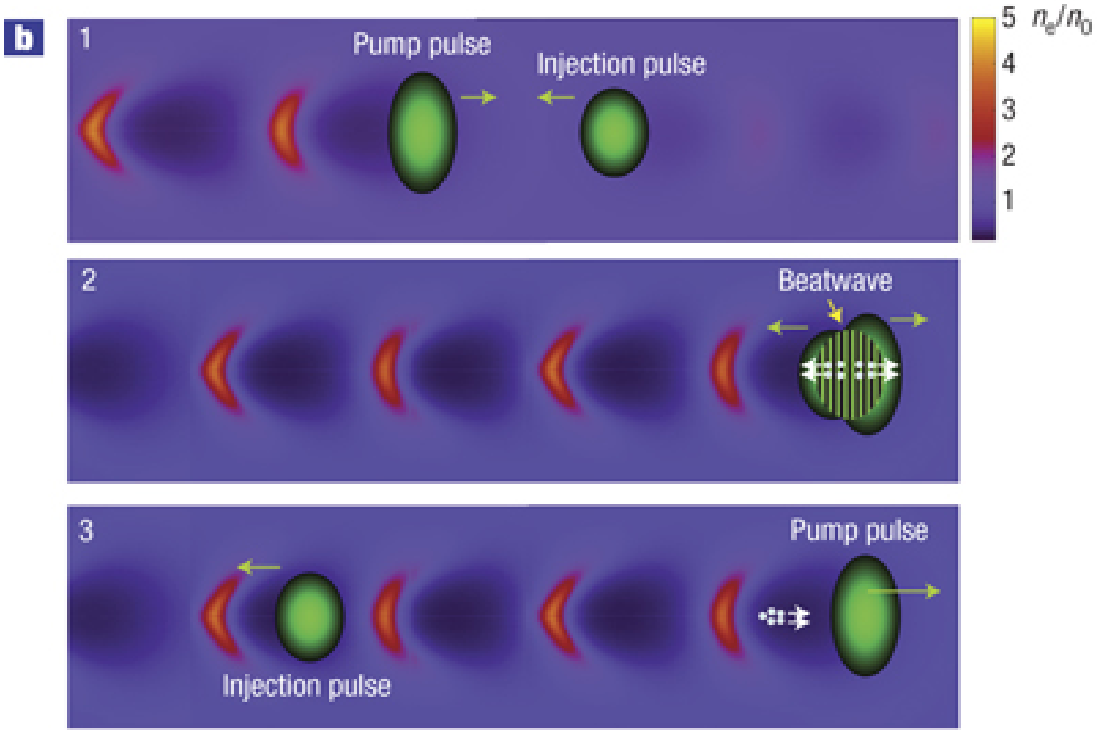


Injection of electrons to the bubble

Self injection



Laser injection



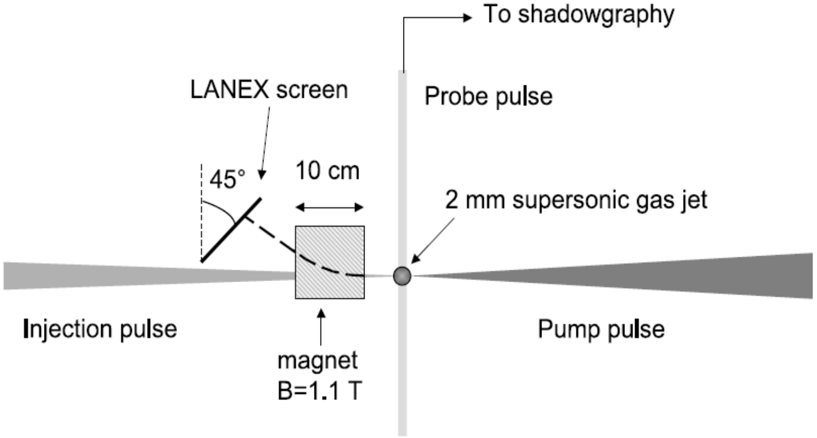
a, A schematic diagram of the self-injection mechanism in the bubble regime. The figure represents a plot of plasma electron density behind the laser pulse. The plasma wake is highly nonlinear with regions where electrons have been evacuated (black) and regions where electrons accumulate (yellow). The arrows show how electrons are deflected outward and then accumulate at the back of the wakefield, where some of them are trapped and accelerated. **b**, Schematic diagrams of the injection mechanism in the counterpropagating colliding pulse scheme. (1) The two laser pulses have not collided yet; the pump pulse drives a strong plasma wake, although less nonlinear than in the bubble regime case. (2) The pulses collide and their interference sets up a beatwave that preaccelerates electrons. (3) Some of the preaccelerated electrons are trapped and further accelerated in the wake.

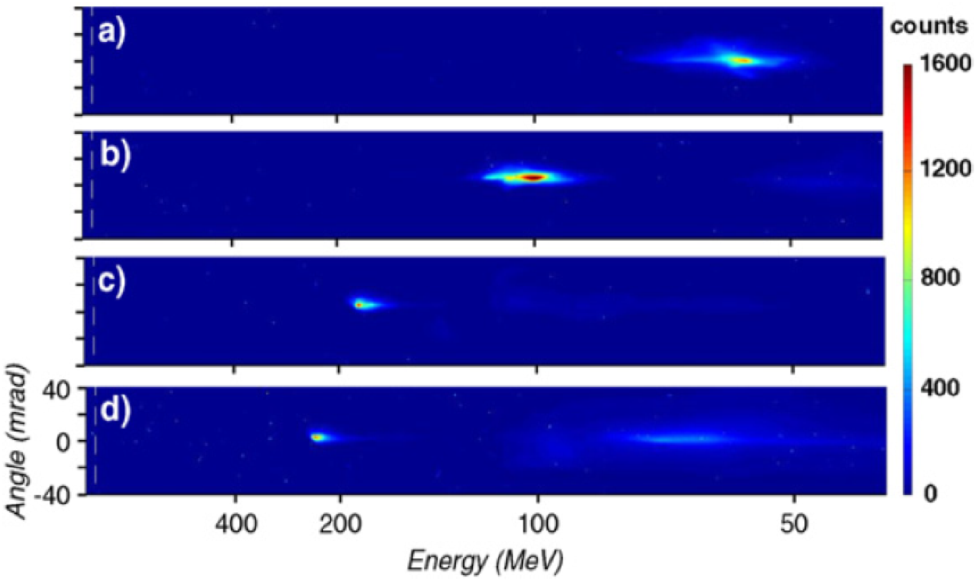
***V. Malka et al., 'Principles and applications of compact laser–plasma accelerators' Nature Physics* 4**, 447 - 453 (2008)

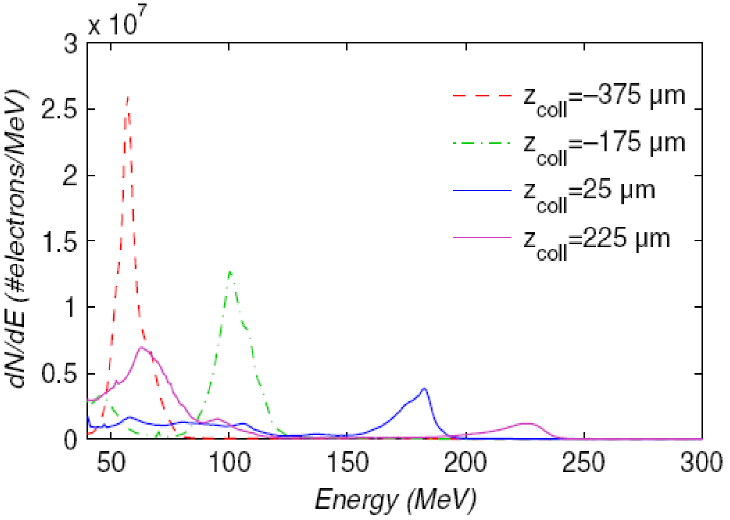
Laser plasma accelerator: an experimental example

- Bubble acceleration with injection

Peak energy	117 ± 7 MeV
Energy spread (FWHM)	11 ± 2%
Charge	19 ± 6.8 pC
Divergence	5.8 ± 2 mrad
Beam pointing stability	0 ± 2 mrad



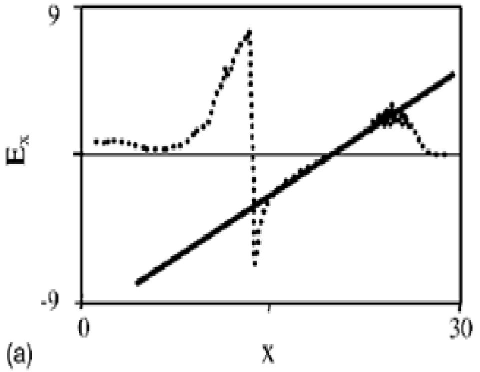




Faure et al., *Nature* **444** 737 (2006)

Plasma electron accelerator: outlook

- Pros
  - High accelerating gradient: GV/cm
  - Compact
- Cons
  - Low duty cycle
  - Low charge per shot (<100 pC)
  - Large emittance
  - Fluctuation still not under control
  - Phase mismatch between wave and beam. The speed of plasma wave is
$$v_p = c\sqrt{1-n_e/n_c}$$
  - Normally 0.997 c, but for 50 MeV beam, v=0.9999 c
- Current effort?
  - Staging
    - *Currently demonstrated beam energy: 1 GeV, Leemans et al.,* ***Nature Physics* 2**, 696 - 699 (2006)



***V. Malka et al., 'Principles and applications of compact laser–plasma accelerators' Nature Physics* 4**, 447 - 453 (2008)

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- Advanced accelerator concepts
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  - Lawson–Woodward theorem
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    - *Vacuum accelerators*
    - *Plasma accelerators*
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    - *Inverse free electron lasers*
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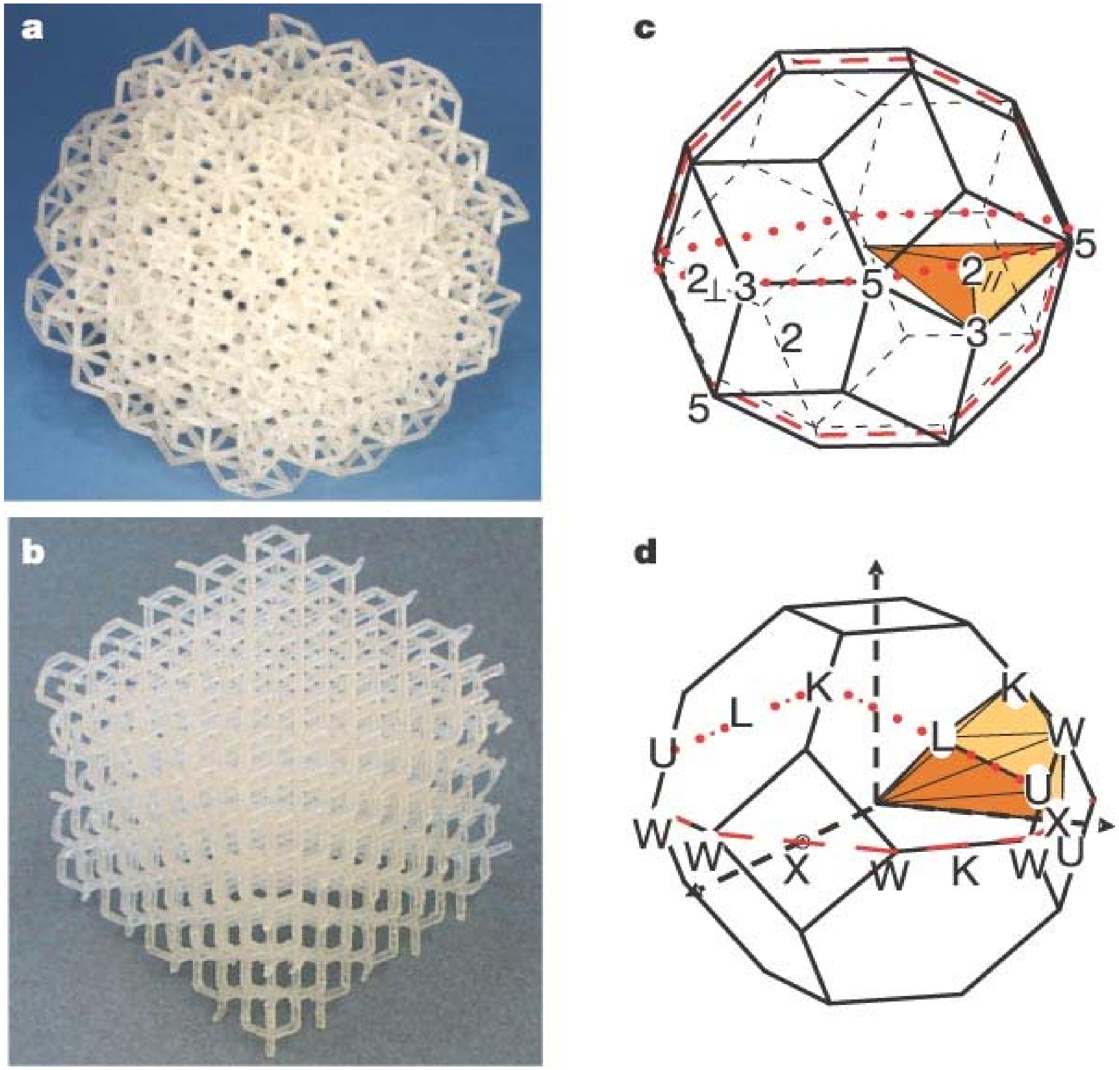
  - Table top free electron lasers
    - *Laser-laser concept*
    - *Laser undulator*
  - Mini colliders concept

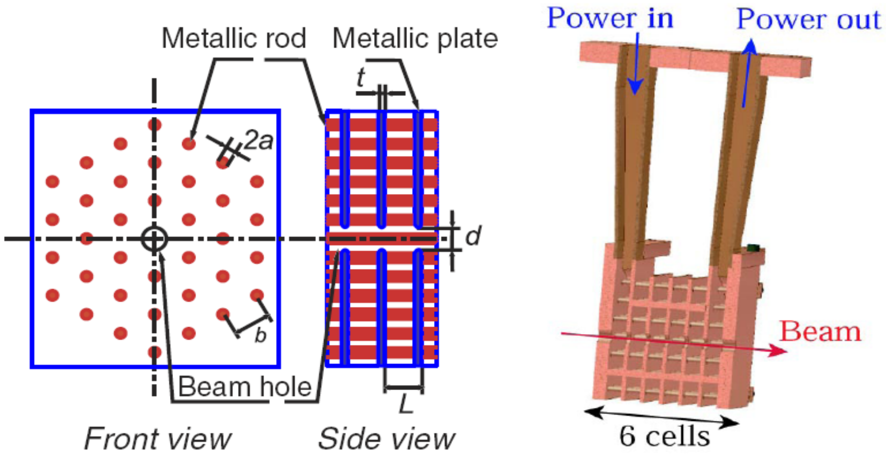
Accelerating meta structures and Photonic band-gap materials

- Band gap materials
  - Tailoring structure of materials for desired optical properties
  - J. Joannopoulos, R. D. Meade, and J. Winn, *Photonic Crystals* (Princeton University, Princeton, NJ,1995).
  - Can be made in 3D structure, W. Man, et al. Nature 436, 993 (2005)

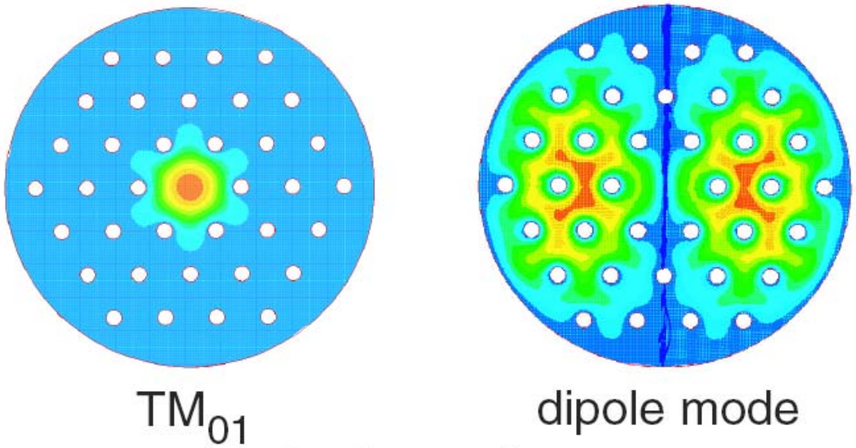


RF driven band gap accelerating structures

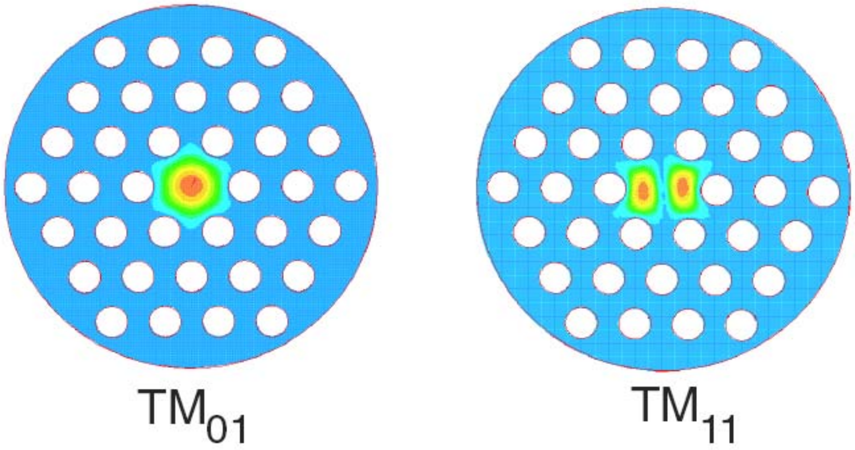
- Support a TM01 like accelerating mode, but suppresses HOM
- Electric field patterns in the TM01-like mode and the TM11-like mode in a PBG waveguide
  - (a) the TM11-like mode is not supported by the PBG structure when *a*/*b* < 0.2; (b) the TM11-like mode is confined by the PBG structure when *a*/*b* > 0.2



(a) (b)



(a) Cavity 1, a/b = 0.15

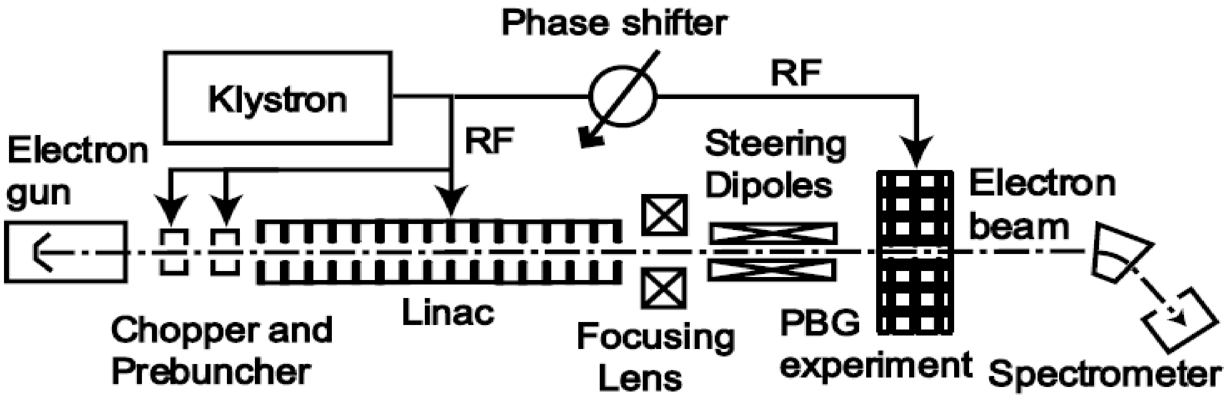


(b) Cavity 2, a/b = 0.30

E. I. Smirnova, PRL **95**, 074801 (2005)

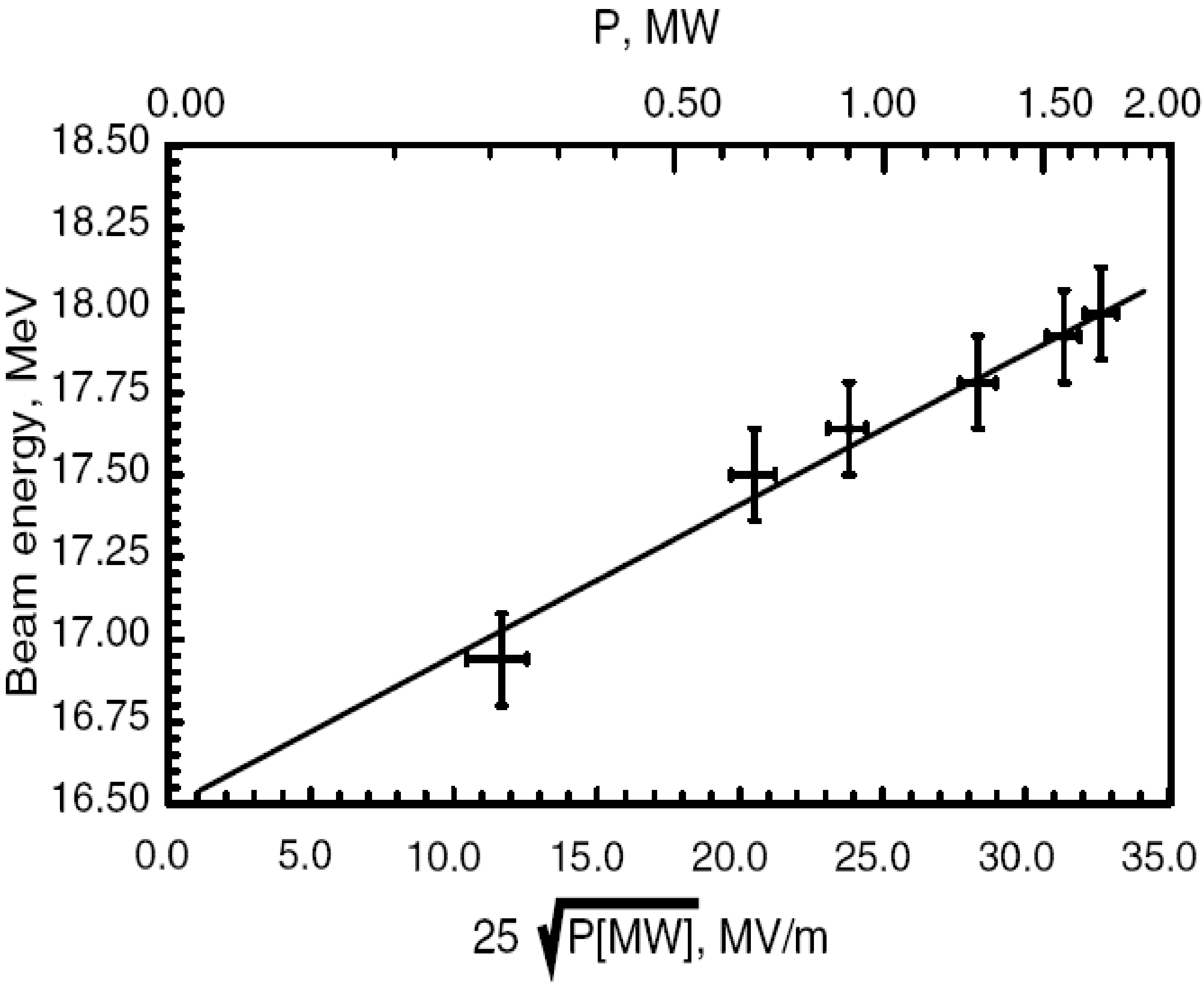
Demonstration of acceleration

Rod radius (TW cell/coupler cell), a	1.04 mm/1.05 mm
Spacing between the rods, b	6.97 mm
Plates spacing, L	5.83 mm
Iris radius, $d/2$	2.16 mm
Iris thickness, t	1.14 mm
Frequency (TM_{01} mode)	17.140 GHz
Ohmic Q factor, Q_w	4188
Shunt impedance, r_s	98 MΩ/m
$[r_s/Q_w]$	23.4 kΩ/m
Group velocity	$0.013c$
Gradient	$25.2\sqrt{P[\mathrm{MW}]}$ MV/m



E. I. Smirnova, PRL **95**, 074801 (2005)

Demonstration of acceleration



Max gradient: 35 MV/m

E. I. Smirnova, PRL **95**, 074801 (2005)

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    - *Plasma accelerators*
    - *Laser driven dielectric structures*
    - *Inverse free electron lasers*
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Towards optical band gap accelerator

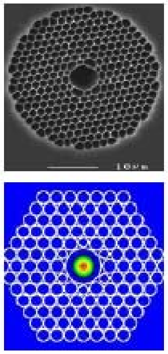
Photonic bandgap accelerator microstructure experiments

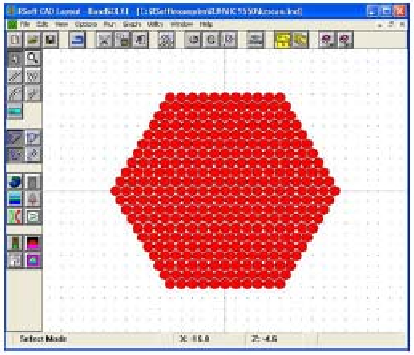
E-163

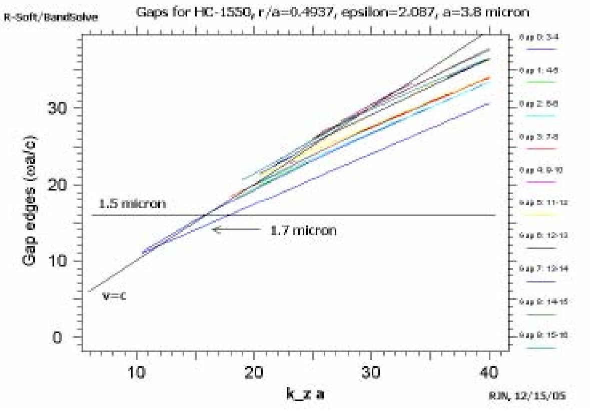
The Blaze Photonics HC-1550-02 fiber for laser-driven particle acceleration

Modeling and studies with commercial software packages

R.H. Siemann,
R. Noble, et. al







Proposed parameters for a laser-driven particle acceleration experiment with a PBG hollow core fiber

Parameter	value
Structure impedance	$Z_C = 1\Omega$
Damage factor	$D_F = 0.11$
Laser wavelength	$\lambda = 1.6\ \mu\mathrm{m}$
Laser pulse energy	1 μJ
Laser pulse duration	1 psec
Laser group velocity	$\beta \sim 0.6$
Expected gradient	0.6 GeV/m
Structure length	0.5 mm
Energy gain	0.3 MeV

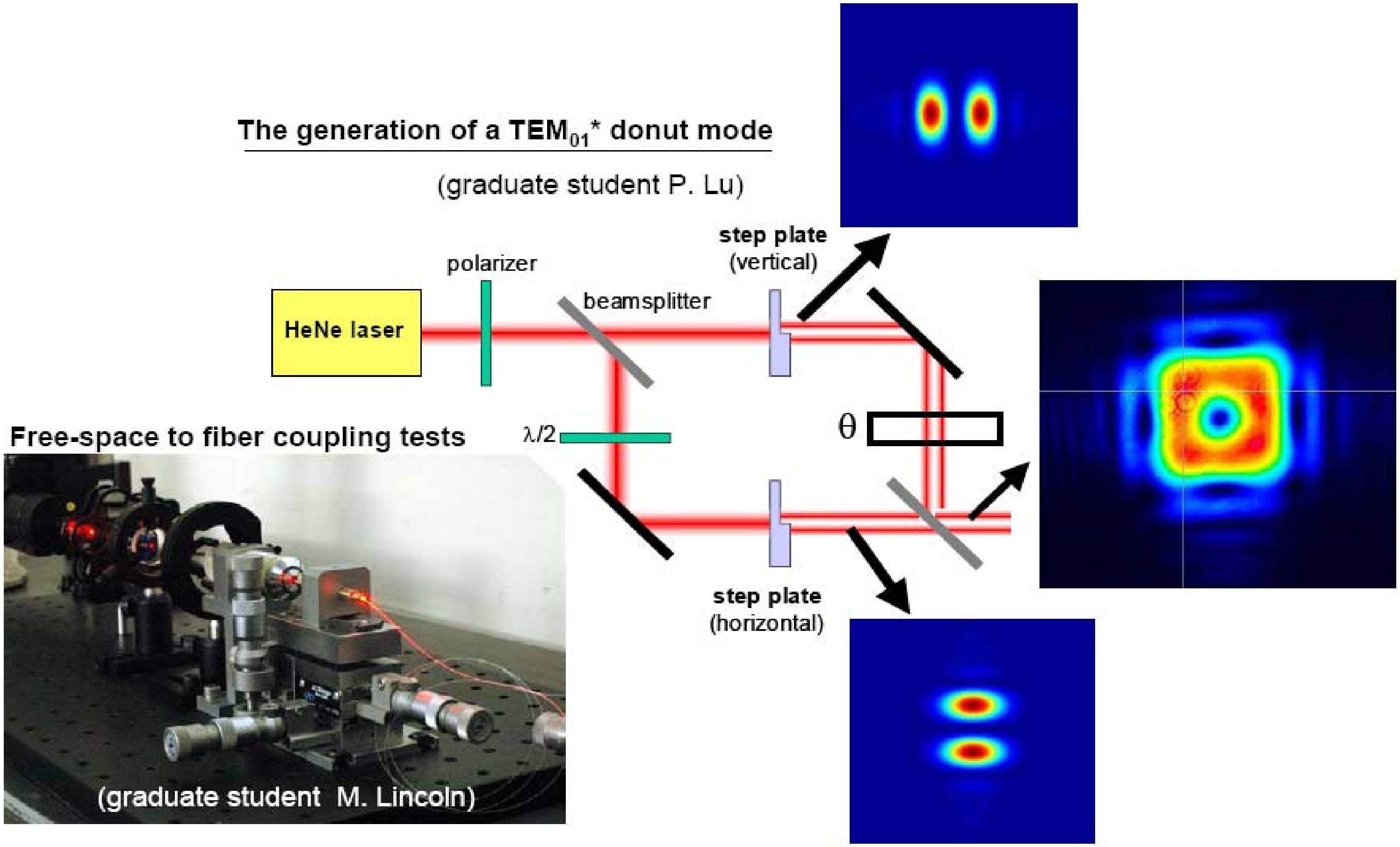
X.E. Lin, "Photonic band gap fiber accelerator", Phys. Rev. ST Accel. Beams 4, 051301 (2001)

T. Plettner, AAC 06, Lake Geneva, 2006

Towards optical band gap accelerator

Photonic bandgap accelerator microstructure experiments

Simple optical tests with HeNe lasers



The generation of a TEM_{01}* donut mode

(graduate student P. Lu)

Free-space to fiber coupling tests

(graduate student M. Lincoln)

T. Plettner, AAC 06, Lake Geneva, 2006

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Laser ion accelerations

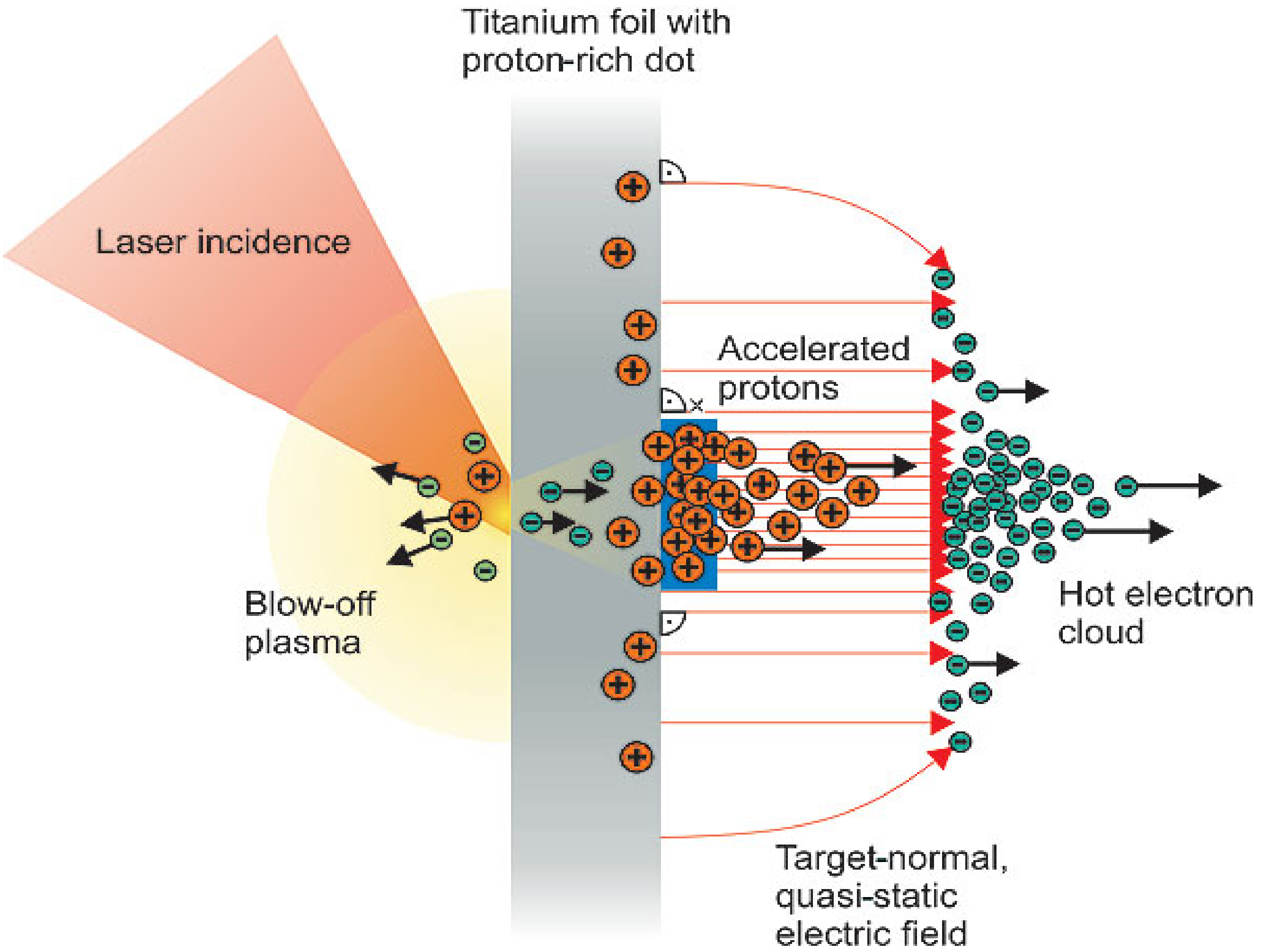
- Proposed mechanisms
  - Laser direct acceleration: light pressure (Shen, PRE 64, 056406 (2004)), needs a=300
  - Laser driven electrostatic shock (Silva, PRL. 92, 015002 (2004)).
  - Laser plasma buble (Shen, PRE 76, 055402 (r), 2007), a=300
  - “Target normal sheath acceleration” (B. M. Hegelich, et al., Nature 439, 441 (2006); H. Schwoerer, et al., Nature 439, 445 (2006).)

- Demonstrated “Target normal sheath acceleration” :
  - quasi mono energetic protons of MeV/proton
  - B. M. Hegelich, et al., Nature 439, 441 (2006); H. Schwoerer, et al., Nature 439, 445 (2006).

V. Malka et al., ‘Principles and applications of compact laser–plasma accelerators’ Nature Physics 4, 447 - 453 (2008)

Target normal sheath acceleration of ptotons

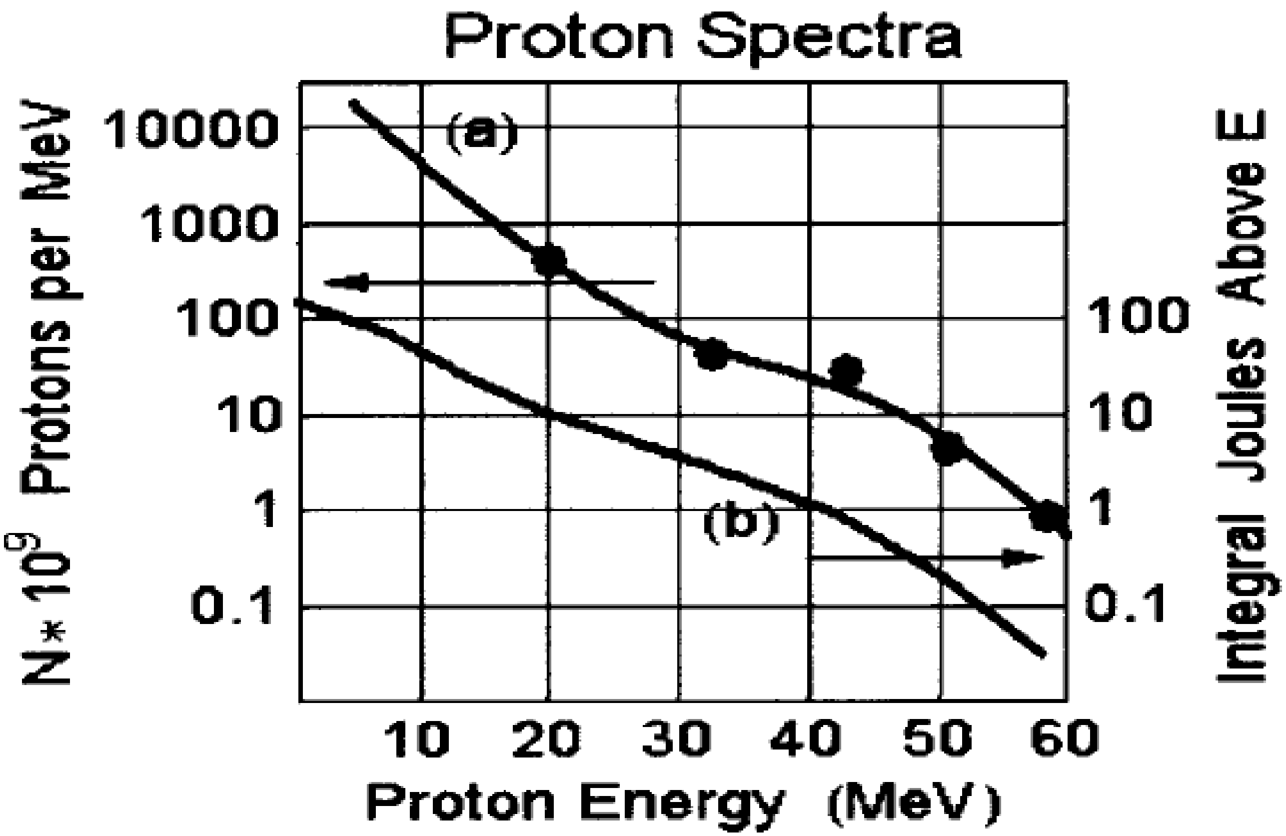
- Mechanism



laser intensity $I_L = 3\times10^{19}$ W cm^{-2}

Schwoerer, et al., Nature (London) 439, 445 (2006).

Proton accleration to 50 MeV with PW laser



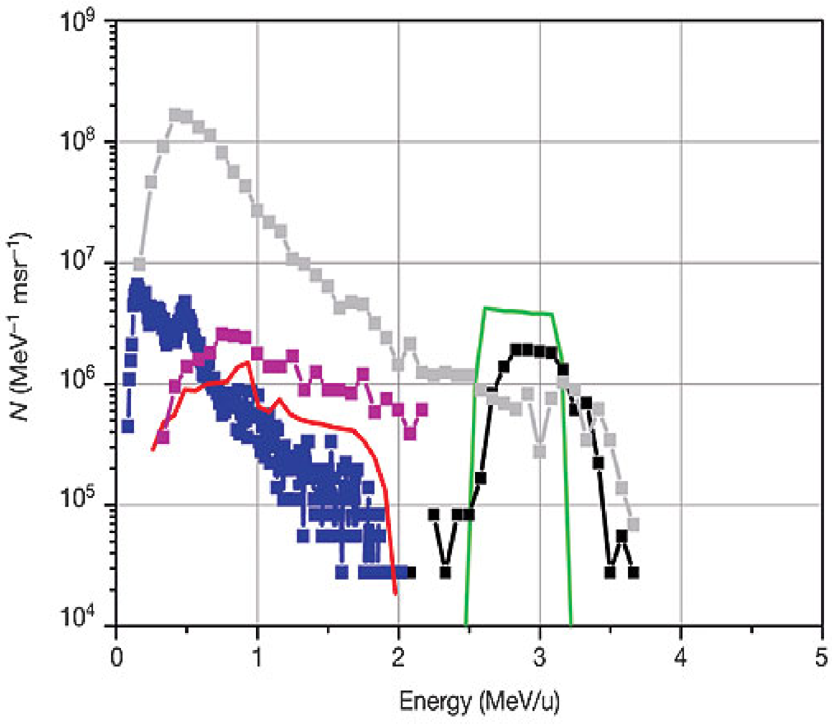
An intense collimated beam of high-energy protons is emitted normal to the rear surface of thin solid targets irradiated at 1 PW power and peak intensity 3×10^{20} W cm^{-2}. Up to 48 J (12%) of the laser energy is transferred to 2×10^{13} protons of energy >10 MeV. The energy spectrum exhibits a sharp high-energy cutoff as high as 58 MeV on the axis of the beam which decreases in energy with increasing off axis angle. Proton induced nuclear processes have been observed and used to characterize the beam.

Snavely et al., Phys. Rev. Lett. 85, 2945–2948 (2000).

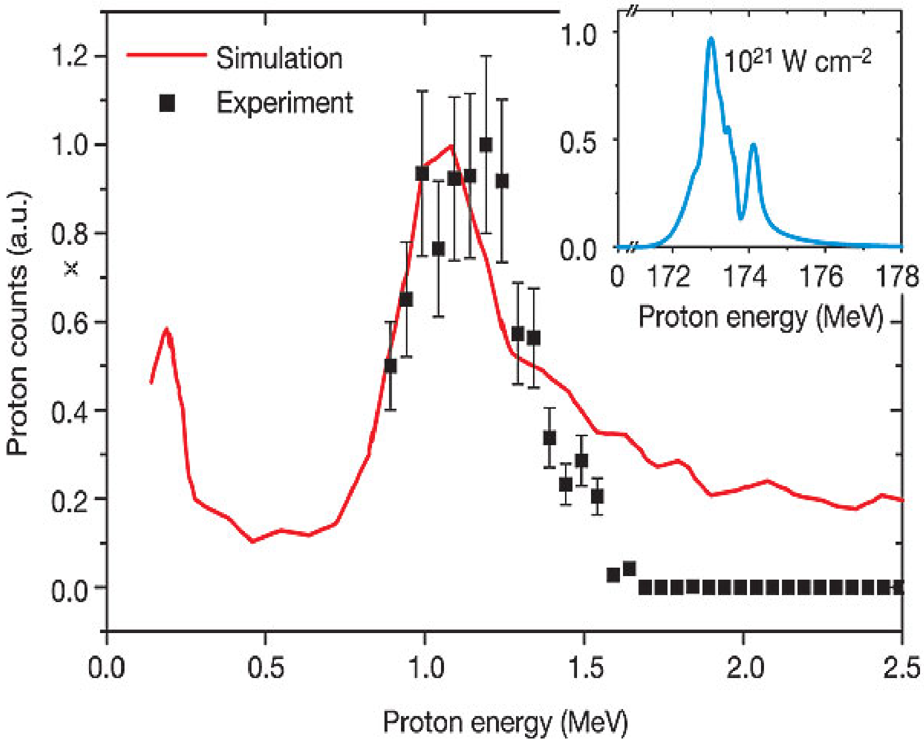
Target normal sheath acceleration of protons

- Experimental results

B. M. Hegelich, et al., Nature 439, 441 (2006);



Schwoerer, et al., Nature (London) 439, 445 (2006).



Ion acceleration challenges

- Higher beam energy
  - More intense lasers
  - Ultrathin target and high contrast laser pulse
    - *Neely, D. et al., Appl. Phys. Lett. 89, 021502 (2006).*
    - *Antici, P. et al., Phys. Plasmas 14, 030701 (2007).*
    - *Ceccotti, T. et al., Phys. Rev. Lett. 99, 185002 (2007).*
  - Target micro structuring
    - *B. M. Hegelich, et al., Nature 439, 441 (2006);*
    - *H. Schwoerer, et al., Nature 439, 445 (2006).*
- Staging?
- Beam quality and manipulation
  - Focusing
    - *Toncian, T. et al., Science 312, 5772 (2006).*
  - Quasi mono-energetic beam
  - Emittance looks to be low
    - Cowan, T. E. et al., Phys. Rev. Lett. 92, 204801 (2004).

      (<0.004 $mm\ mrad$ and $<10^{-4}$ eV s, i.e., at least 100-fold and may be as much as 10^{4}-fold better than conventional accelerator beams.)

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  - Table top synchrotron source due to betatron oscillation
  - Table top Thomson scattering source
  - Table top free electron lasers
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Application laser plasma accelerated beams

- Betatron oscillation and radiation
- Thomson scattering for X-ray sources
  - Compact
  - Short pulse
  - Tunable
- Undulator radiations: towards free electron lasers
  - Needs higher beam energy
  - Better emittance
  - Smaller energy spread
- Mini colliders
  - Needs TeV of beam energy to be useful
  - To be explored

Betatron Oscillation in Plasma bubble

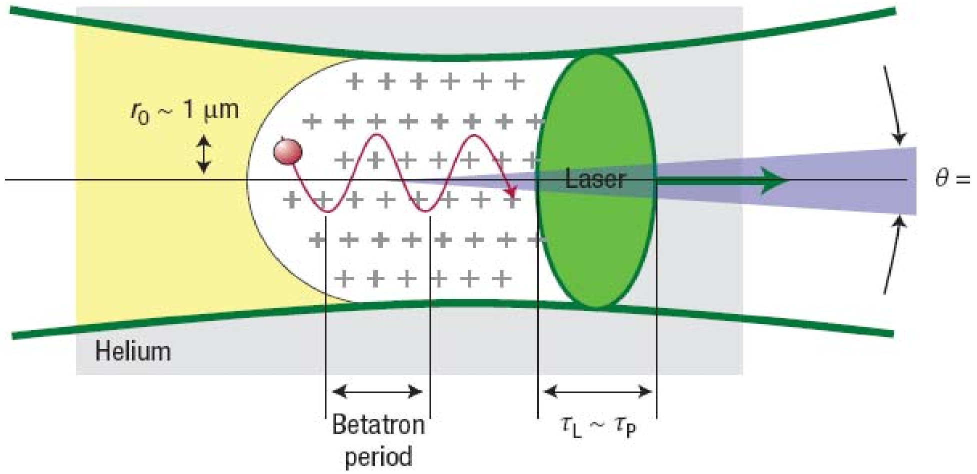
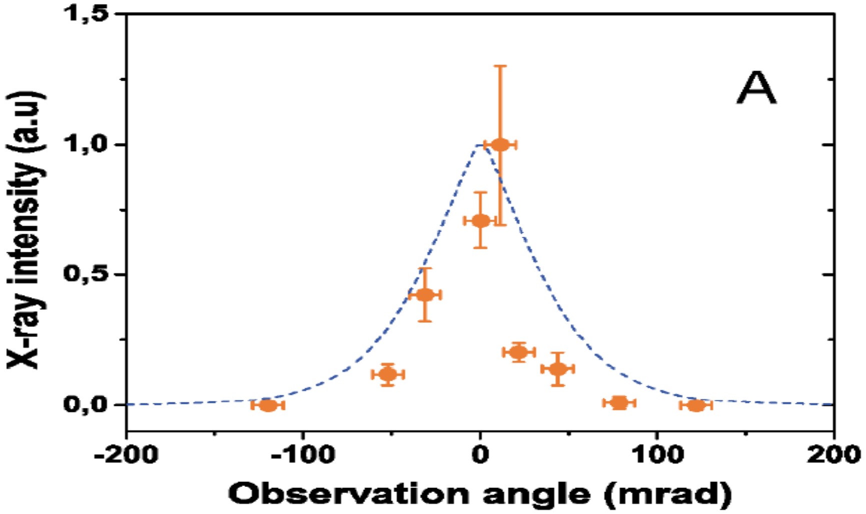
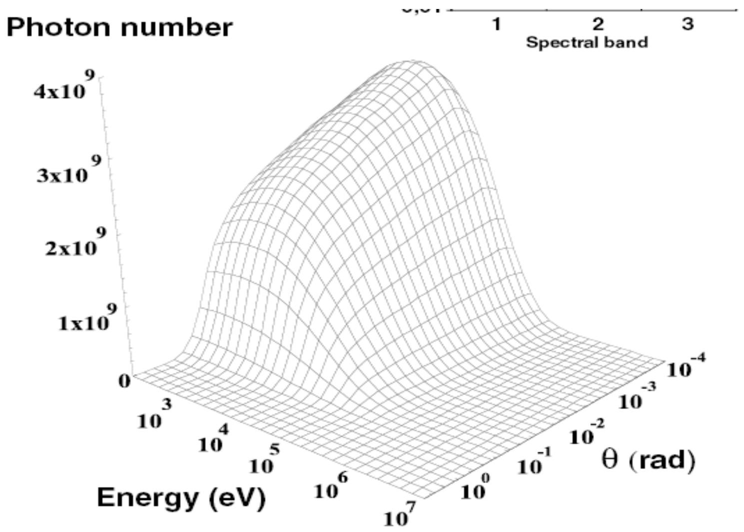


Figure 3 Principle of the betatron radiation produced in a wakefield cavity. The electron is accelerated to relativistic energies and wiggled in the cavity. As a result of this motion, an X-ray beam is emitted in the direction of the electron momentum.

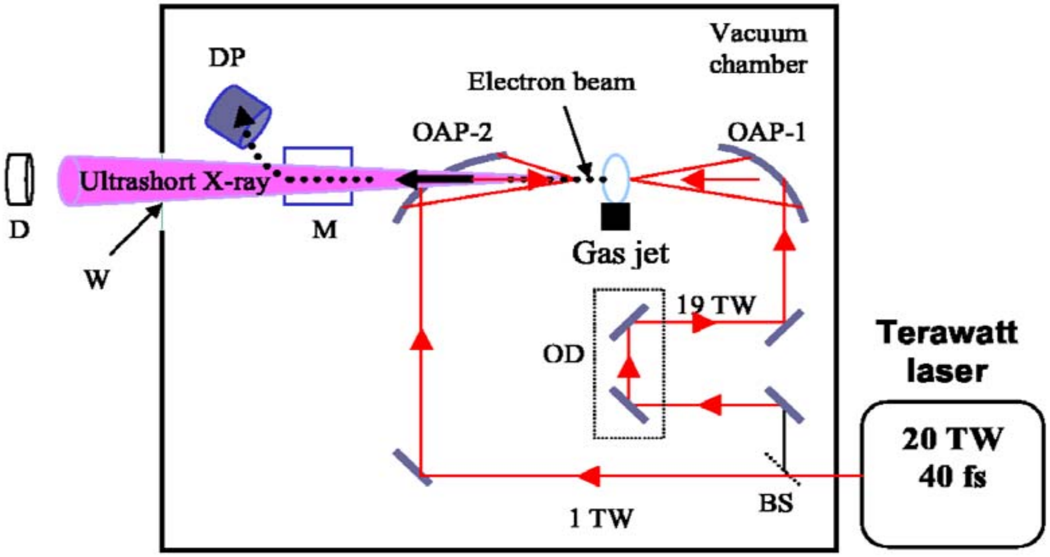


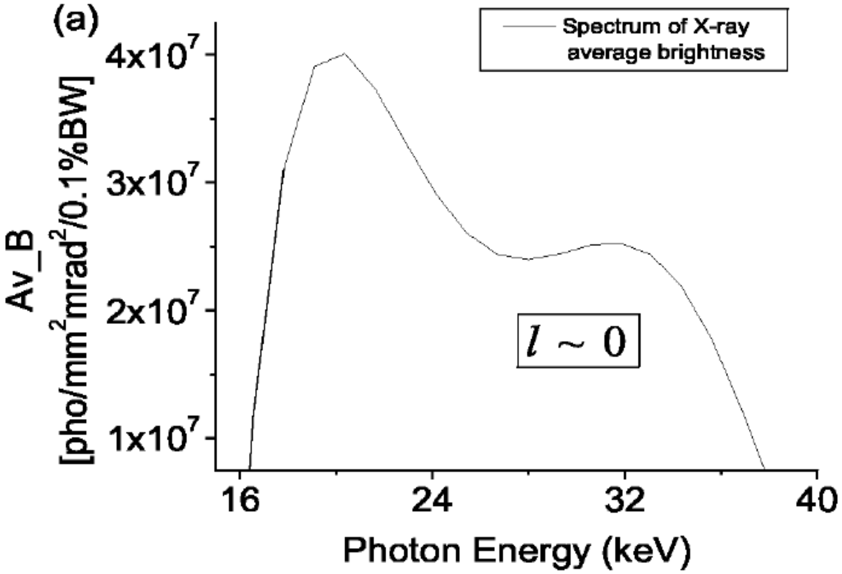


***V. Malka et al., 'Principles and applications of compact laser–plasma accelerators' Nature Physics* 4**, 447 - 453 (2008)
Rousse et al., Phys. Rev. Lett. 93, 135005 (2004).

LWA Thomson scattering source, a proposal

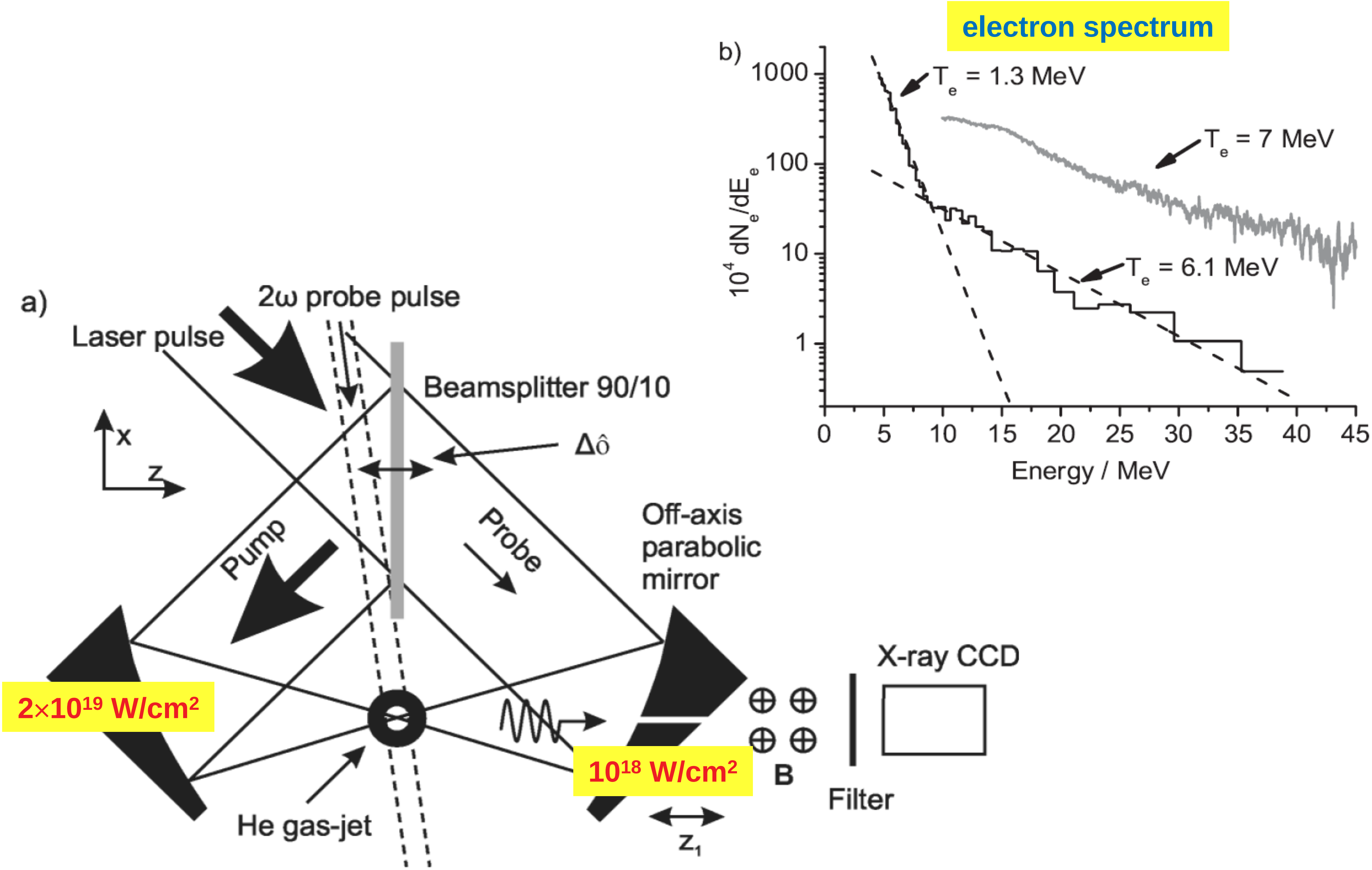
Electron bunch produced from LWFA with $l \sim 0$ density transition (2D-PIC simulation)	Laser pulse (a small portion of the main laser pulse)
Average energy $\bar{E} = 37$ MeV	Power, P $= 0.5\ TW$
rms energy spread $\sim 15\%$	Pulse duration, $\tau_L = 60 fs$
Bunch length, $\tau_b = 17 fs$	$\lambda = 800$ nm
Number of electrons (inside circle)$= 6\ \times 10^8$	Spot radius $r_0 = 5\mu$m
Bunch current, $I_b = 100pC/17fs = 5.8$ kA	$a_0 = 0.7$
Bunch radius (at IP), $r_b = 10\mu$m	
Emittance, $\epsilon_n\ = 20$ mm·mrad (outside of plasma)	





N. Hafz, J. Kor. Phys. Soc. 44, 1274 (2004).

LWA Thomson scattering source, a implementation

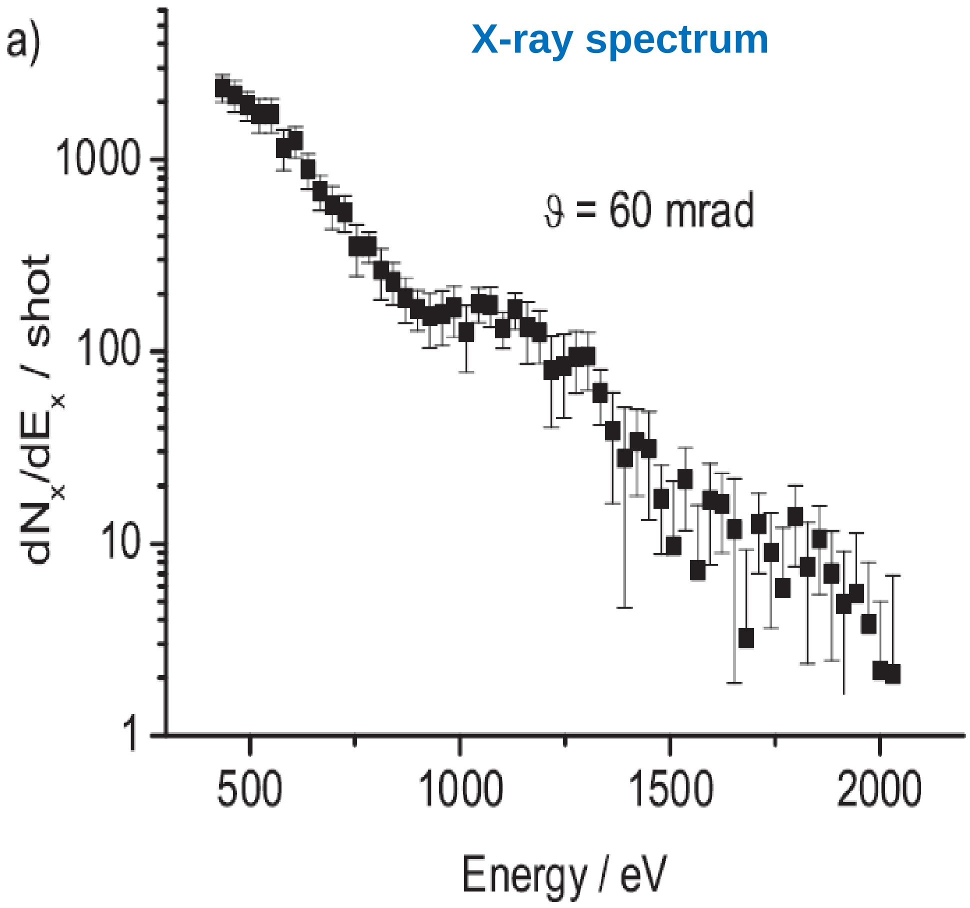

electron spectrum

2×10^{19} W/cm^2

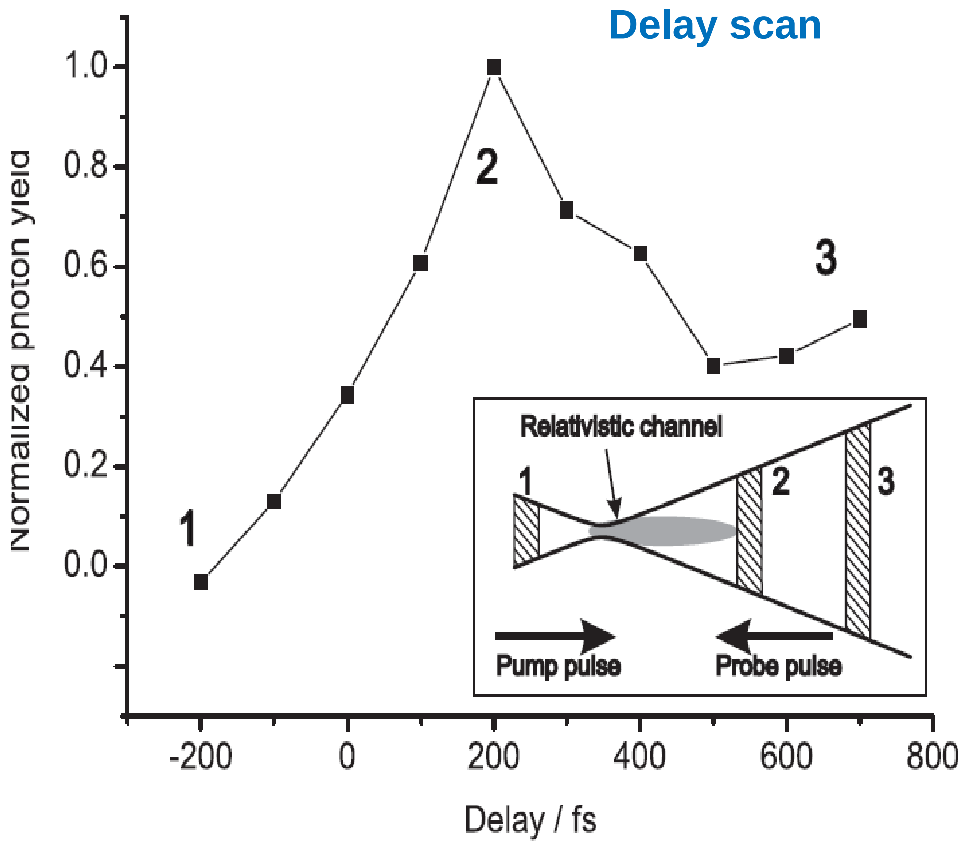
10^{18} W/cm^2

H. Schwoerer et al., PRL 96, 014802 (2006).

LWA Thomson scattering source, a implementation



X-ray spectrum

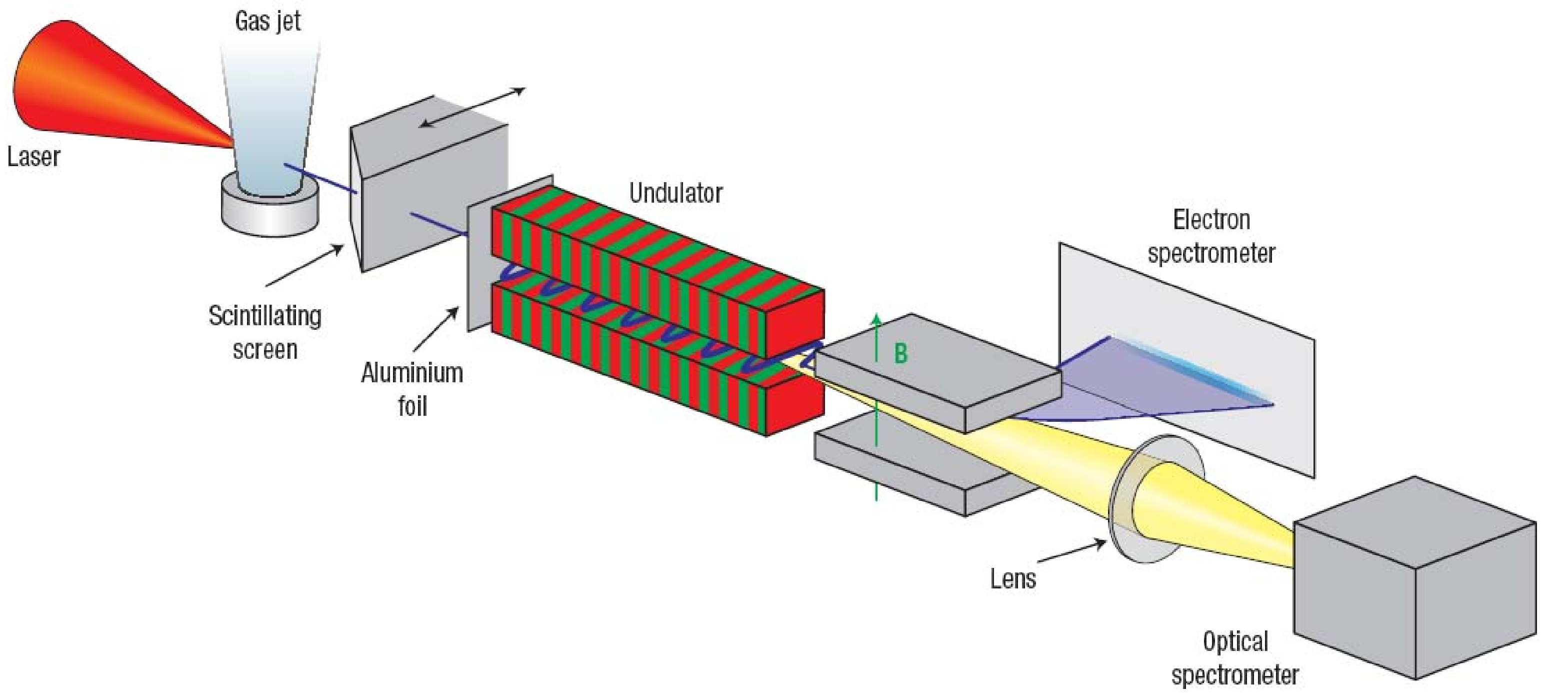


Delay scan

H. Schwoerer et al., PRL 96, 014802 (2006).

Undulator radiation

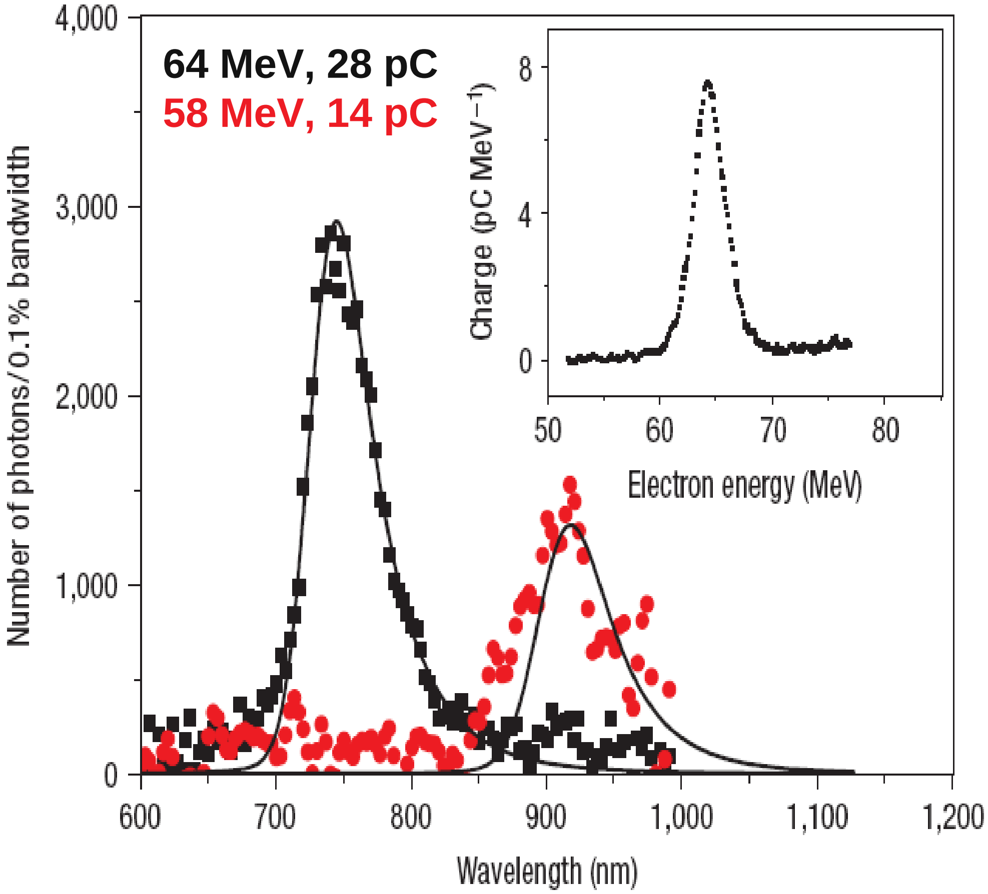
- It is natural to think of an undulator
  - As a beam diagnostics (expensive one)
  - A radiation source for potential x-ray laser



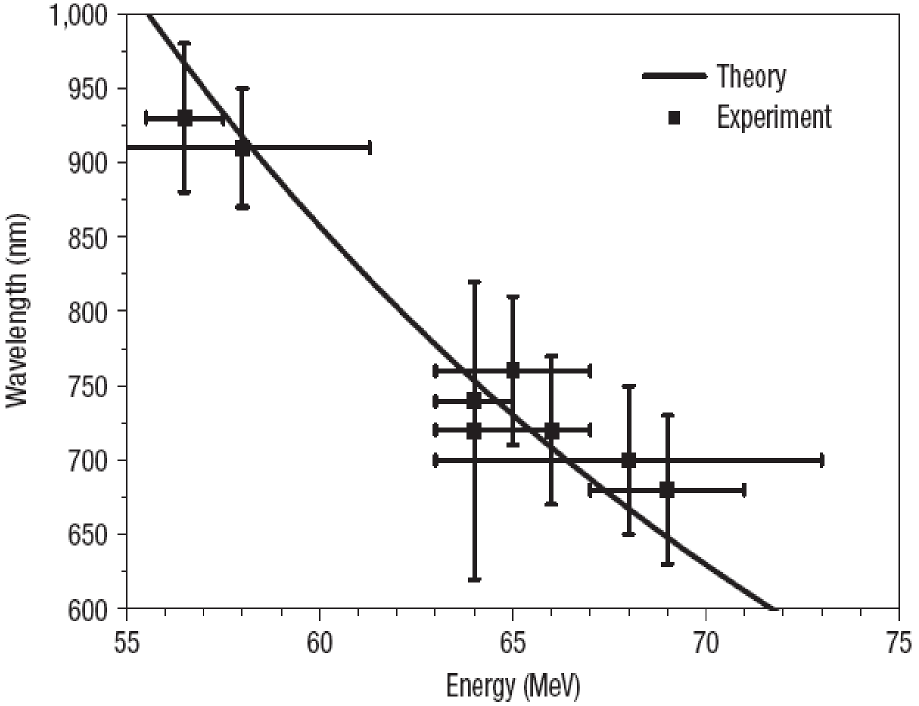
H.-P. Schlenvoigt et al., ***Nature Physics* 4**, 130 - 133 (2008)

Undulator radiation: results

Radiation spectrum



Rad wavelength vs. beam energy

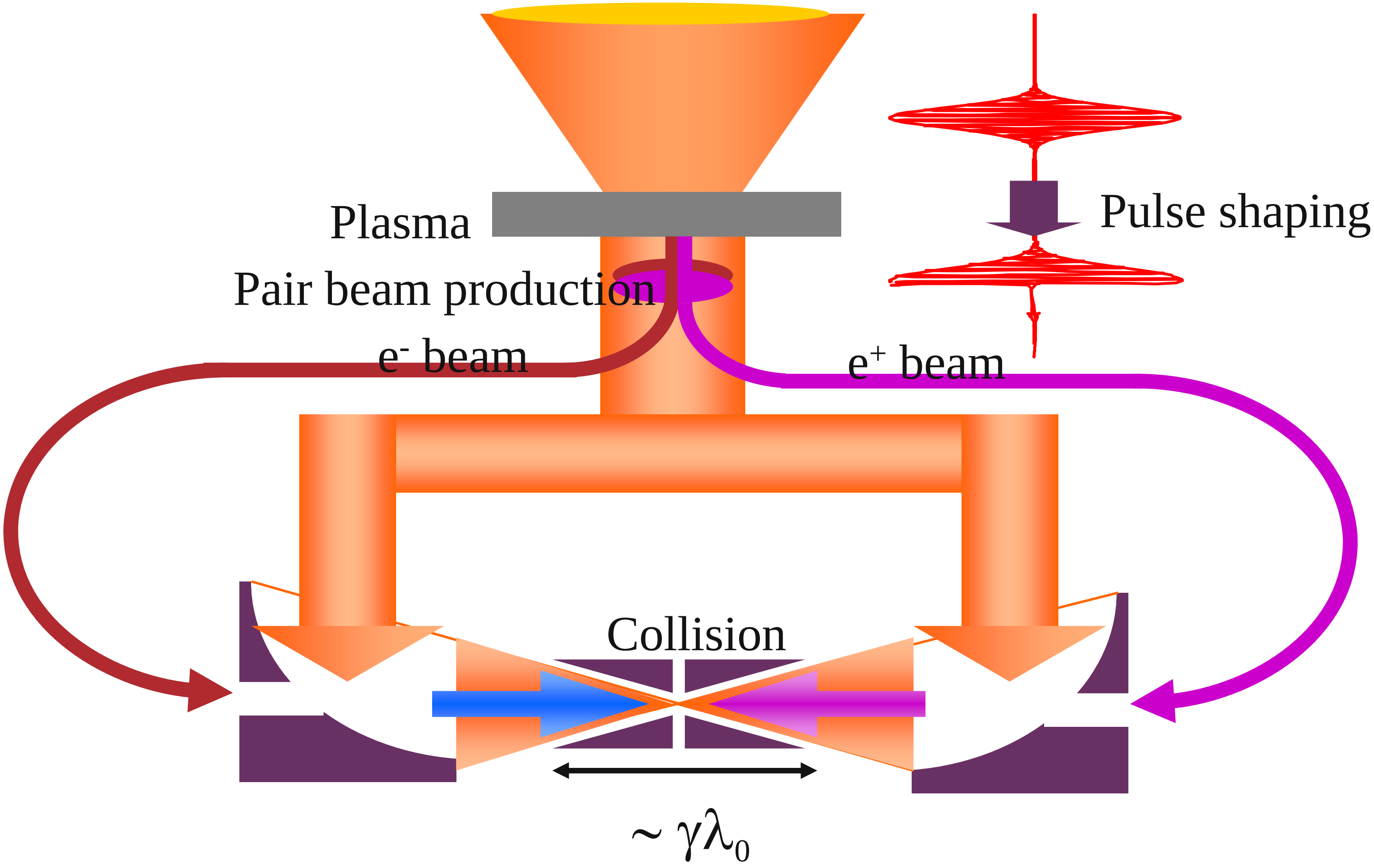


$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

H.-P. Schlenvoigt et al., ***Nature Physics* 4**, 130 - 133 (2008)

Mini colliders

Two counter-propagating laser-accelerated pair beams will create a new e^+e^-, e^-e^-, e^+e^+ micr-size collider without beam disruption at collision.



Nakajima, 2nd ORION WORKSHOP, SLAC, Feb. 18-20, 2003

Summary

- Wide open field for exploration
  - Vacuum accelerator
  - Plasma based accelerator
  - And band gap structures
- Still far from practical, again wide open for exploration
  - high beam energy
  - higher charge
  - better emittance

- Physics at light beam interaction at extreme high field [*Science* 301, 154 (2003)]