Advanced Concepts for Laser-Driven Acceleration

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John Adams Institute & Department of Physics, University of Oxford, UK

Outline

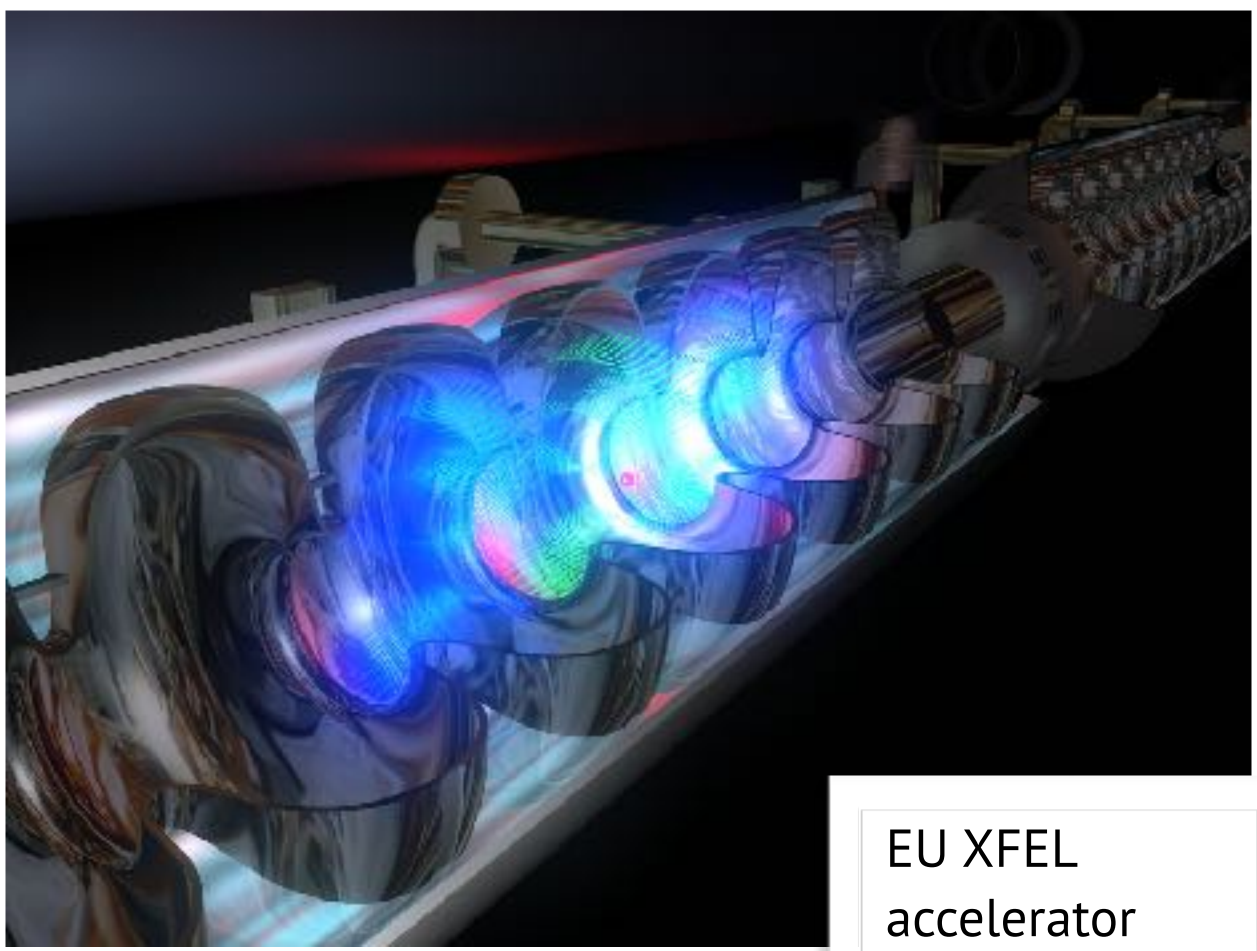
- Motivation
- Some key concepts for laser-plasma accelerators
- Further considerations
- A brief review of progress in laser-plasma accelerators
- Some status & challenges
- Multi-pulse laser wakefield acceleration

Further reading

- General interest review articles
  - S. M. Hooker, "Developments in laser-driven plasma accelerators," *Nature Photonics* **7** 775 - 782 (2013)
  - W. Leemans & E. Esarey, "Laser-driven plasma-wave electron accelerators," *Physics Today* **62** 44 - 49 (2009)
  - C. Joshi, "Plasma accelerators," *Scientific American,* pp. 41 - 47, February (2006)
- Physics of laser-plasma accelerators
  - E. Esarey et al, "Physics of laser-driven plasma-based electron accelerators," *Reviews of Modern Physics* **81** 1229 - 1285 (2009)
  - V. Malka, "Laser plasma accelerators," *Physics of Plasmas* **19** 055501 (2012)
- Applications
  - F. Albert *et al.*, "Laser wakefield accelerator based light sources: potential applications and requirements," *Plasma Physics and Controlled Fusion* **56** 084015 (2014)
  - S. Corde *et al.*, "Femtosecond x rays from laser-plasma accelerators," *Reviews of Modern Physics* **85** 1 - 48 (2013)

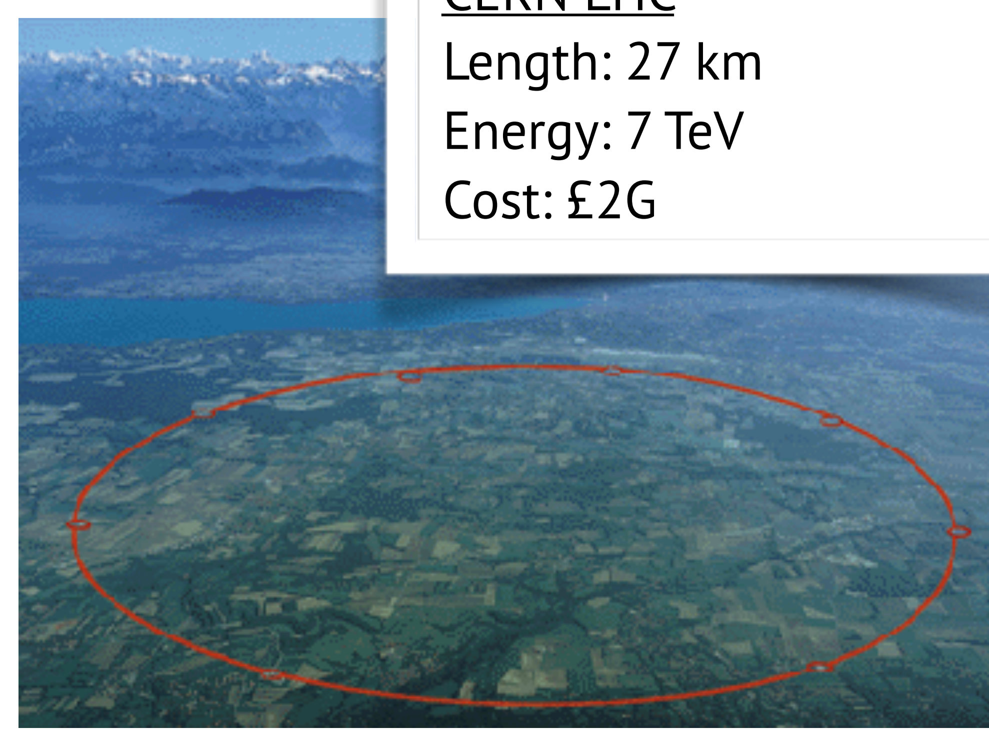
Motivation

- "Conventional" accelerators are widely used in science and medicine
  - Acceleration gradient limited by electrical breakdown to < **100 MV / m**
  - To a significant degree, this sets the size (& cost) of the machine



EU XFEL accelerator

Diamond
Length: 150 m
Energy: 3 GeV
Cost: £370M



CERN LHC
Length: 27 km
Energy: 7 TeV
Cost: £2G

Original concept

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.

- Pioneering paper by Tajima & Dawson in 1979
- First to suggest laser-driven plasma wakefield for accelerating charged particles
- Predicted **acceleration gradients 1000 times higher than radio-frequency machines**

Key concepts

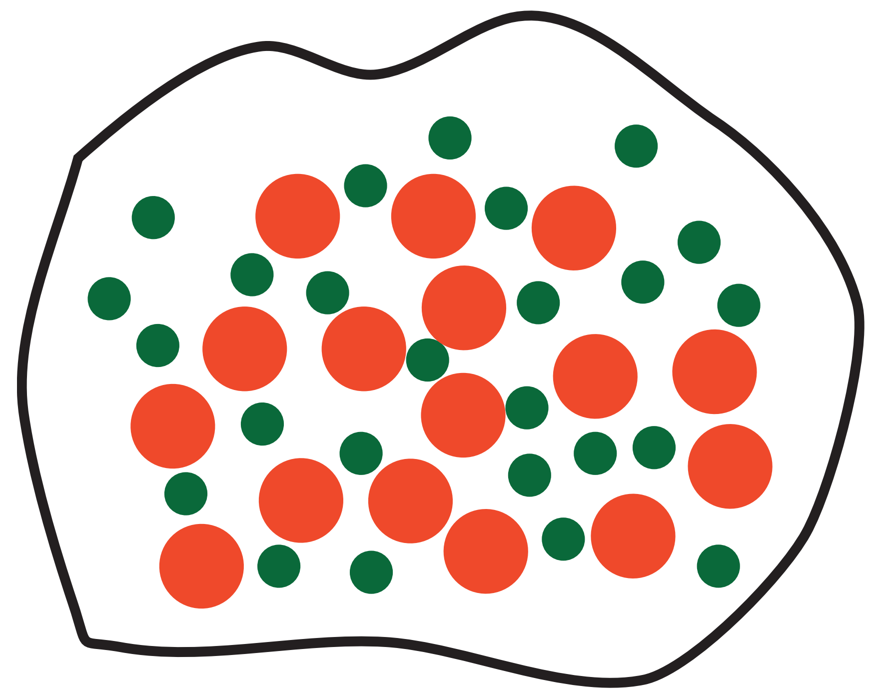
The plasma frequency

- Natural frequency for collective oscillations of plasma
- Derived by considering 3 equations (exercise for student!):

$$\vec{J} = -n_\mathrm{e} e \vec{v} \qquad \text{Current density}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 \frac{\partial \vec{E}}{\partial t} \approx 0 \qquad \text{Maxwell equation}$$

$$m_\mathrm{e} \frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = -e\vec{E} \qquad \text{Equation of motion}$$

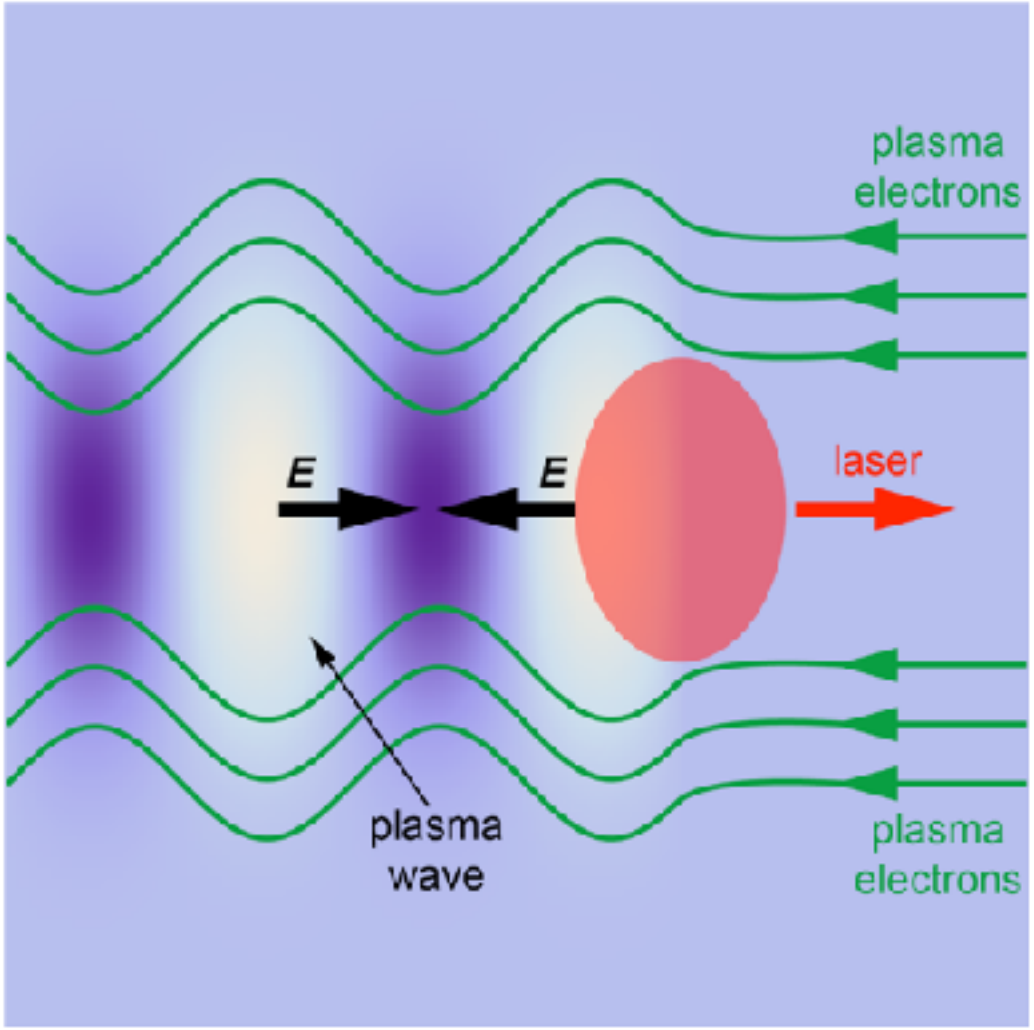


- Combining these gives,

$$\frac{\mathrm{d}^2 \vec{J}}{\mathrm{d}t^2} = -\frac{n_\mathrm{e} e^2}{m_\mathrm{e} \epsilon_0} \vec{J} = -\omega_\mathrm{p}^2 \vec{J}$$

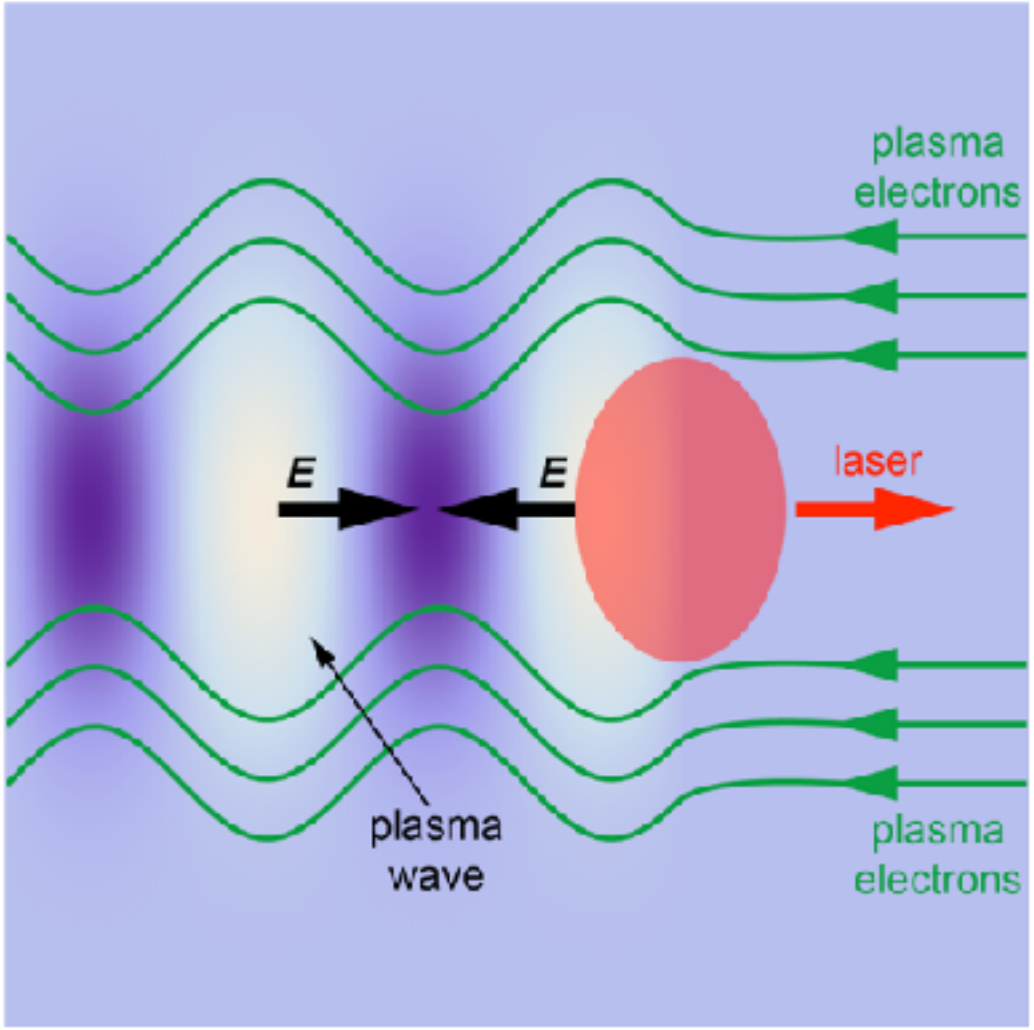
$$\text{where} \quad \omega_\mathrm{p} = \left(\frac{n_\mathrm{e} e^2}{m_\mathrm{e} \epsilon_0} \right)^{1/2}$$

The basic idea



- Ponderomotive force of an intense laser pulse expels electrons from the region of the pulse to form a trailing plasma wakefield (a Langmuir wave).

The basic idea



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- The wakefield moves at speed of laser pulse (close to speed of light)
- Electric fields within wakefield can accelerate charged particles

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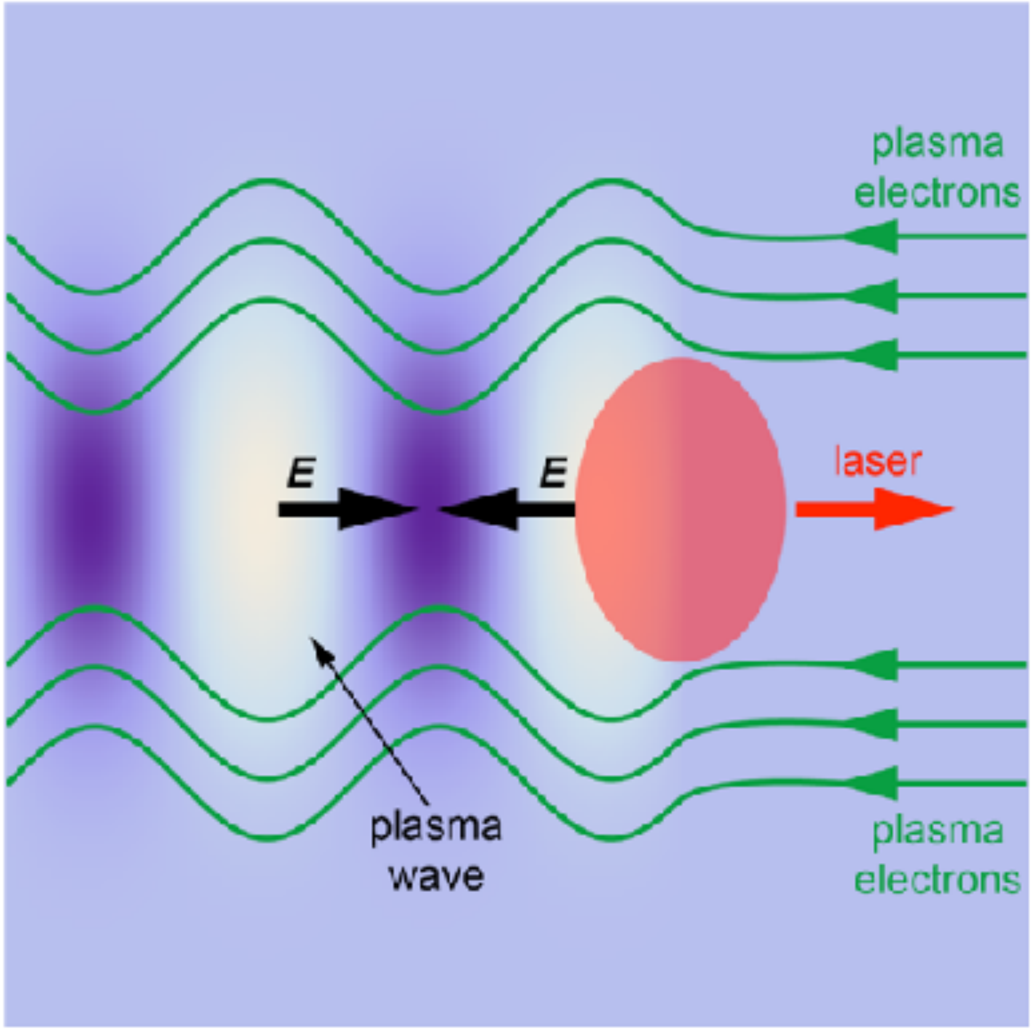

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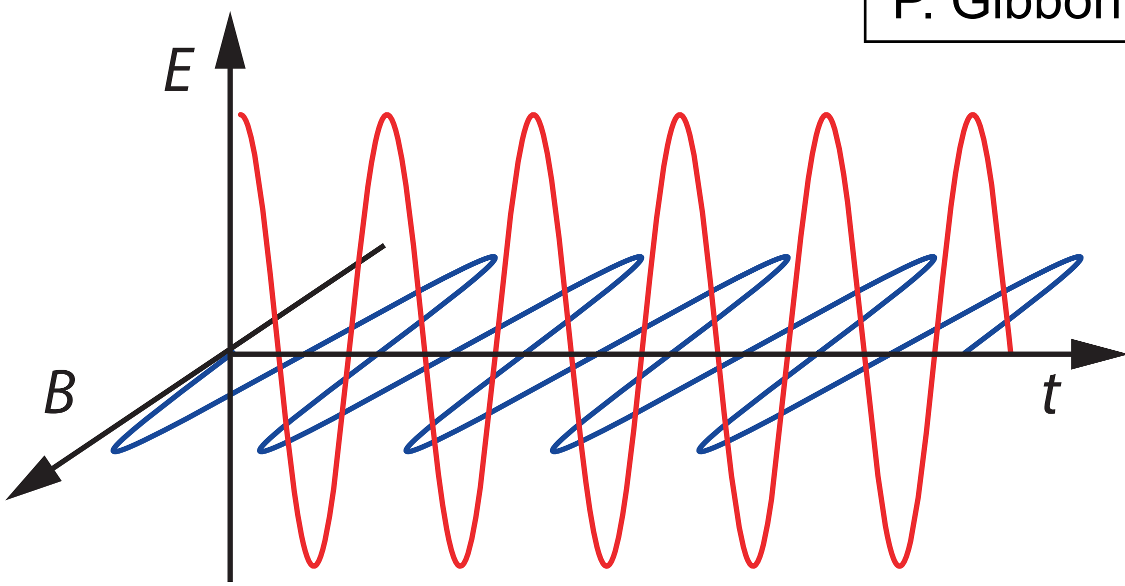
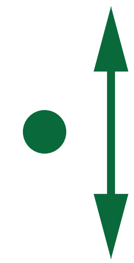
Important things I will not talk about:

- Plasma accelerators driven by **particle beams** ("beam-driven" or "plasma wakefield accelerator")
- **Ion acceleration**: acceleration of protons, positive ions etc by fields generated in laser-solid interactions

Motion of free electron in laser field I

E. Esarey *et al. Rev. Mod. Phys.* **81** 1229 (2009)
P. Gibbon, "Short Pulse Laser Interactions with Matter: An Introduction"





$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + \vec{v}\times\vec{B}\right] \approx -e\vec{E}$$

$$\vec{v}_{\mathrm{osc}} = i\frac{e}{m_{\mathrm{e}}\omega}\vec{E}_0\exp\left(-i\omega t\right)$$

$$U_{\mathrm{p}} = \frac{1}{2}m_{\mathrm{e}}\left\langle\left|\vec{v}_{\mathrm{osc}}\right|^2\right\rangle = \frac{e^2}{4m_{\mathrm{e}}\omega^2}E_0^2$$

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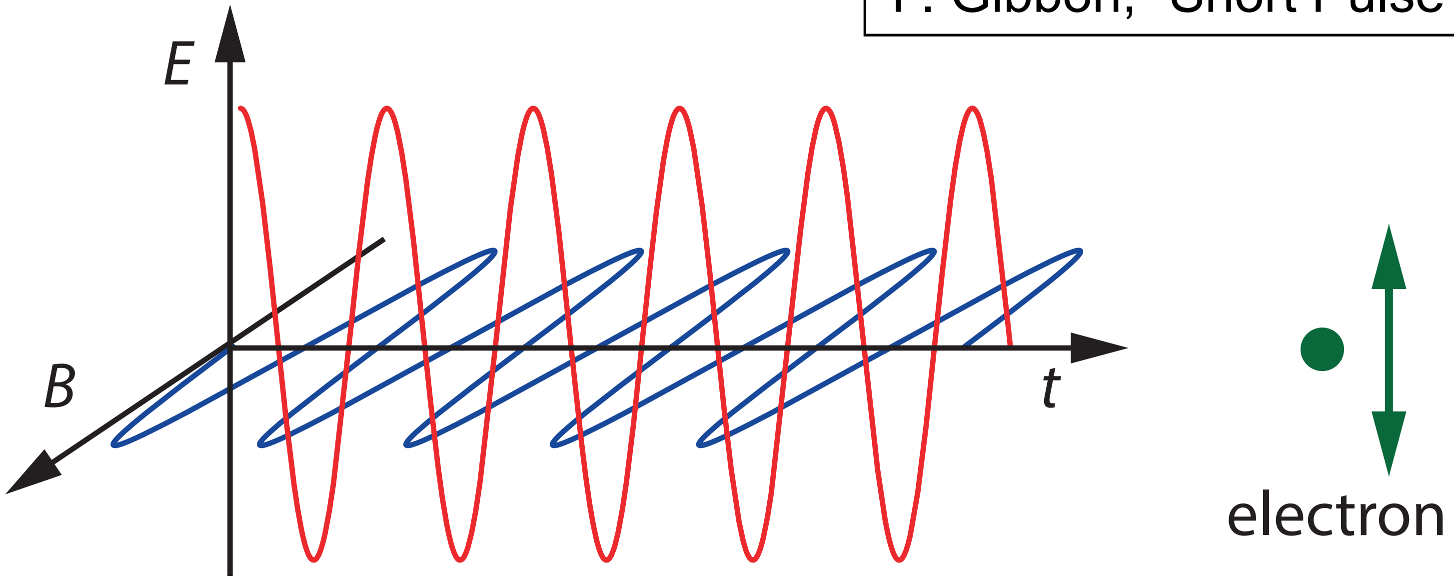

Eqn of motion of electron in field:

$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + \vec{v} \times \vec{B}\right]$$
$$\approx -e\vec{E}$$

For a harmonic field,

$$\vec{v}_{\mathrm{osc}} = i\frac{e}{m_{\mathrm{e}}\omega}\vec{E}_0 \exp\left(-i\omega t\right)$$

The **ponderomotive potential** is the mean "quiver" energy:

$$U_{\mathrm{p}} = \frac{1}{2}m_{\mathrm{e}}\left\langle\left|\vec{v}_{\mathrm{osc}}\right|^2\right\rangle = \frac{e^2}{4m_{\mathrm{e}}\omega^2}E_0^2$$

Motion of free electron in laser field II

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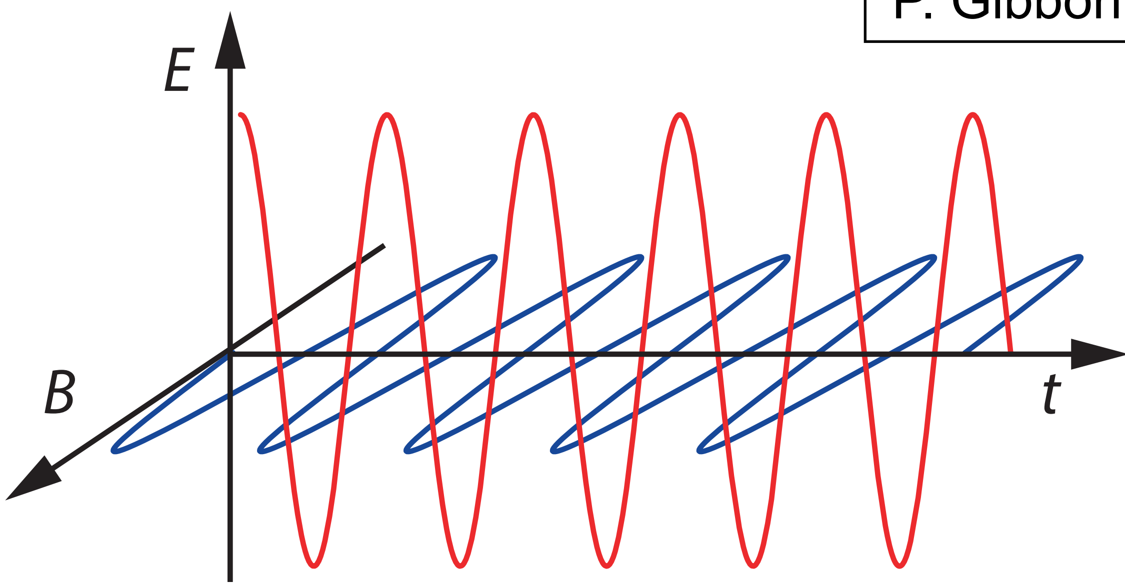

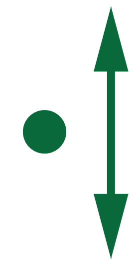

More correctly....

$$\frac{d\vec{p}}{dt} = -e\left[\vec{E} + \vec{v} \times \vec{B}\right]$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t}$$

$$\vec{B} = \nabla \times \vec{A}$$

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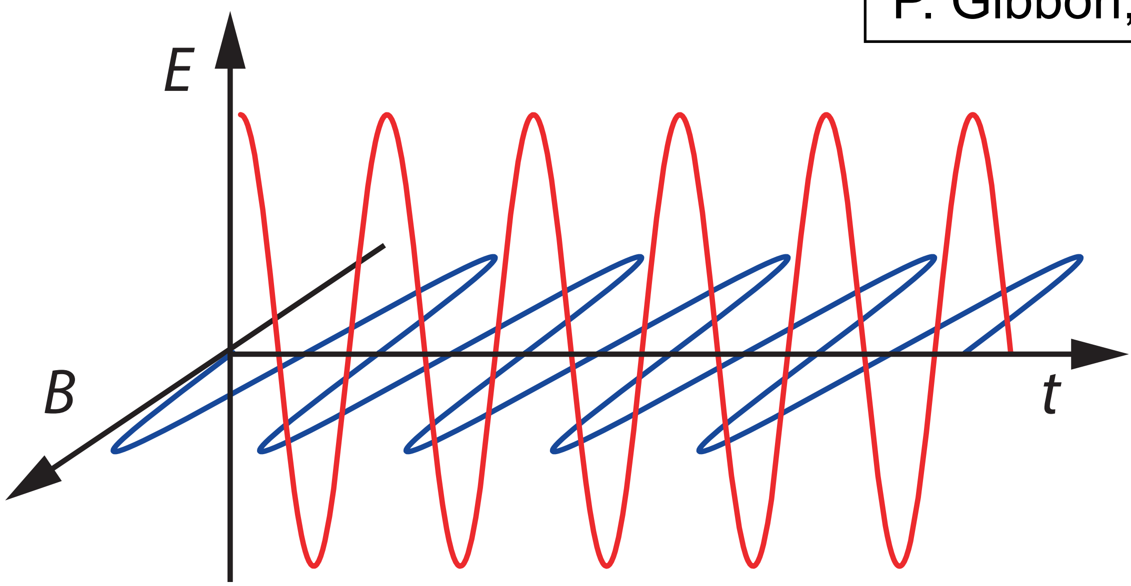

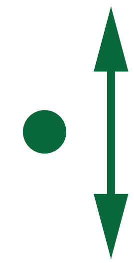

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Can write eqn of motion of electron in field as:

$$\frac{1}{mc}\frac{d\vec{p}}{dt} = \frac{\partial}{\partial t}\left(\frac{e}{mc}\vec{A}\right) - \vec{v} \times \nabla \times \left(\frac{e}{mc}\vec{A}\right)$$

Hence define normalized vector potential as

$$\vec{a} = \frac{e\vec{A}}{mc}$$

Motion of free electron in laser field II

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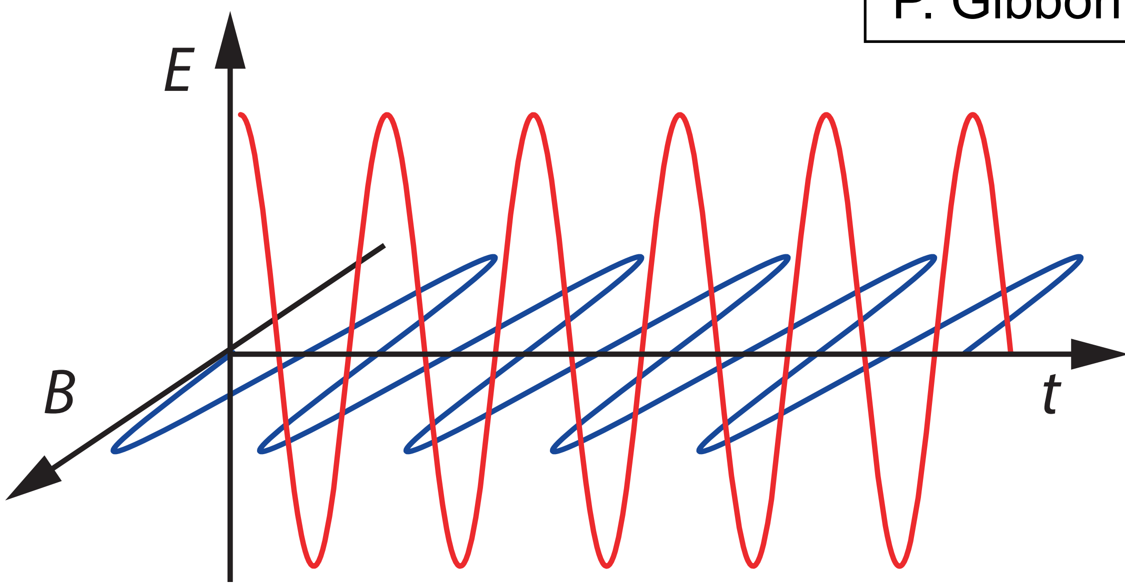

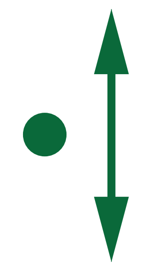

electron

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Hence define normalized vector potential as

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For linear poln:

$$a_0^2 \approx 0.73 \times 10^{-18} \left(\lambda[\mu\mathrm{m}]\right)^2 I_0[\mathrm{Wcm}^{-2}]$$

Electron motion relativistic when $a_0 \approx 1$

Ponderomotive force

"There are few topics in laser-plasma interactions that have caused such persistent argument as the curiously named ponderomotive force."

Paul Gibbon, Chapter 3 of "Short-pulse laser interactions with matter," Imperial College Press

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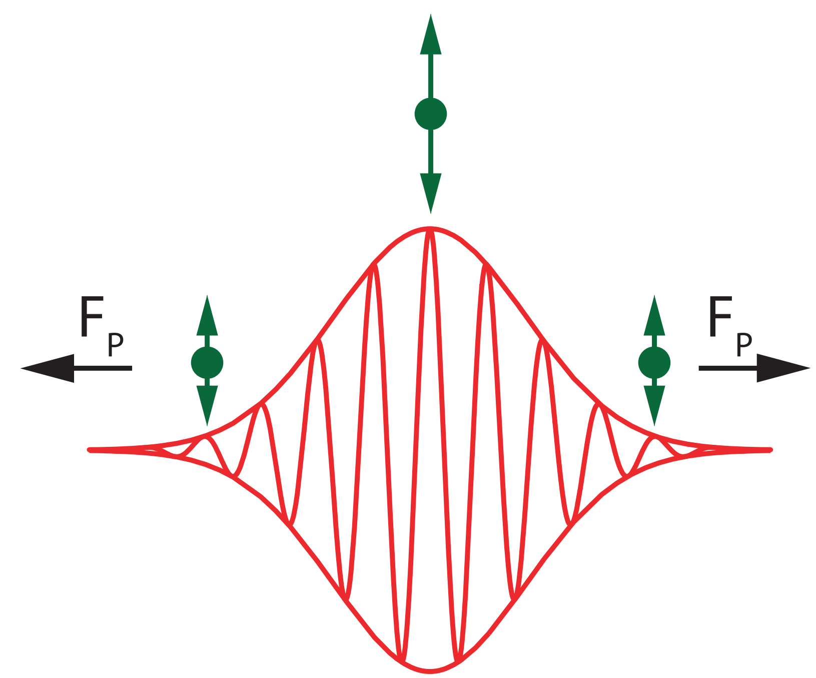
- In essence it is simply the cycle-averaged force experienced by a charged particle in a non-uniform EM field
- A non-relativistic expression is,

$$\vec{F}_{\mathrm{p}} = -\frac{e^2}{4m_{\mathrm{e}}\omega^2}\nabla E_0^2 = -\nabla U_{\mathrm{p}}$$



Estimate of size of accelerating fields

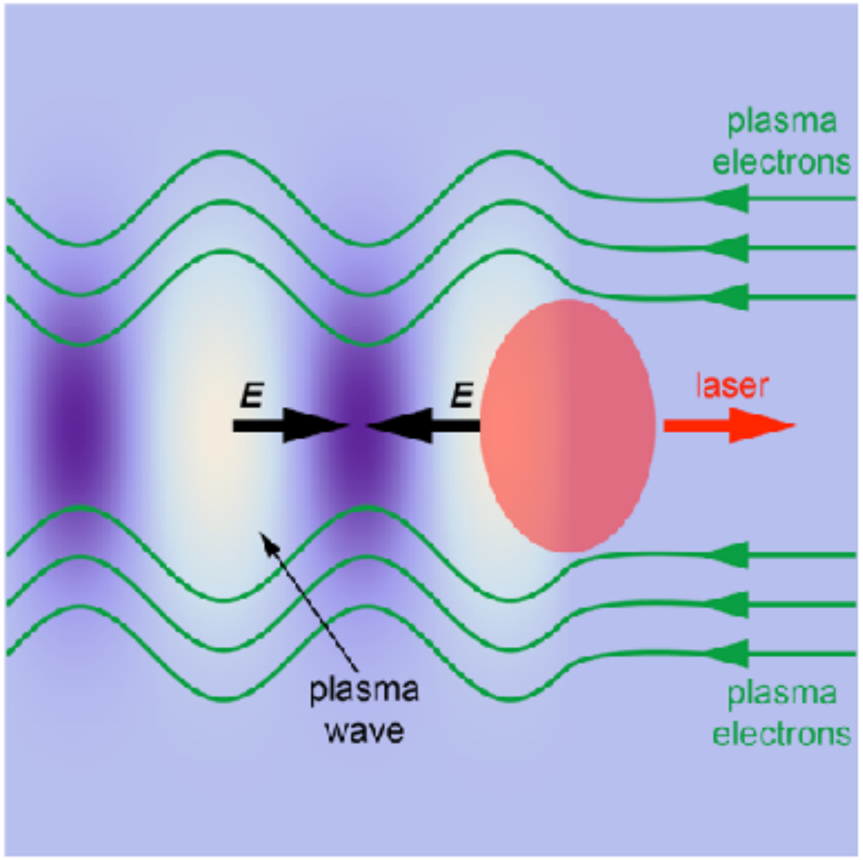
- Consider 1 D plasma wave: $$n_\mathrm{e} = n_0 + \Delta n_\mathrm{e} \sin(k_\mathrm{p} z - \omega_\mathrm{p} t)$$

- From Maxwell: $$\nabla \cdot \vec{D} = \rho$$
$$\Rightarrow \frac{\partial D_z}{\partial z} = (n_0 - n_\mathrm{e})e = -\Delta n_\mathrm{e} e \sin(k_\mathrm{p} z - \omega_\mathrm{p} t)$$

- Integrating gives: $$E_z = \frac{\Delta n_\mathrm{e}}{n_0} \frac{m_\mathrm{e} \omega_\mathrm{p} c}{e} \cos(k_\mathrm{p} z - \omega_\mathrm{p} t)$$

- So max possible field is the **wave-breaking field:** $$E_\mathrm{wb} = \frac{m_\mathrm{e} \omega_\mathrm{p} c}{e}$$ $$\omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

The basic idea



- Laser & plasma wave propagate at group velocity of laser
- Plasma oscillates at plasma frequency ω_p
- Wake amplitude greatest when $\omega_p \tau \approx 1$
- Electric fields up to order of **wave-breaking field**,

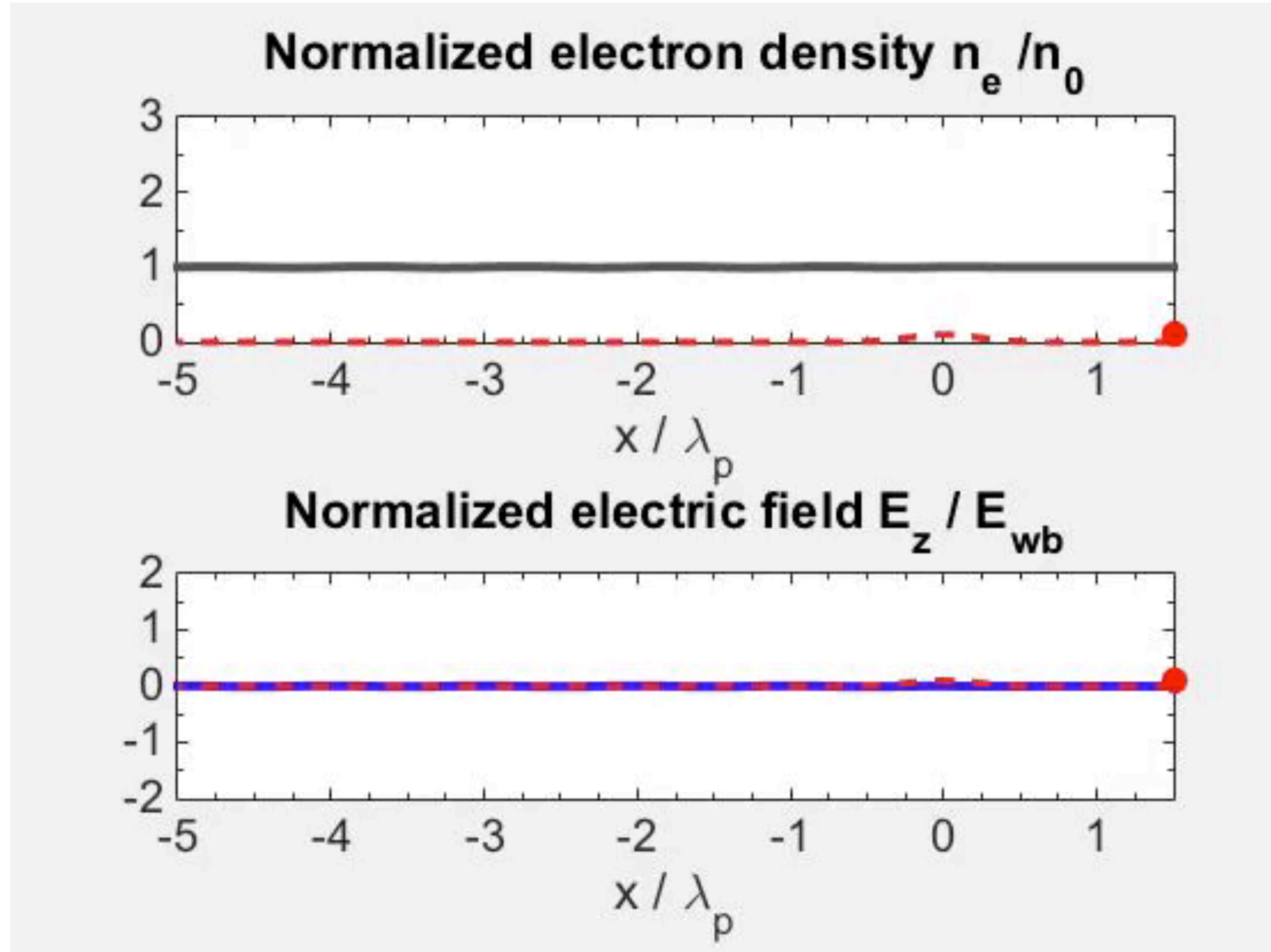
$$E_{wb} = \frac{m_e \omega_p c}{e} \qquad \omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

		Comment
Laser intensity	10^{18} W cm^{-2}	1 J, 50 fs, 25 μm
Plasma density	10^{18} cm^{-3}	i.e. 100 mbar
Accel. field	100 GV m^{-1}	10^3 to 10^4 > RF machine
Plasma period	**100 fs**	Need short laser pulses, get short electron bunches
Plasma wavelength	**30 μm**	

Linear & nonlinear wakefields

- Linear regime
  - Occurs when $a \ll 1$
  - Sinusoidal wakefield
  - Wavelength λ_p
  - $\delta n / n_0 \ll 1$
  - $E_{acc} \ll E_{wb}$

- Nonlinear regime
  - Occurs when $a \gg 1$
  - "Sawtooth" wakefield
  - Wavelength > λ_p
  - $\delta n / n_0 \approx 1$
  - $E_{acc} \approx E_{wb}$



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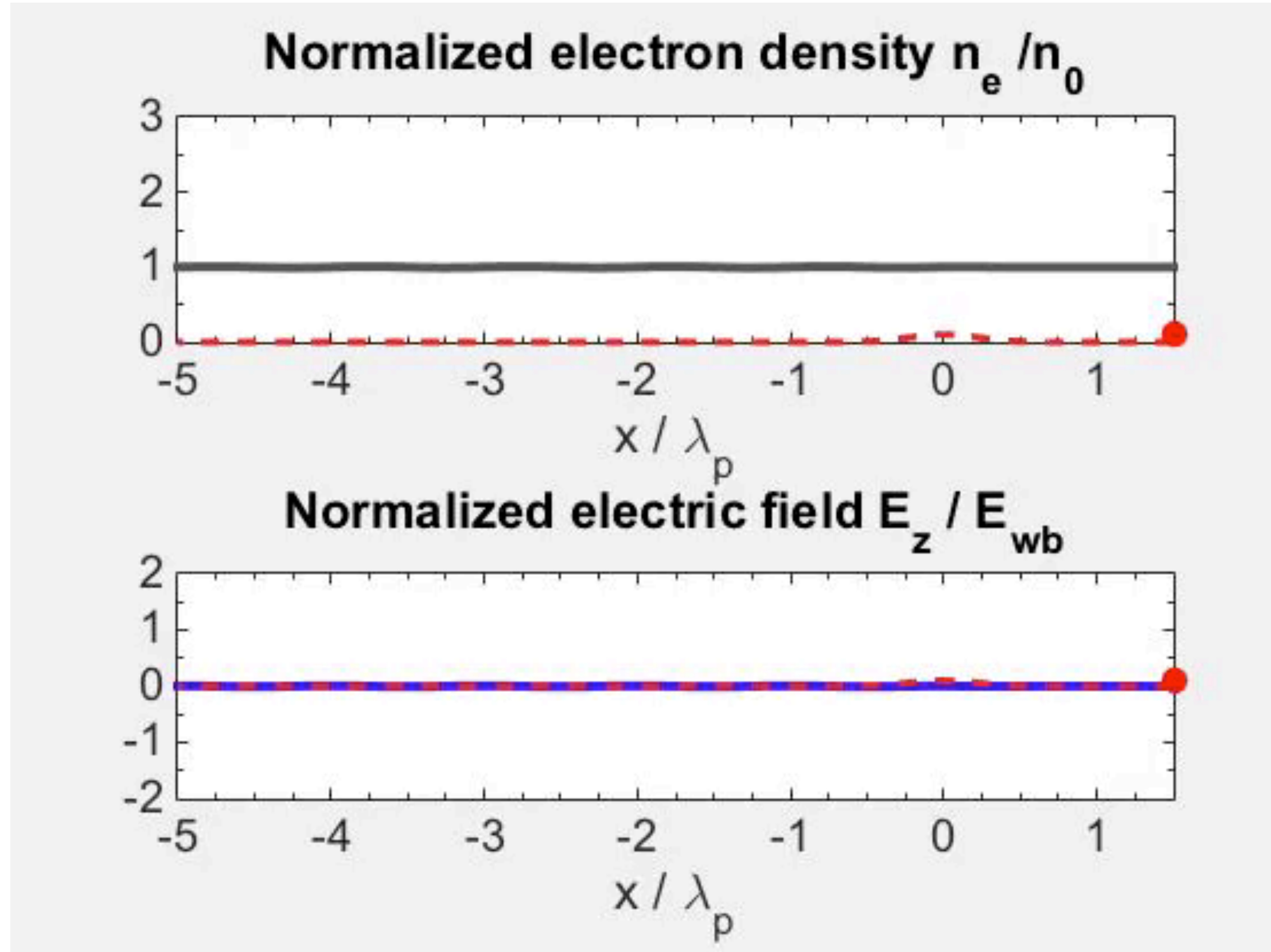
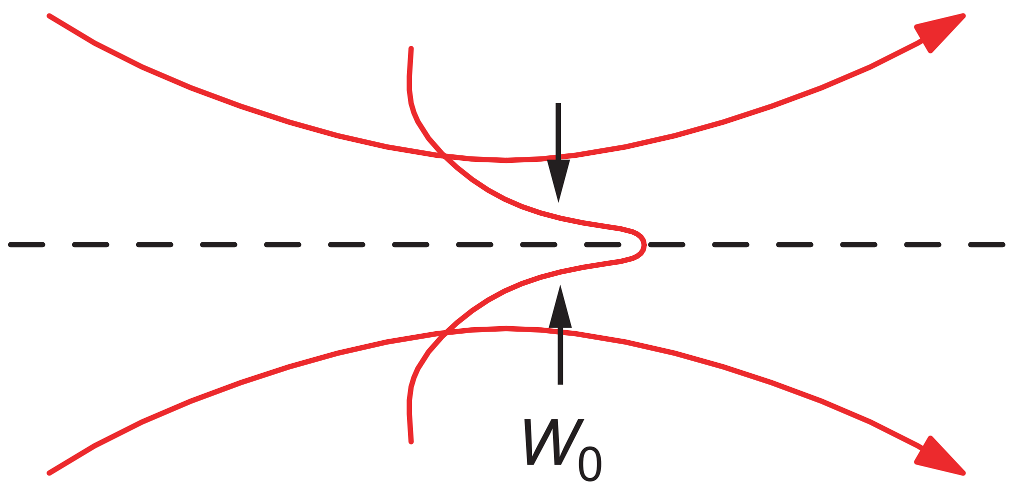


Further considerations

Diffraction of drive pulse



$$Z_R = \frac{\pi w_0^2}{\lambda}$$

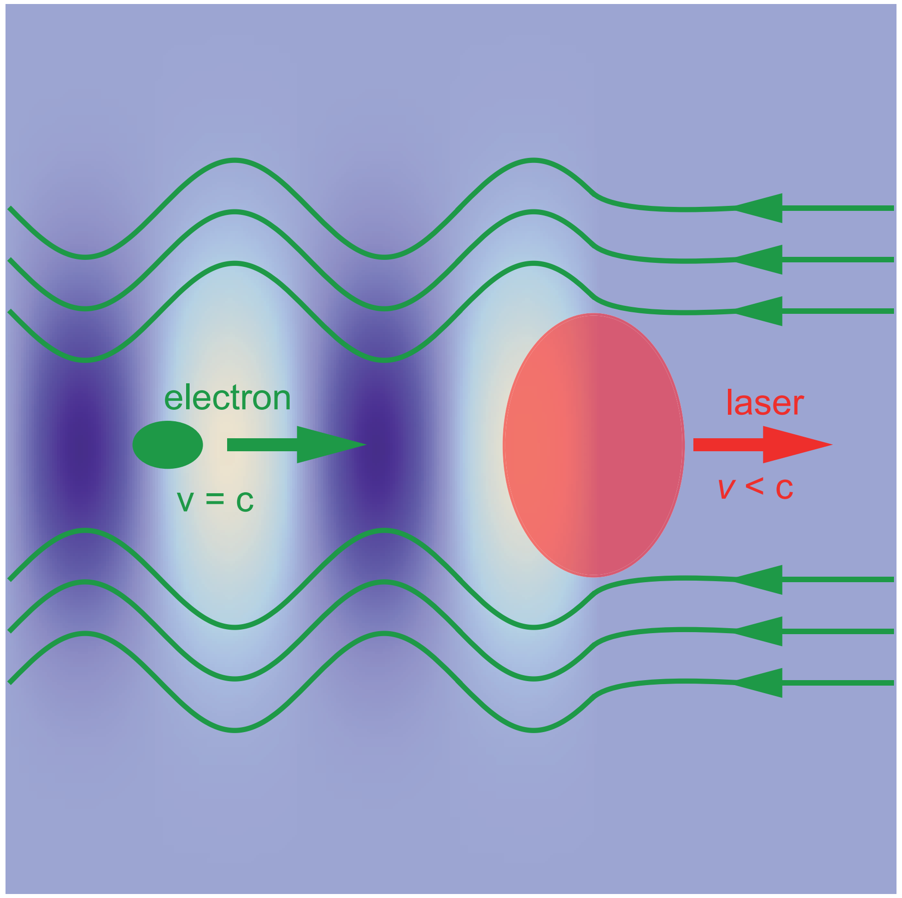
Example :

$$w_0 = 10\,\mu\text{m};\ \lambda = 1\,\mu\text{m}$$

$$\Rightarrow Z_R = 0.3\,\text{mm}$$

- In absence of other effects, driving laser pulse will diffract in distance of order the **Rayleigh range**

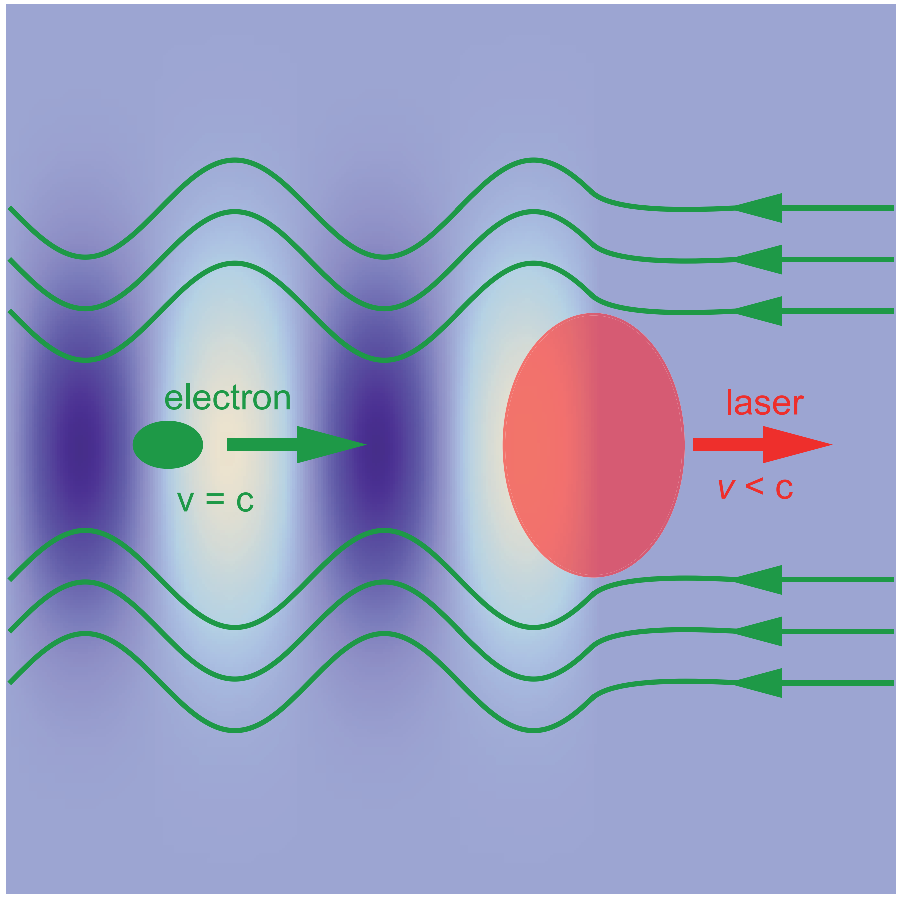
Dephasing & pump depletion



Linear	Nonlinear
$L_\mathrm{d} = \frac{1}{2}\frac{\lambda_p^3}{\lambda_0^2}$	$L_\mathrm{d} = \frac{\sqrt{2}a_0}{\pi}\frac{\lambda_p^3}{\lambda_0^2}$
$L_\mathrm{pd} = \frac{2}{a_0^2}\frac{\lambda_p^3}{\lambda_0^2}$	$L_\mathrm{pd} = \frac{\sqrt{2}a_0}{\pi}\frac{\lambda_p^3}{\lambda_0^2}$
$L_\mathrm{d} \ll L_\mathrm{pd}$	$L_\mathrm{d} \approx L_\mathrm{pd}$

- Electrons move from accelerating to decelerating phase in the **dephasing distance**
- Driving laser loses energy in the **pump depletion length**

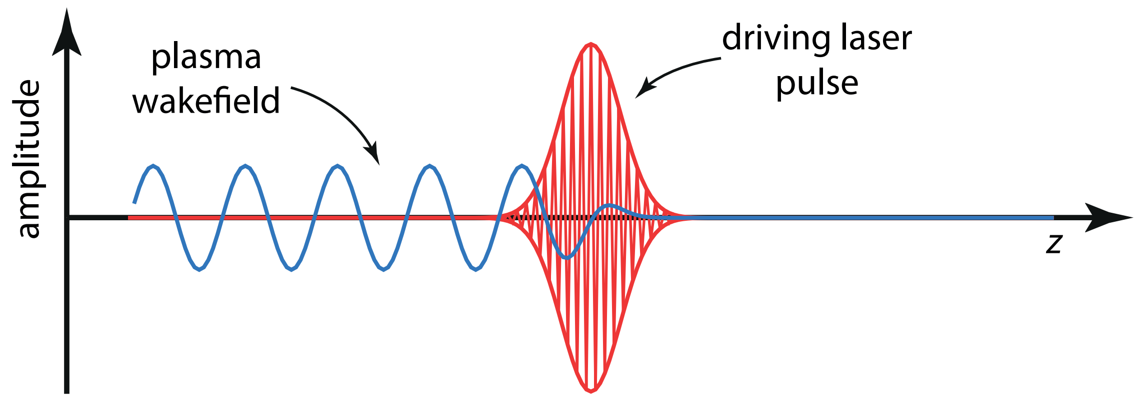
Dephasing & pump depletion



- Accelerated electrons can come from **external source** or **background plasma**
- To be trapped & accelerated an electron needs $v > v_p$ i.e. there is **a threshold momentum**
- Linear regime:
  - Background electrons cannot be trapped
  - Requires "external" injection
- Nonlinear regime
  - Background electrons **can** be trapped ("self-trapping")

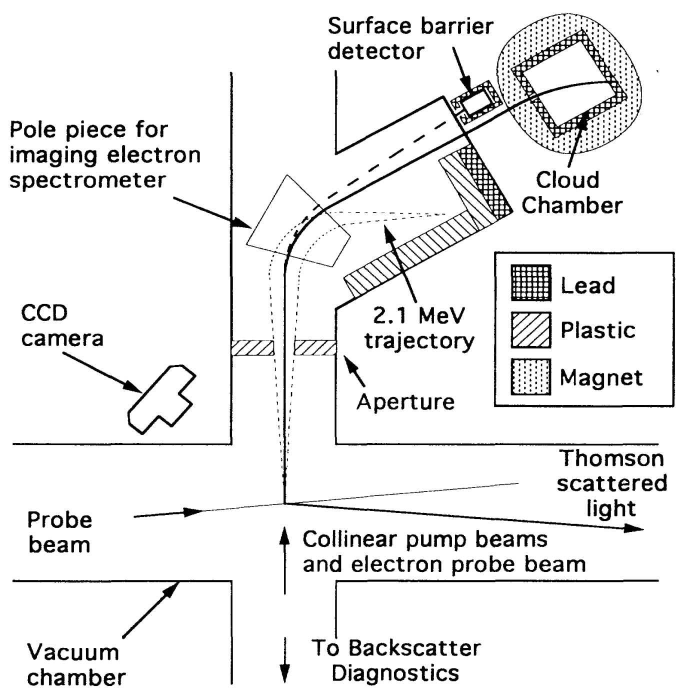
Brief review of progress in plasma accelerators

Progress linked to advances in laser technology



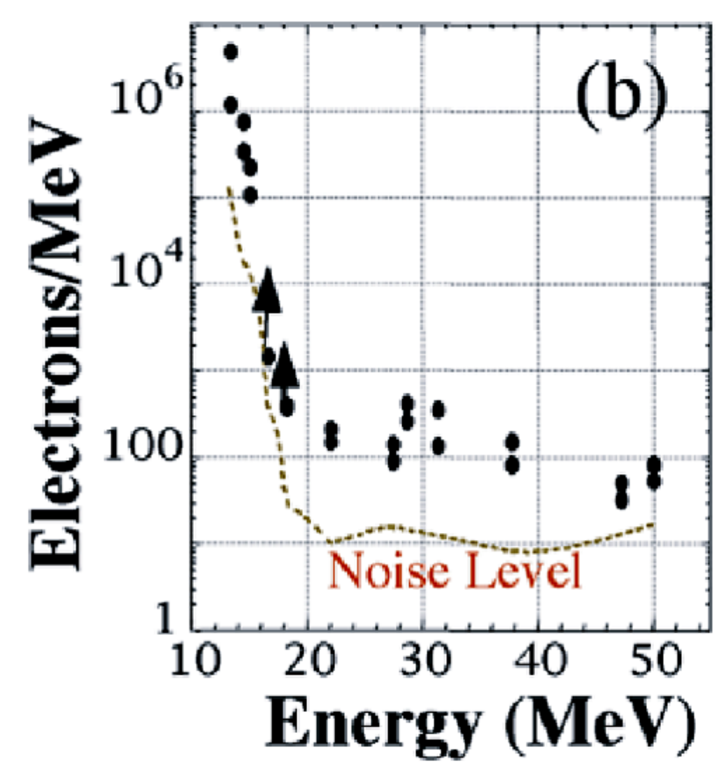
Plasma beat-wave

- Combine 2 long pulses with freqs $\omega_2 - \omega_1 = \omega_p$
  - Wake amplitudes of 28%
  - ΔW = 38 MeV (external injection)
- But wakefield saturates due to relativistic increase in electron mass

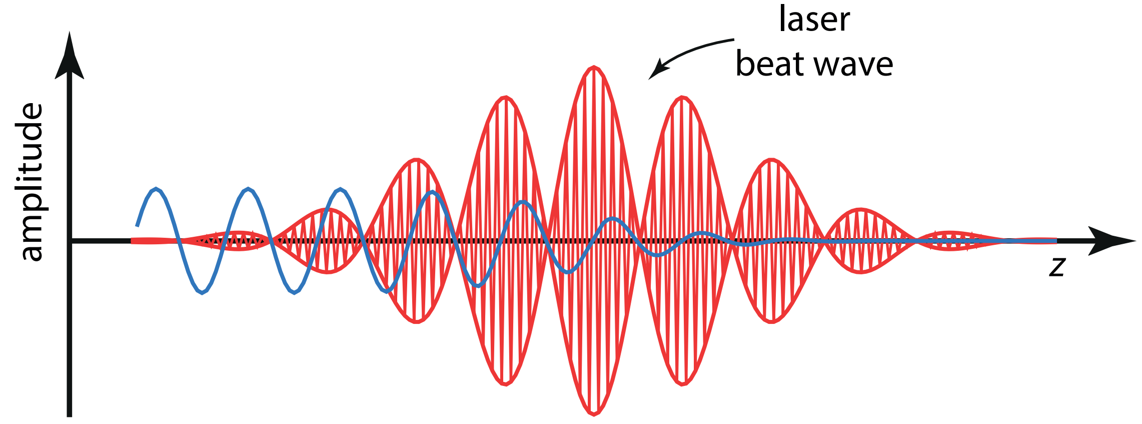


C.E. Clayton *et al. Phys Rev. Lett.* **70** 37 (1993)

Tochitsky *et al. Phys Rev. Lett.* **92** 095004 (2004)
Laser: 200 J, 400 ps (CO_2)
Plasma: $n_e \sim 9 \times 10^{15}$ cm^{-3}
Injected electrons: 12 MeV



Progress linked to advances in laser technology



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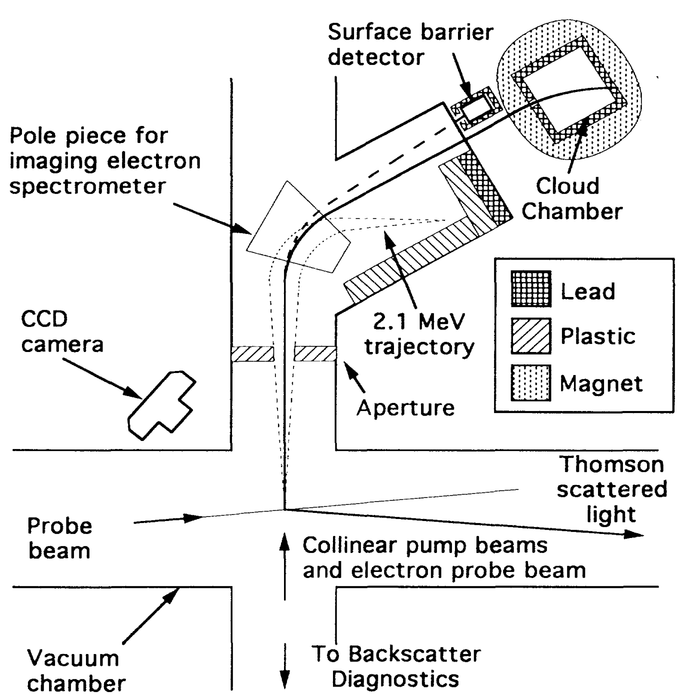

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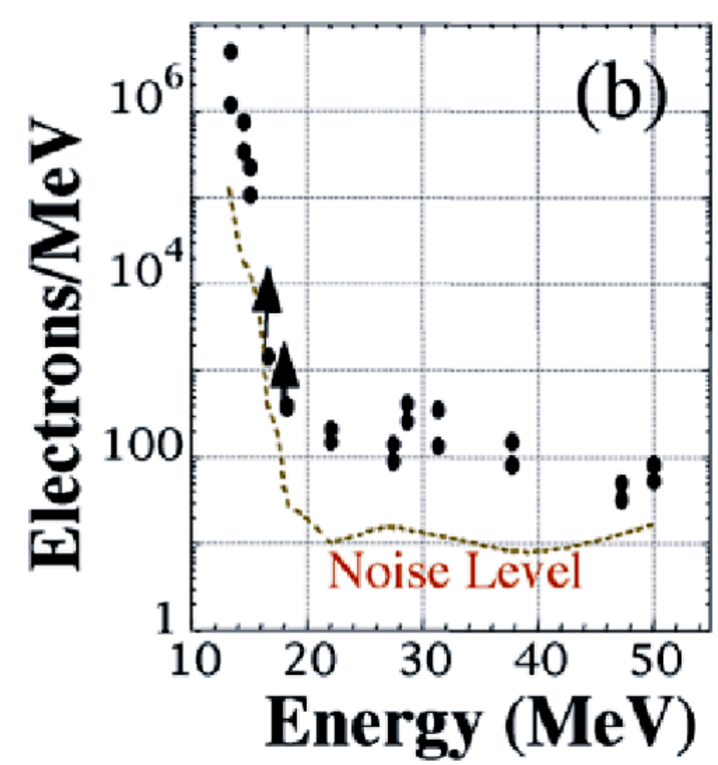

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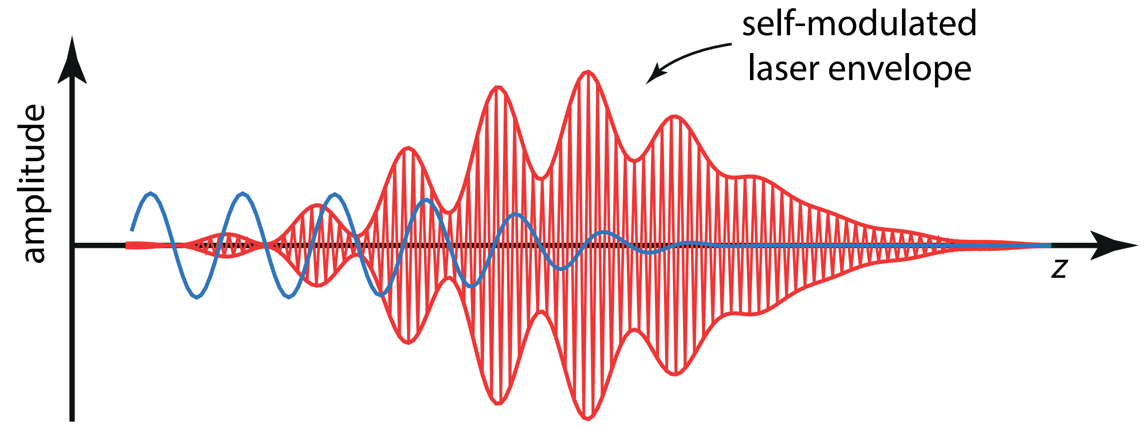
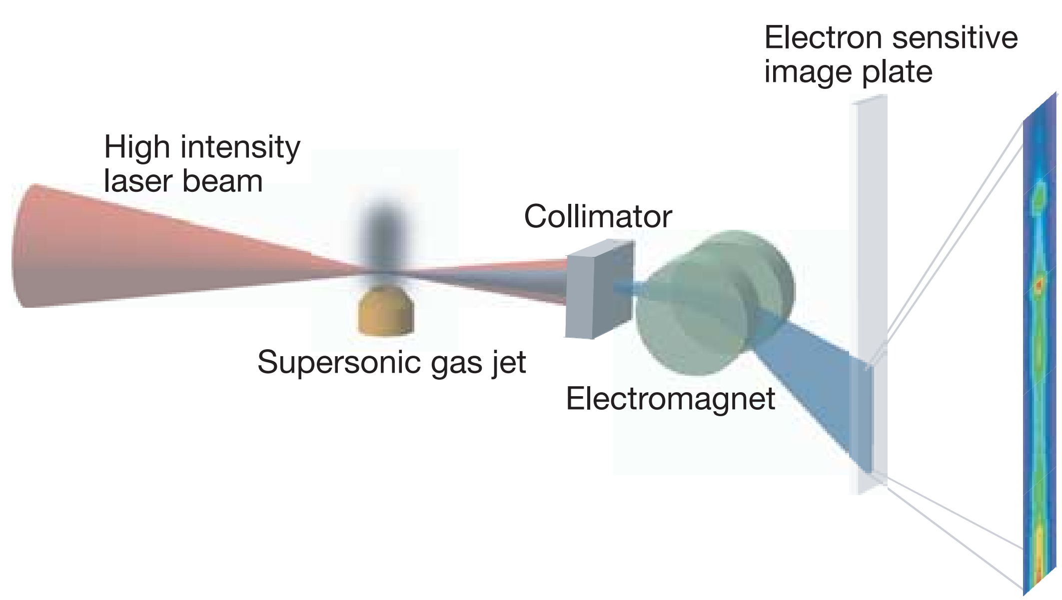
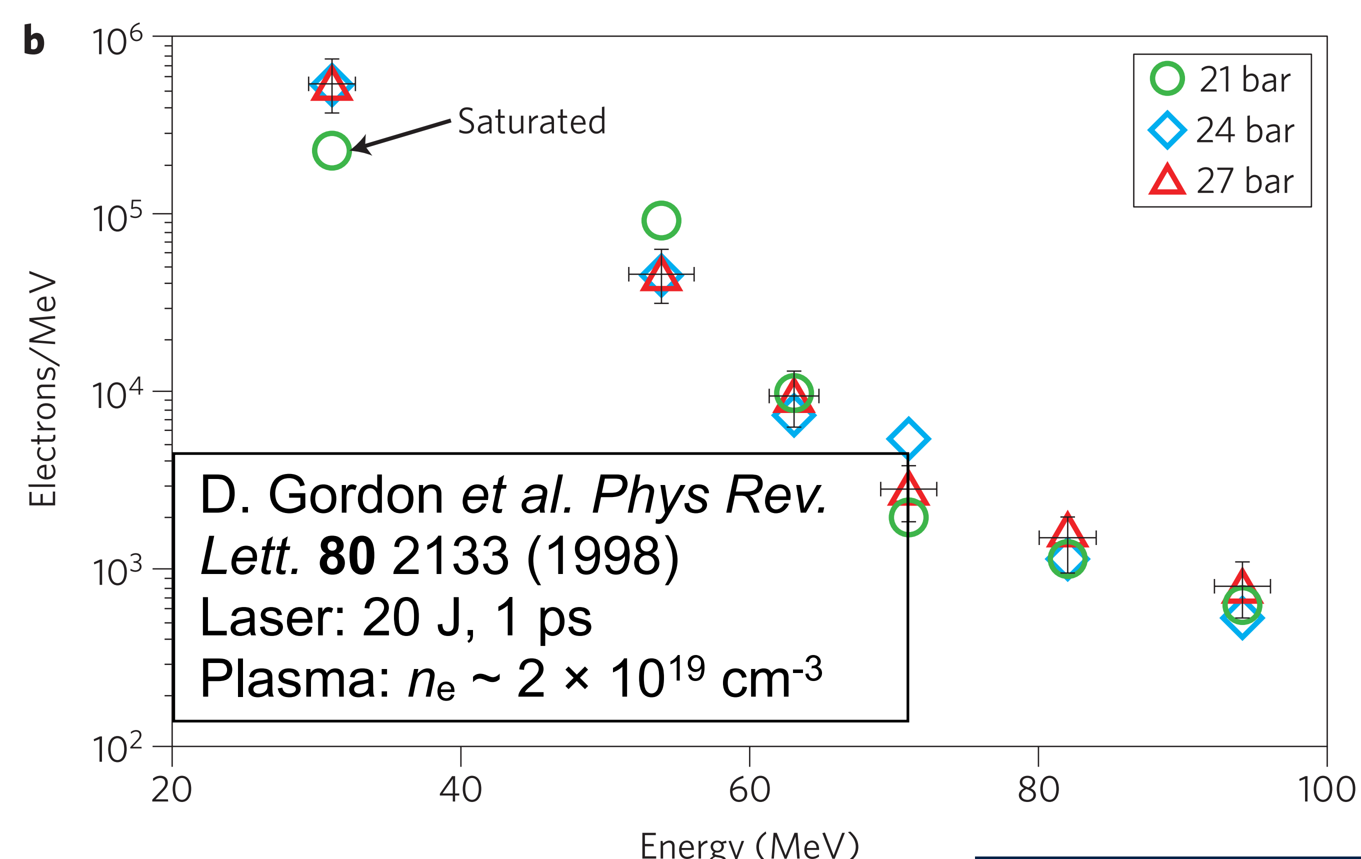


Self-modulated LWFA

- Long laser pulse modulated by plasma
- Automatically maintains resonance
- *W* ~ 100 MeV
- Very broad-band energy spectra



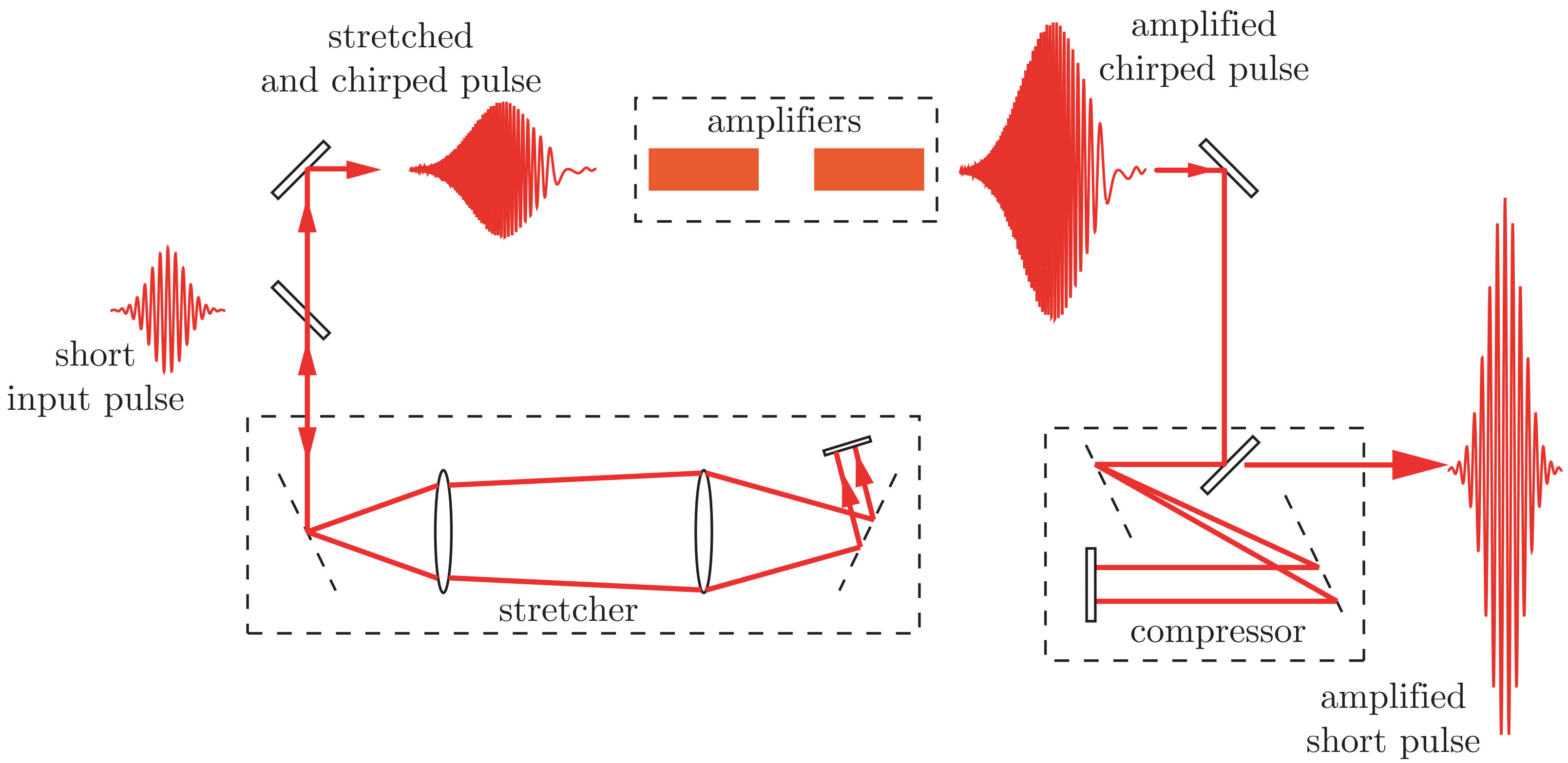
SPD Mangles *et al. Nature* **431** 535 (2004)



D. Gordon *et al. Phys Rev. Lett.* **80** 2133 (1998)
Laser: 20 J, 1 ps
Plasma: n_e ~ 2 × 10^{19} cm^{-3}

An aside: Chirped-pulse amplification

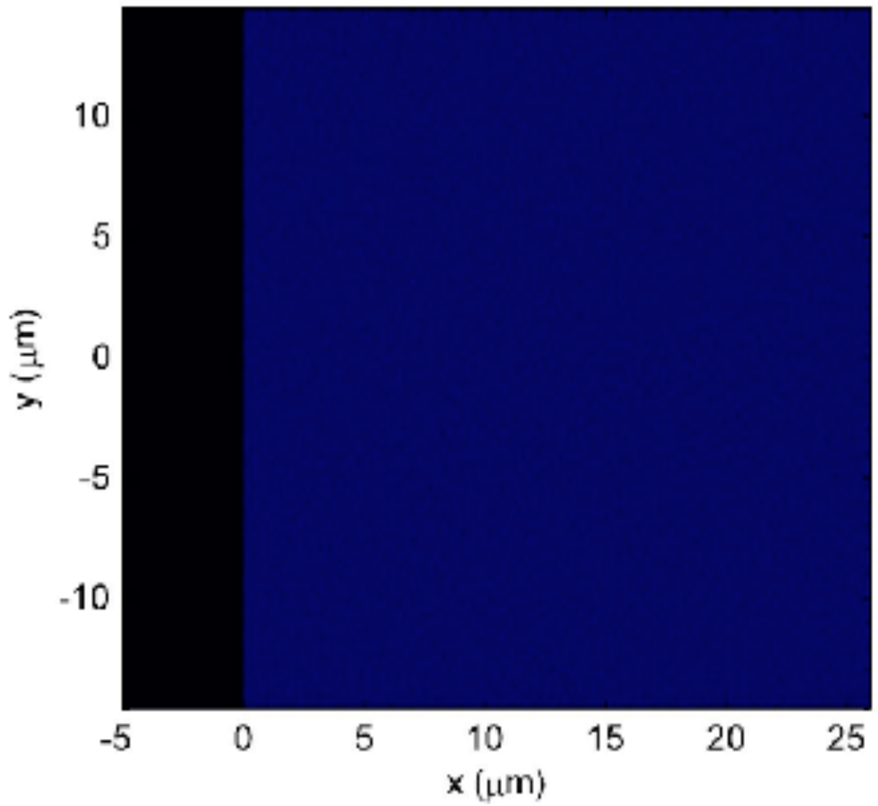
D. Strickland & G. Mourou, *Opt. Commun.* **55** 447 (1985)

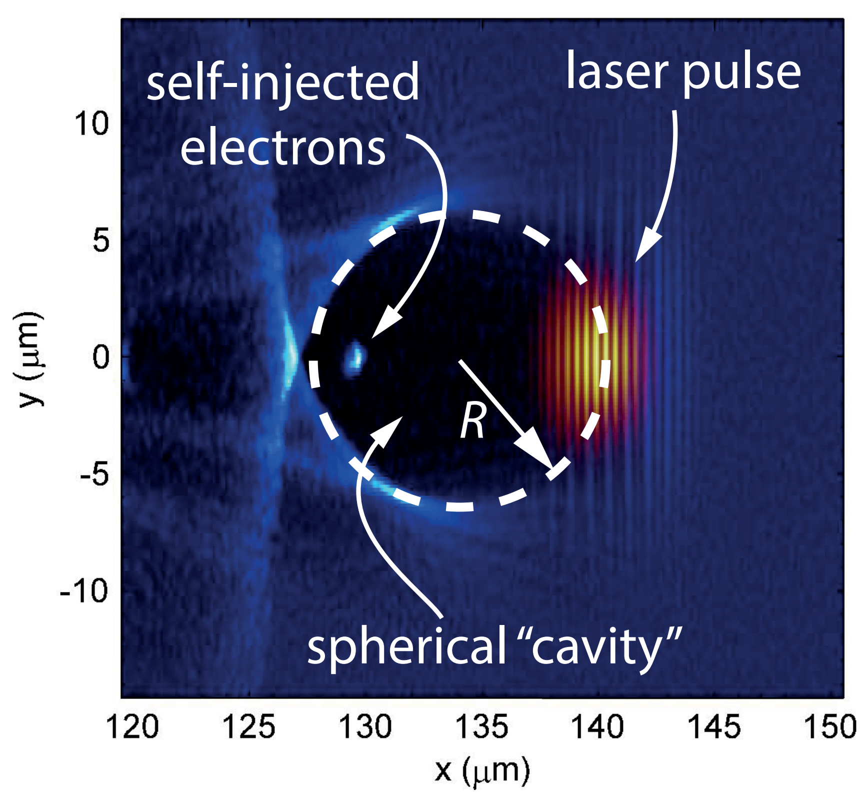


- CPA has allowed the generation of short (< 50 fs) pulses with reasonable energy
- State of art is the BELLA laser at Berkeley:
  - E = 40 J
  - τ = 40 fs
  - P = 1 PW

High-intensity ultrafast lasers: The bubble regime

A. Pukhov & J. Meyer-ter-Vehn *Appl. Phys. B* **74** 355 (2002)
W. Lu *et al. Phys. Rev. STAB* **10** 061301 (2007)





- For short, high-intensity pulses ponderomotive force expels all electrons from region behind laser pulse
- Condition $a_0 > 2$ and:

$$c\tau < w_0 \approx R \approx \frac{\lambda_p}{\pi}\sqrt{a_0}$$

- Approx spherical cavity ("bubble") of radius R formed
- Laser pulse relativistically guided over many Z_R
- Electrons self-injected
- Can give near-monoenergetic beams

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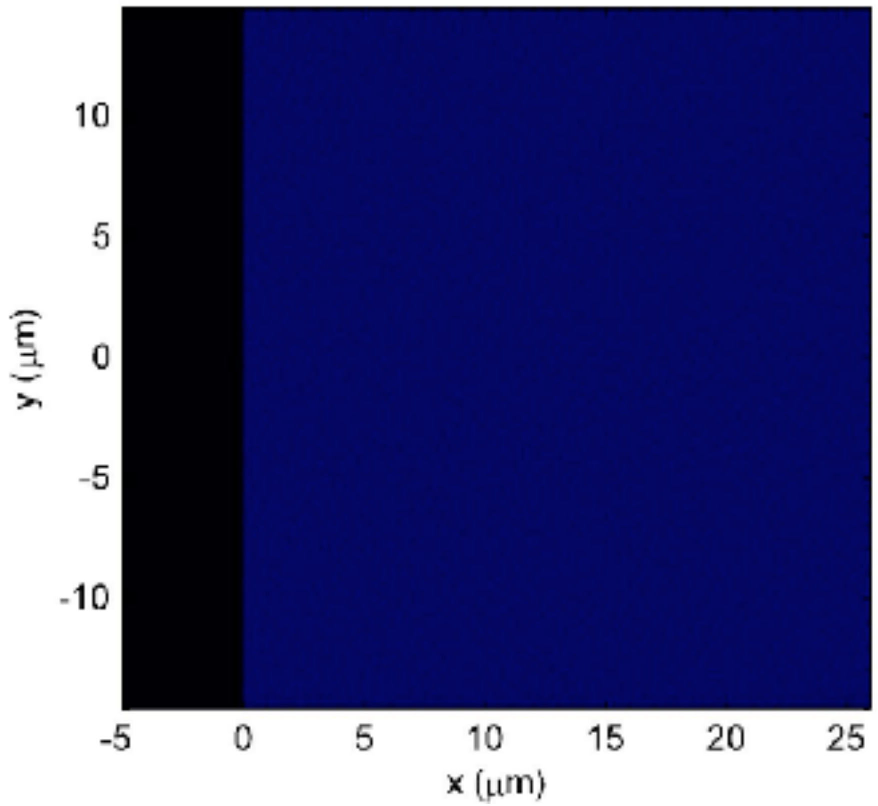
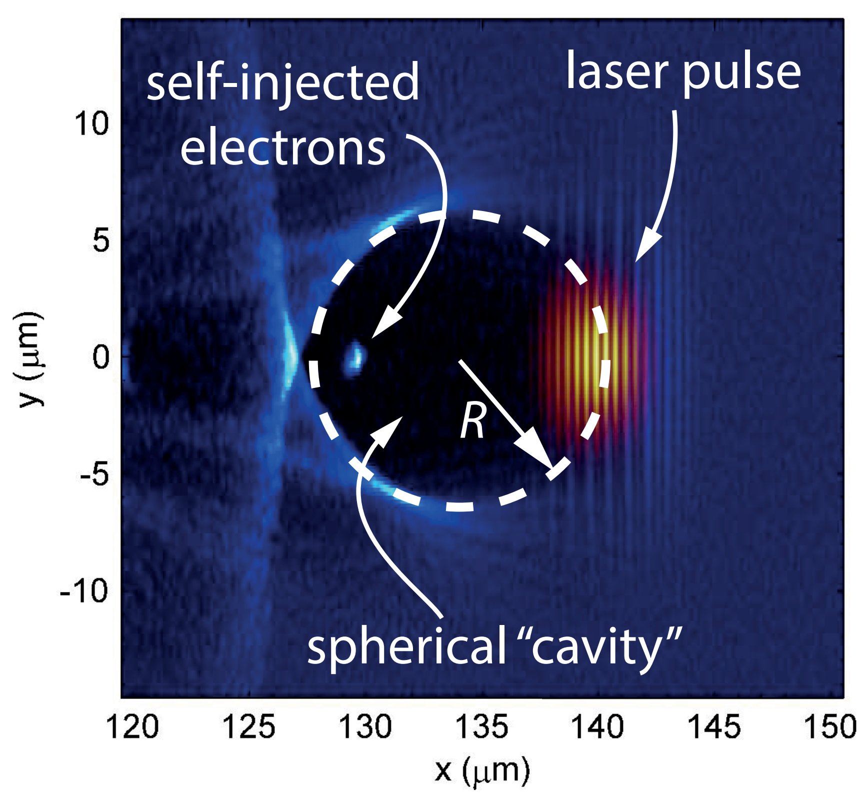
A. Pukhov & J. Meyer-ter-Vehn *Appl. Phys. B* **74** 355 (2002)
W. Lu *et al. Phys. Rev. STAB* **10** 061301 (2007)



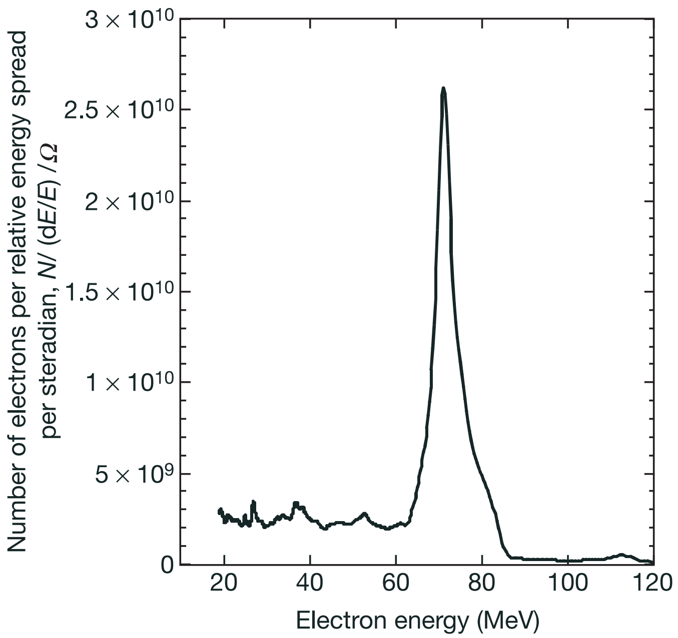
- For short, high-intensity pulses ponderomotive force expels all electrons from region behind laser pulse
- Condition $a_0 > 2$ and:

$$c\tau < w_0 \approx R \approx \frac{\lambda_p}{\pi}\sqrt{a_0}$$

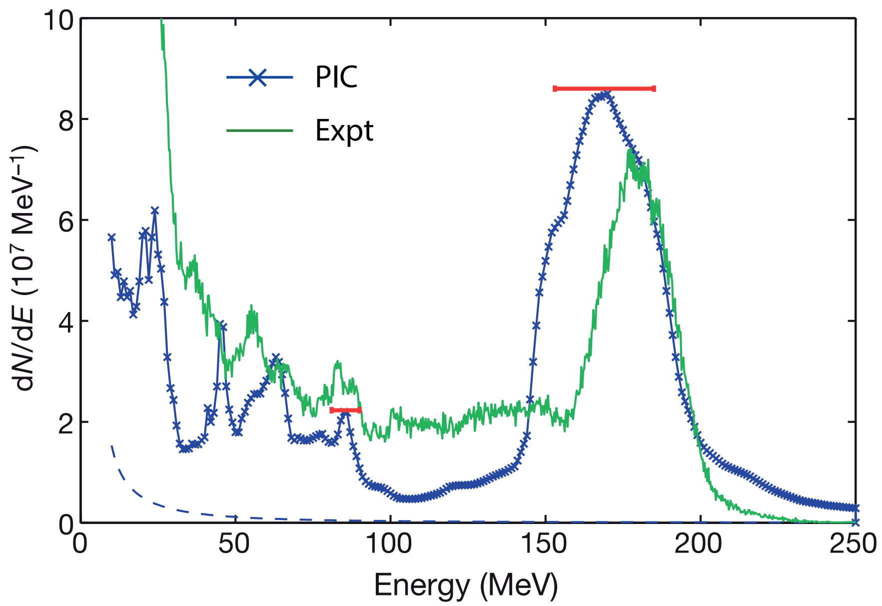


- Approx spherical cavity ("bubble") of radius R formed
- Laser pulse relativistically guided over many Z_R
- Electrons self-injected
- Can give near-monoenergetic beams

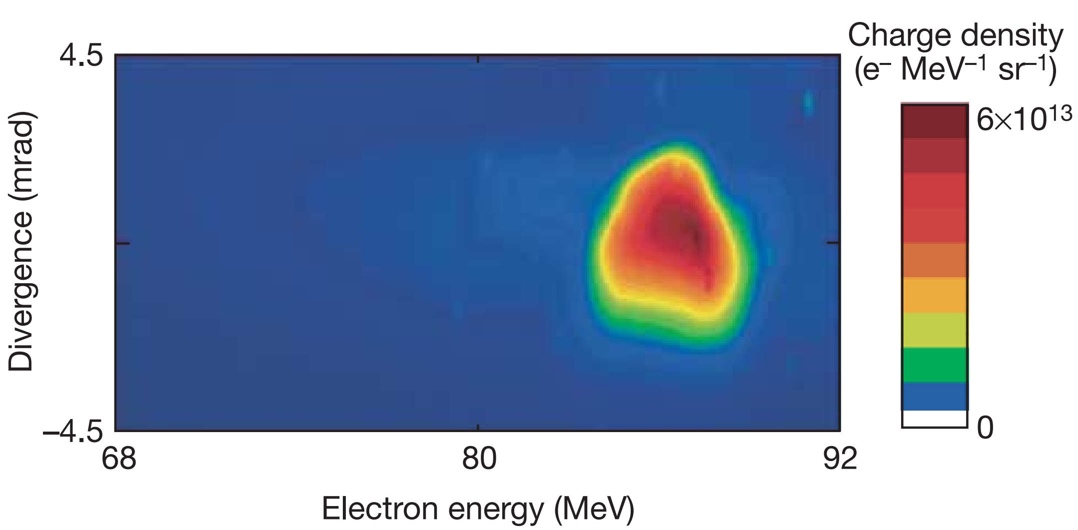
Dream beams!



Mangles *et al.* *Nature* **431** 535 (2004)
E = 0.5 J
τ = 40fs
$a0 \approx 1$
$n_e = 2 \times 10^{19}$ cm^{-3}

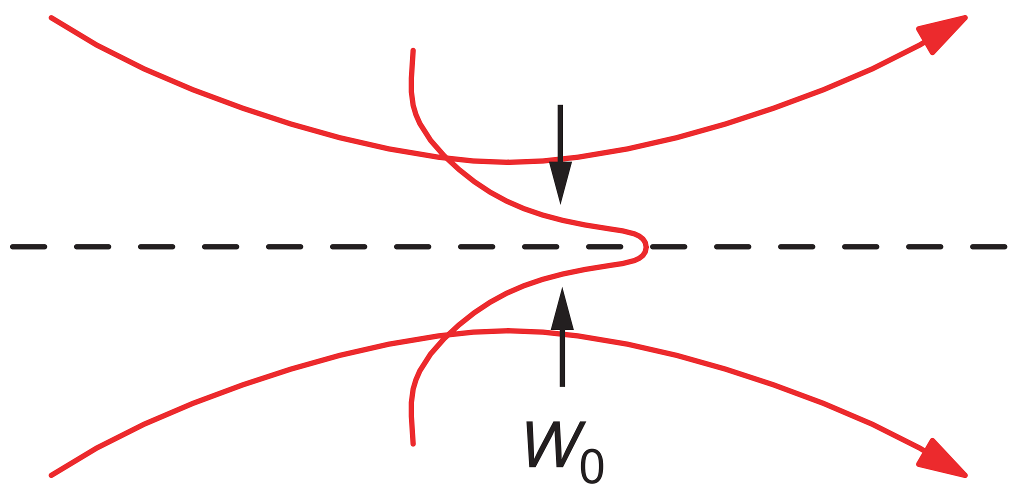


Faure *et al.* *Nature* **431** 541 (2004)
E = 1 J
τ = 33fs
$a0 \approx 1.2$
$n_e = 6 \times 10^{18}$ cm^{-3}



Geddes *et al.* *Nature* **431** 538 (2004)
E = 0.5 J
τ = 55 fs
$a0 \approx 2.3$
$n_e = 2 \times 10^{19}$ cm^{-3}

Scaling to higher energies



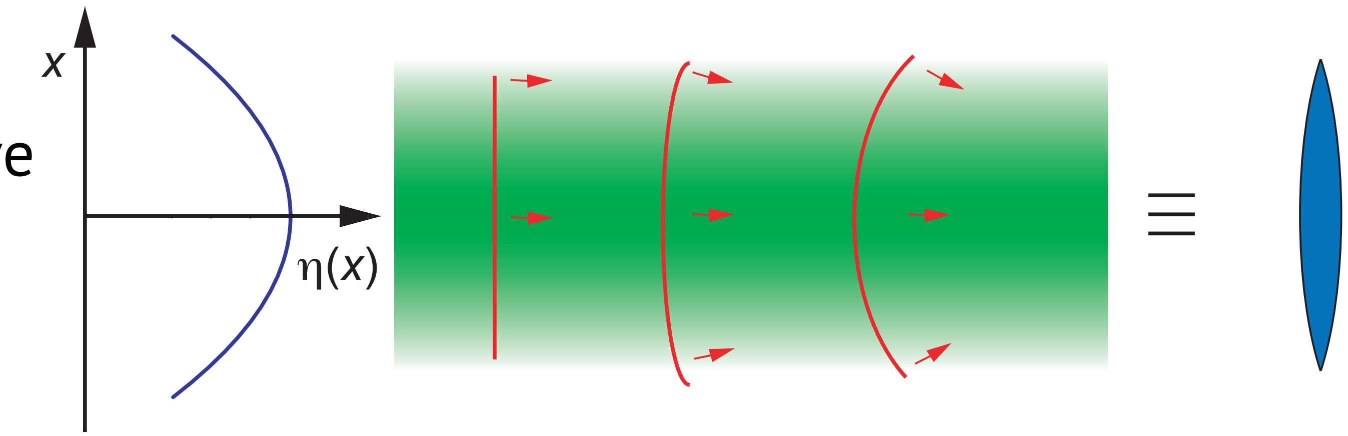
Energy scaling:

$$\Delta W \propto E_{\rm wb} \times \min(L_{\rm d}, L_{\rm pd}) \propto \sqrt{n_e} \quad \frac{1}{n_e^{3/2}} \propto \frac{1}{n_e}$$

- Increasing energy by factor 10 requires factor 10 decrease in density and factor 30 increase in $L_{\rm acc}$
- Hence $L_{\rm acc}$ increases from mm to cm
- Must overcome diffraction of drive pulse….

Gradient refractive index guiding

- Laser beam will be focused if the refractive index decreases with distance from axis



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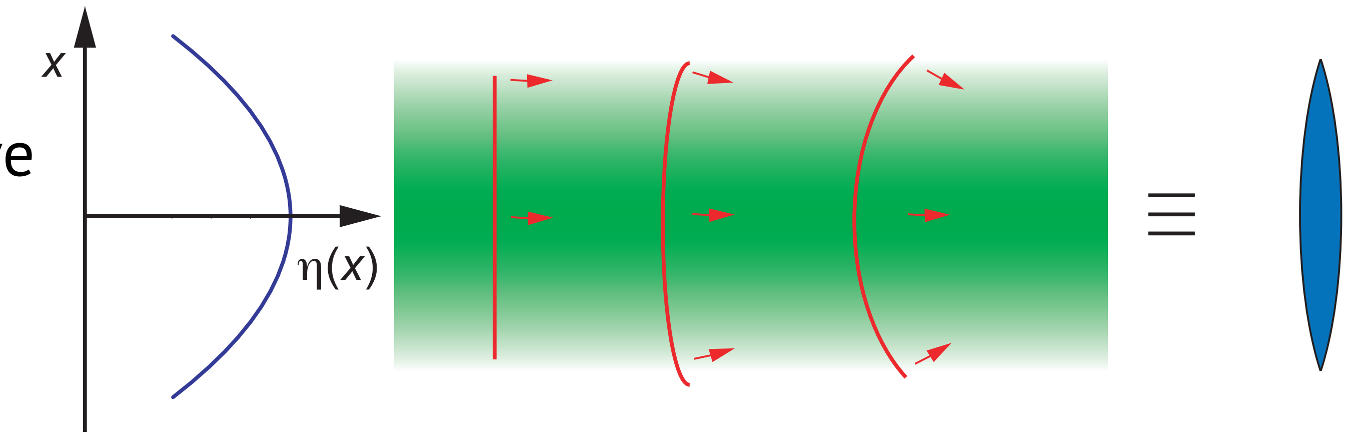
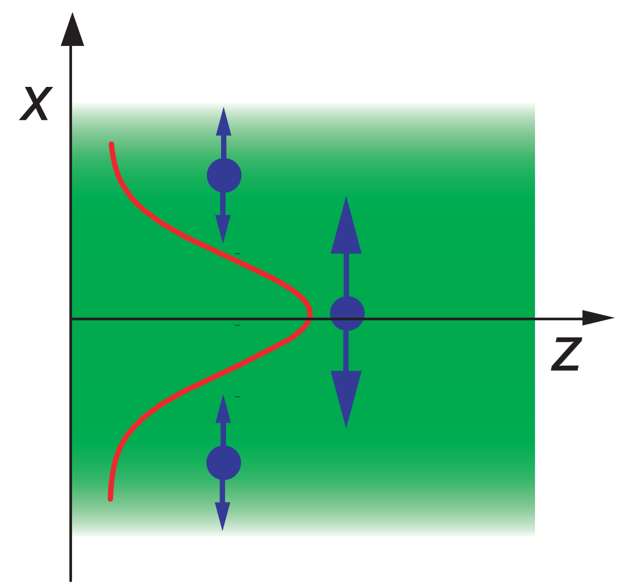


- **Relativistic self-focusing**: transverse variation of intensity gives correct refractive index profile
- Leads to self-focusing for beams above a critical power:

$$P_c = 17.4 \left(\frac{\omega}{\omega_p}\right)^2 \text{ GW}$$

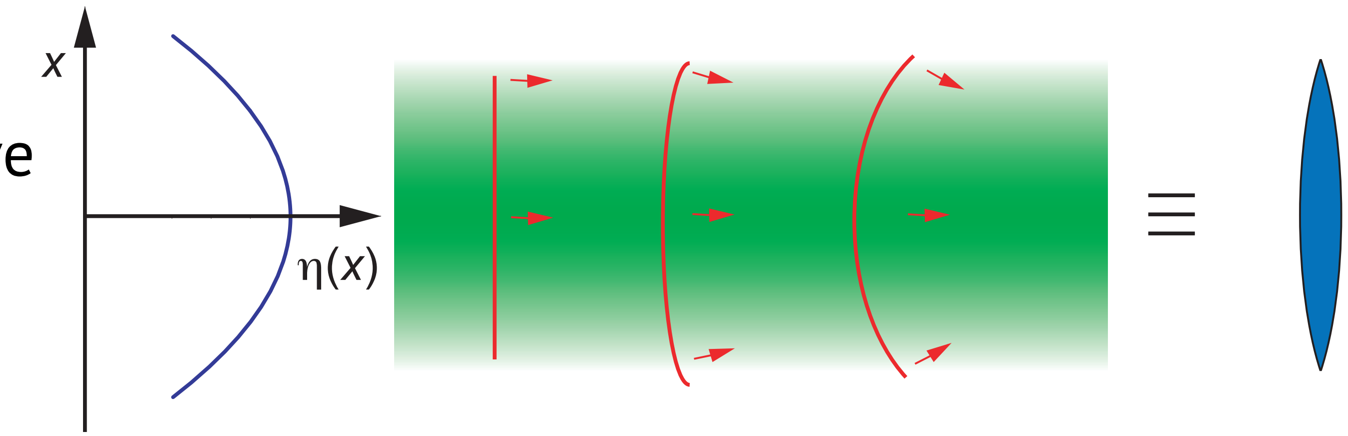


$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$

$$\approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$

Gradient refractive index guiding

- Laser beam will be focused if the refractive index decreases with distance from axis



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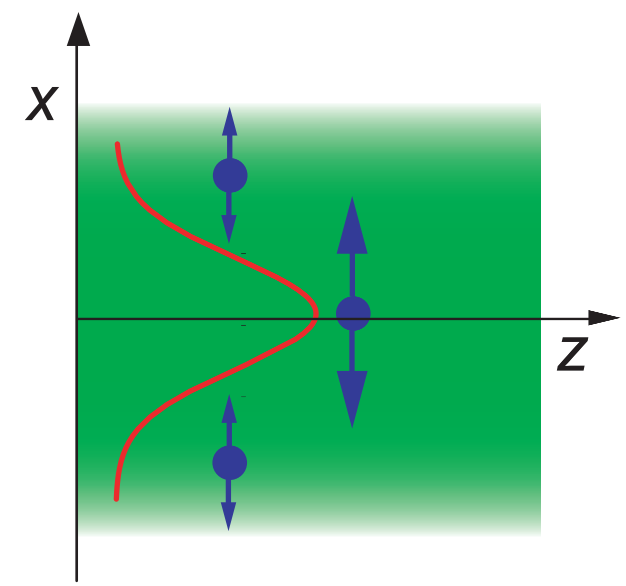

$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$

$$\approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$

Example :

$$n_e = 10^{18}\,\text{cm}^{-3}, \lambda = 800\,\text{nm}$$

$$P_c = 8\,\text{TW}$$

Gradient refractive index guiding

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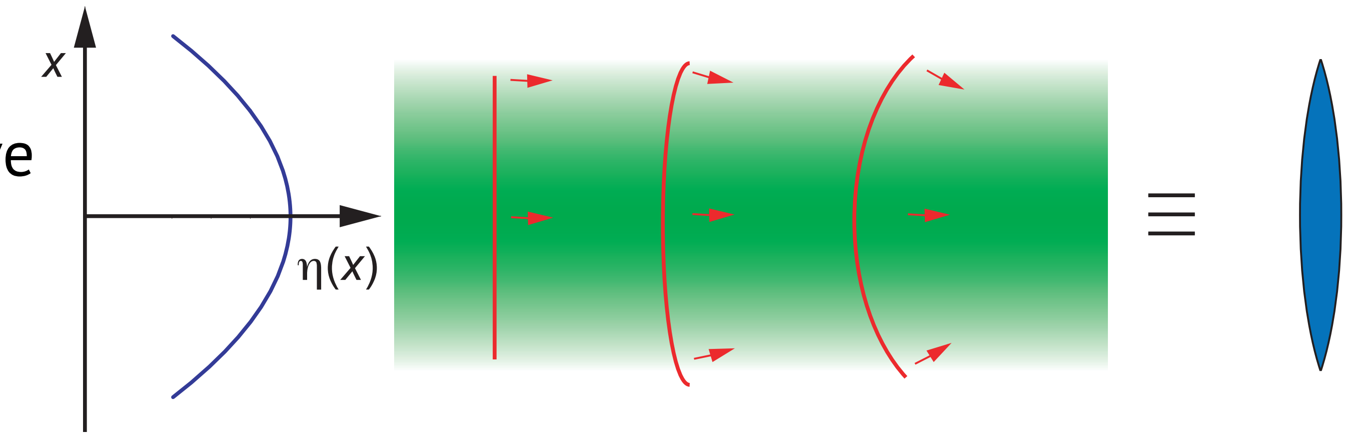

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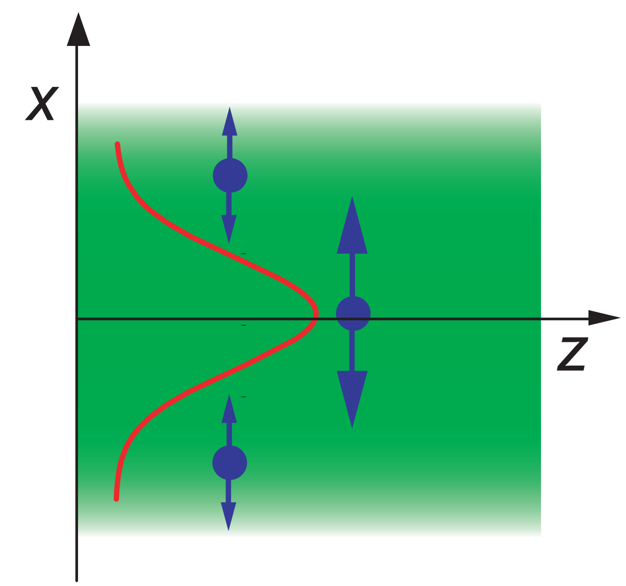
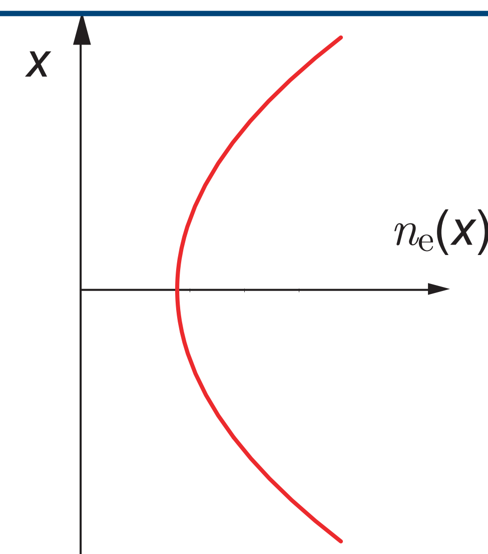


$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \epsilon_0 \omega^2}$$

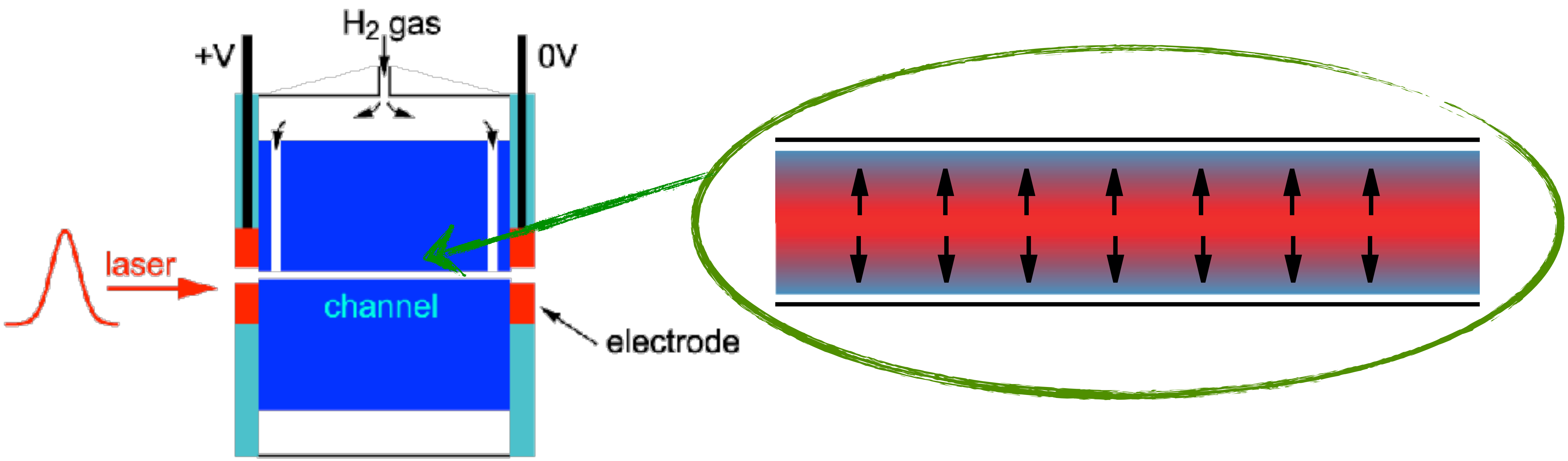
- **Plasma channel**: transverse variation of electron density gives correct refractive index profile



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r) e^2}{\gamma m_e \epsilon_0 \omega^2}$$

Gas-filled capillary discharge waveguide

D. J. Spence et al. *Phys. Rev. E* **63** 015401(R) (2001)
A. Butler et al. *Phys. Rev. Lett.* **89** 185003 (2002)



- Plasma formed by pulsed discharge
  - ~300 A peak
  - ~ 200 ns half-period
- Plasma channel formed by heat conduction to capillary wall
- Channel is fully ionized and stable

Gas-filled capillary discharge waveguide

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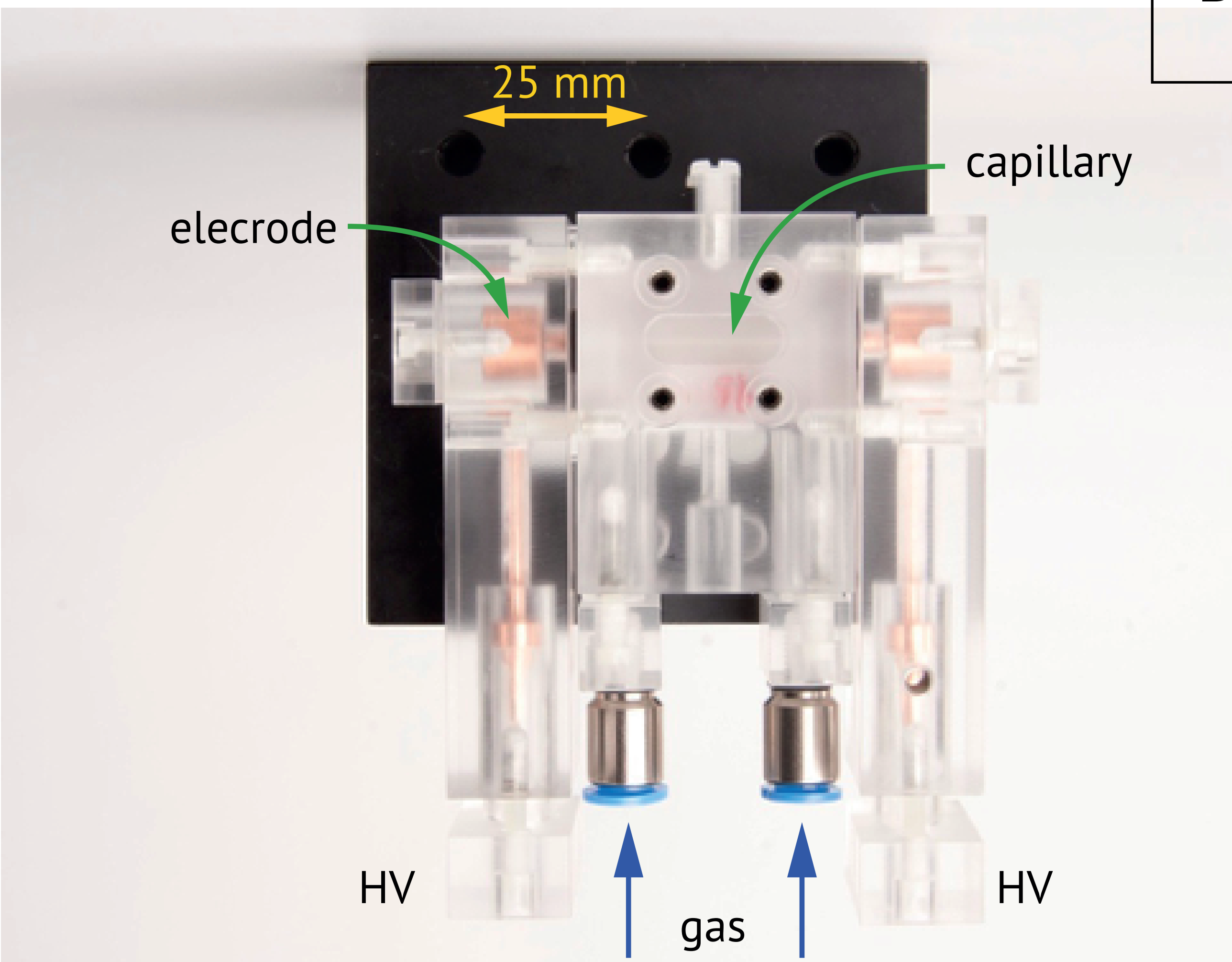

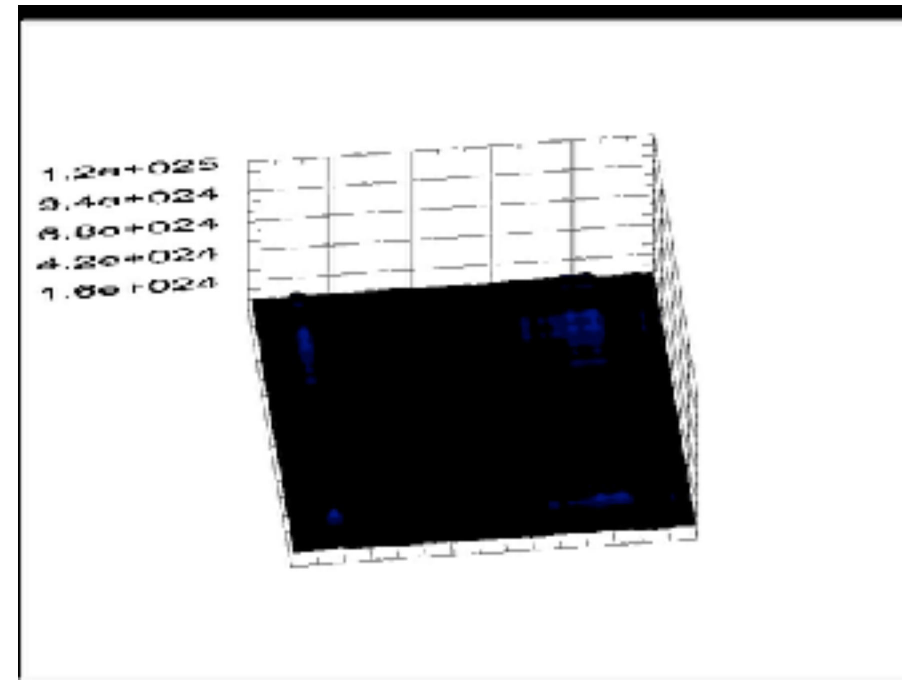

Evolution of plasma channel during discharge pulse

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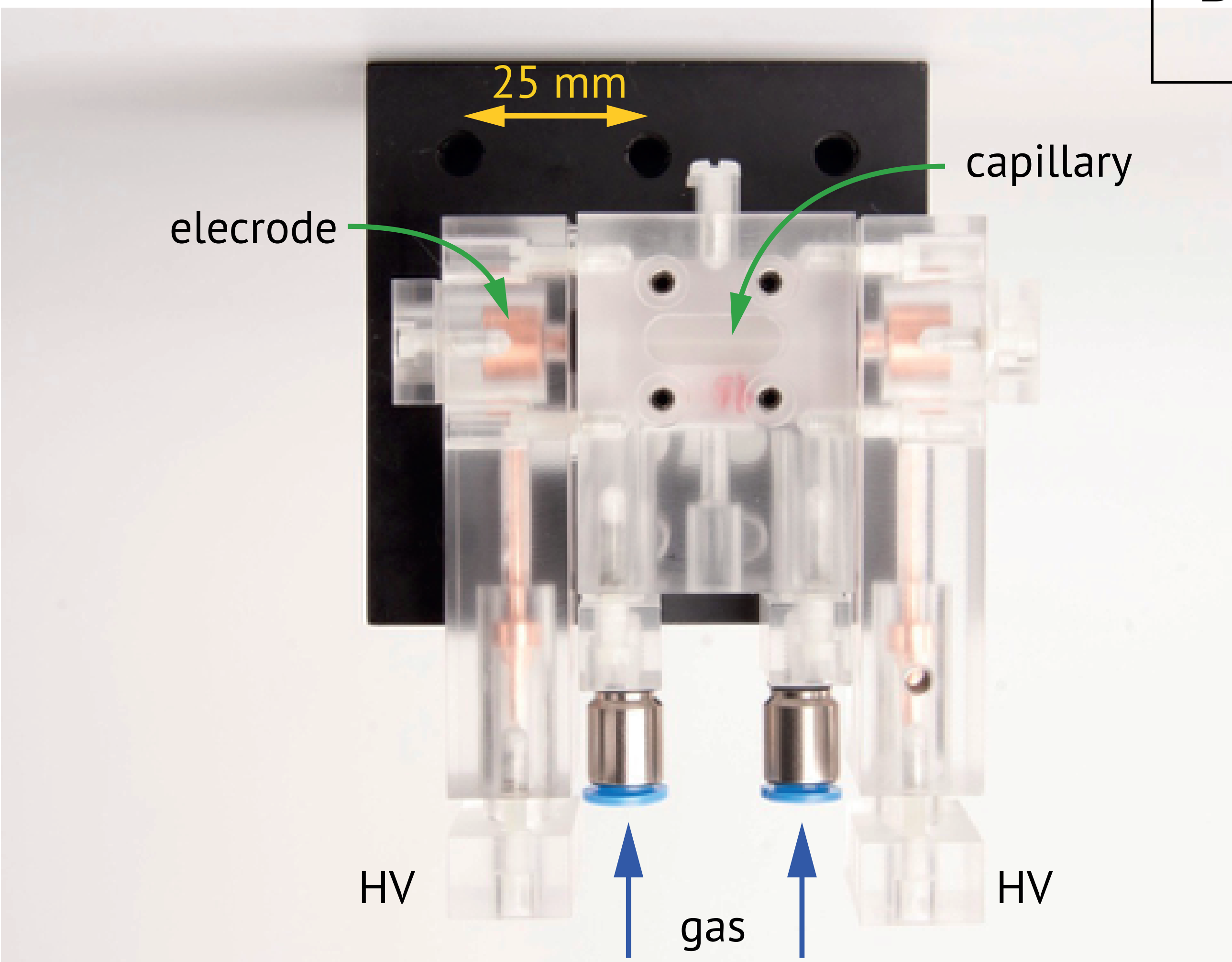

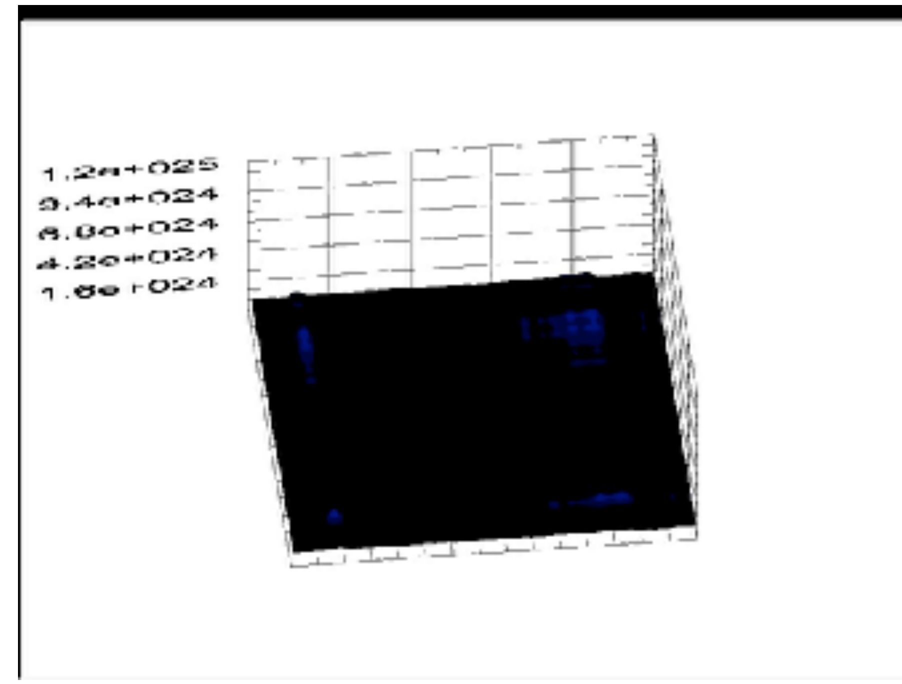

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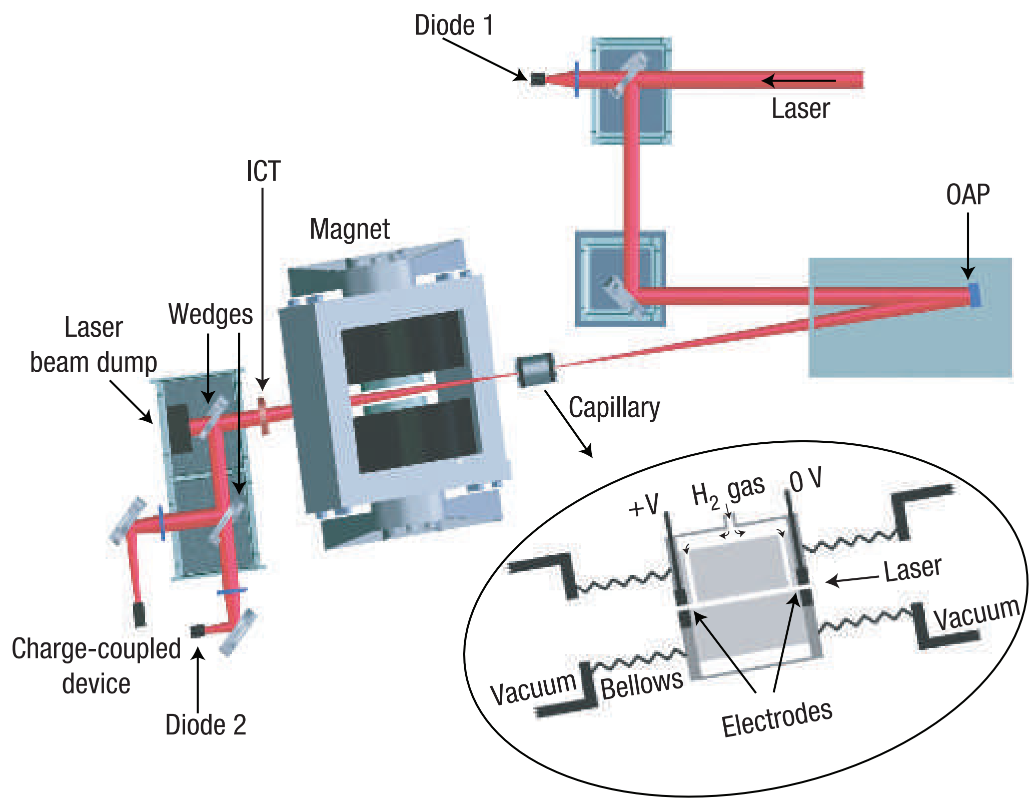
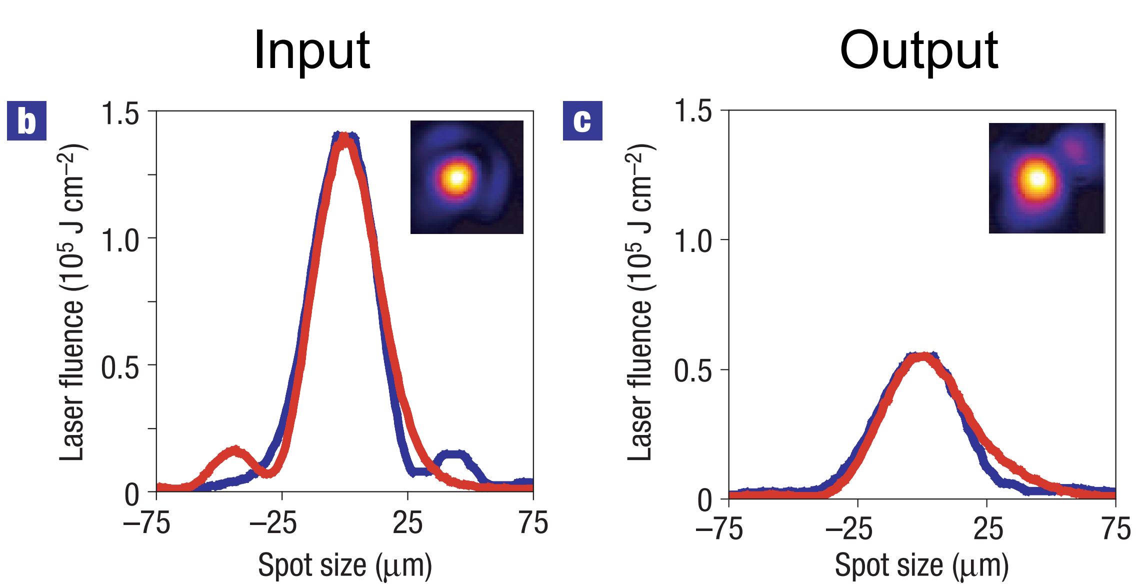
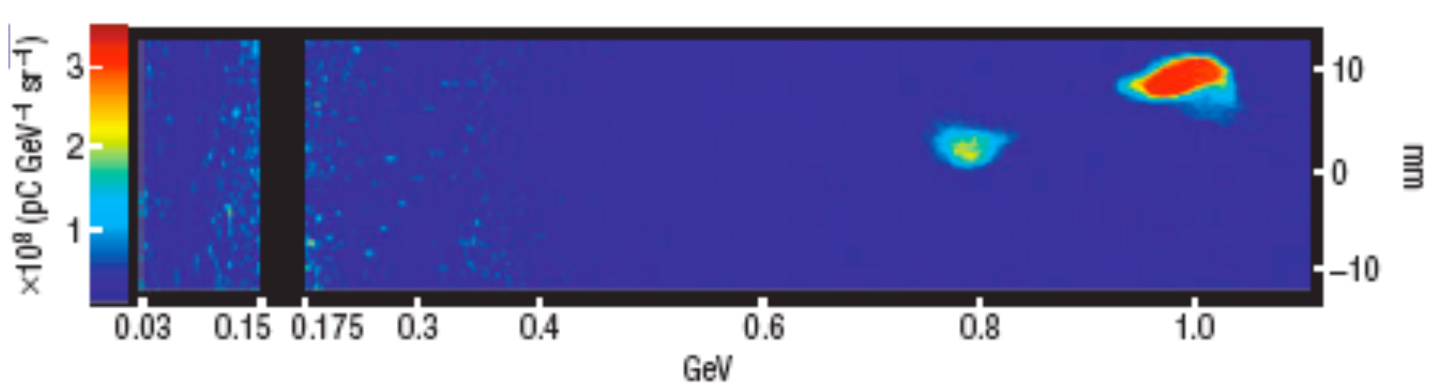
GeV beams!

Leemans *et al. Nat. Phys.* **2** 696 (2006)
E = 1.6 J, τ = 40 fs, $a0 \approx 1.3$, $n_e = 4.3 \times 10^{18}$ cm^{-3}



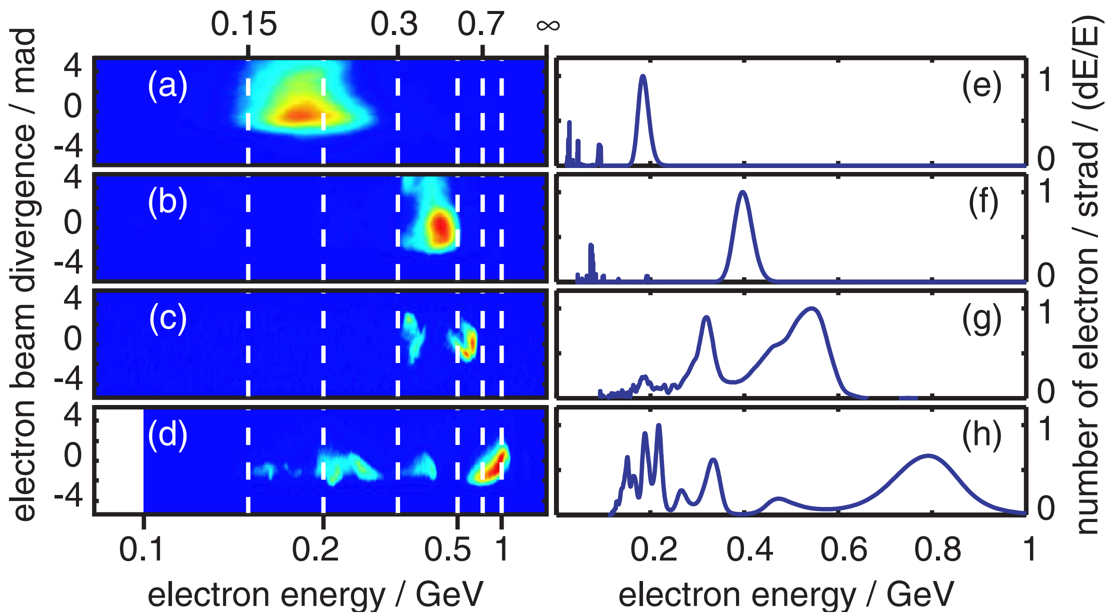
- This waveguide was used to reach GeV milestone for first time
- 33 mm long capillary



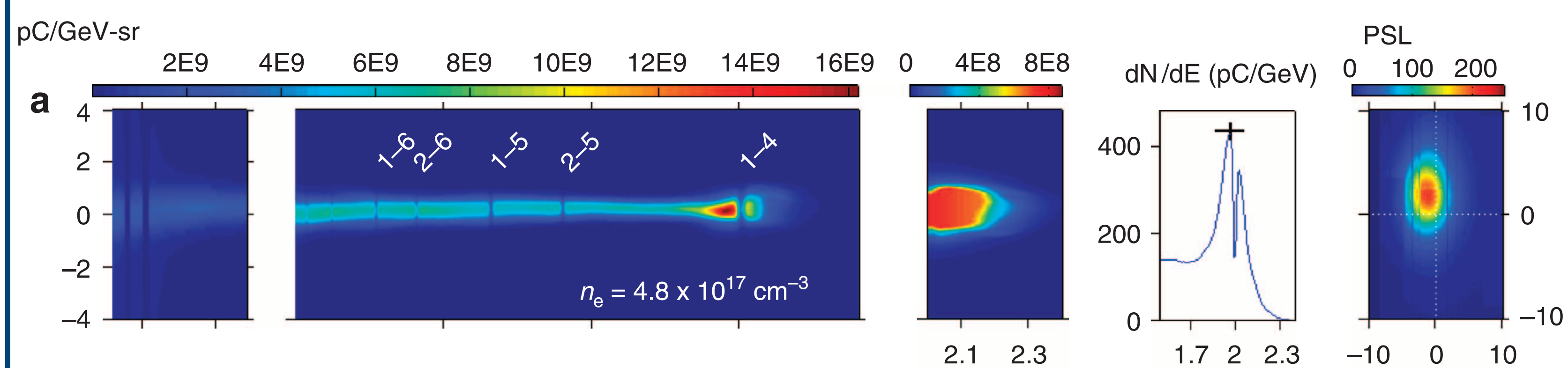


GeV beams!

- Also reached by self-guiding in gas jets and gas cells



Kneip *et al. Phys. Rev. Lett.* **103** 035002 (2009)
E = 11 J, τ = 55 fs, $a0 \approx 3.9$, $n_e = 5.7 \times 10^{18}$ cm^{-3}



Wang *et al. Nat. Comm.* **4** 1988 (2013)
E = 100 J, τ = 160 fs, $n_e = 4.8 \times 10^{17}$ cm^{-3}

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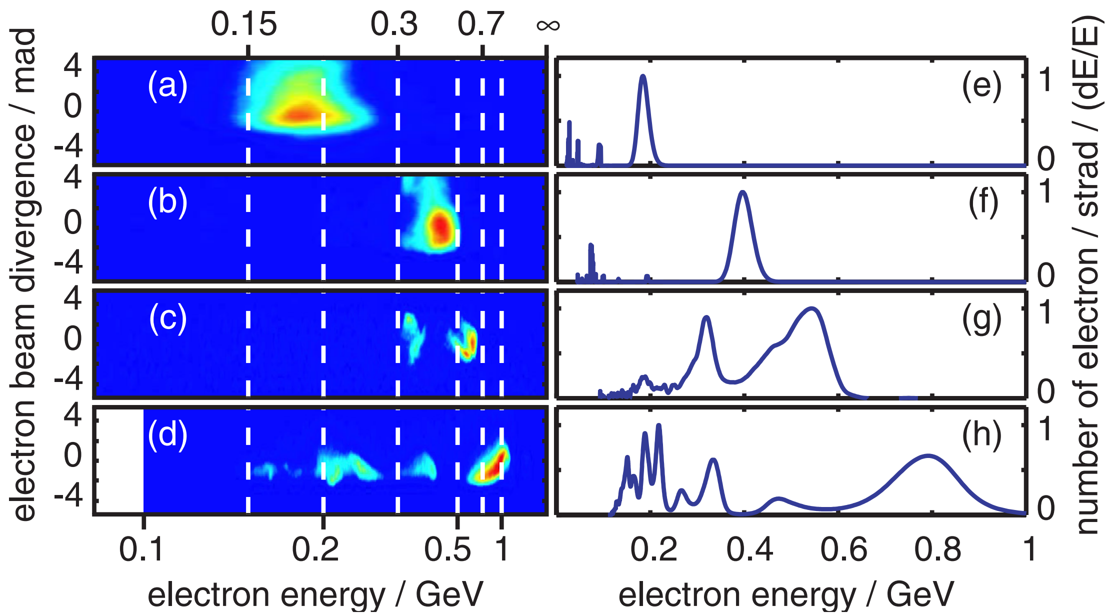

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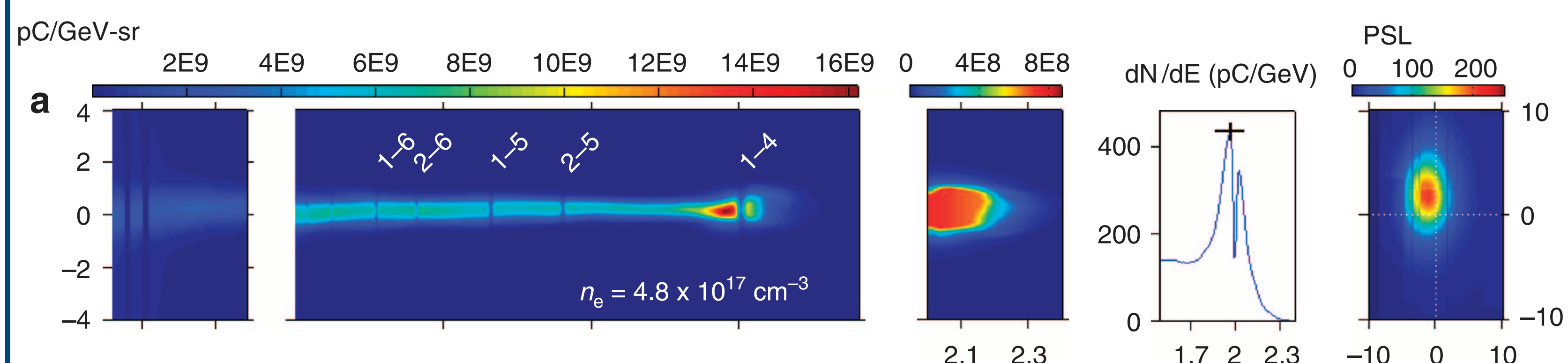

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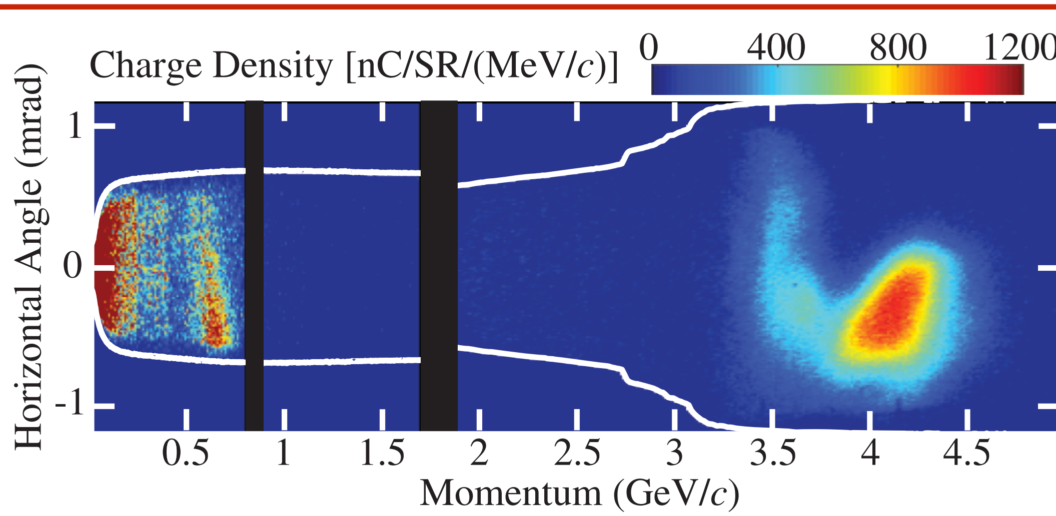


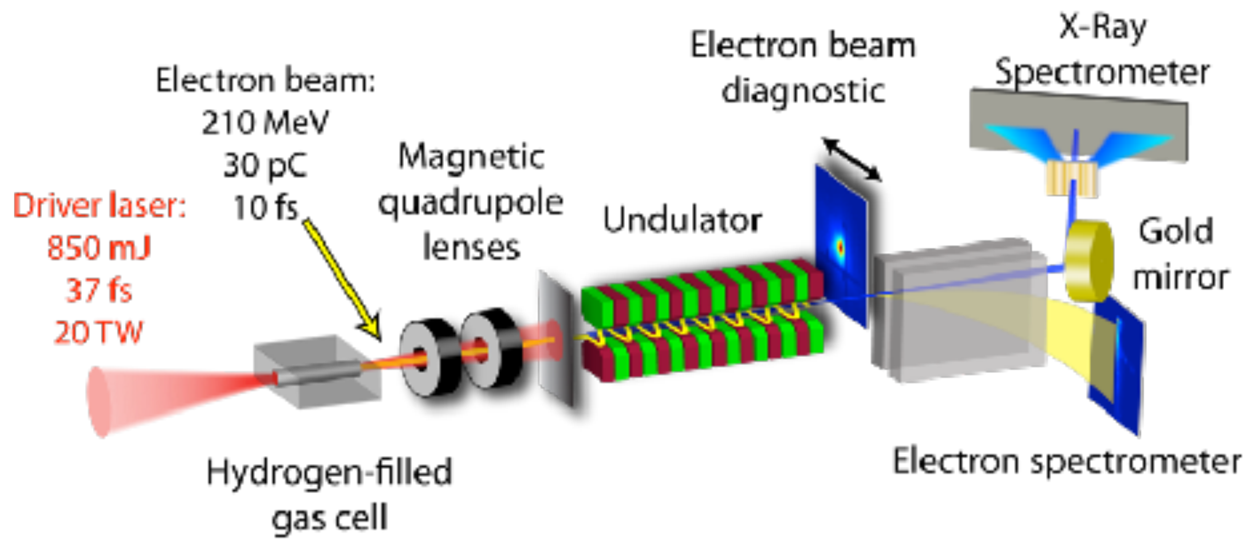
- Results in waveguide recently extended to **4.2 GeV**

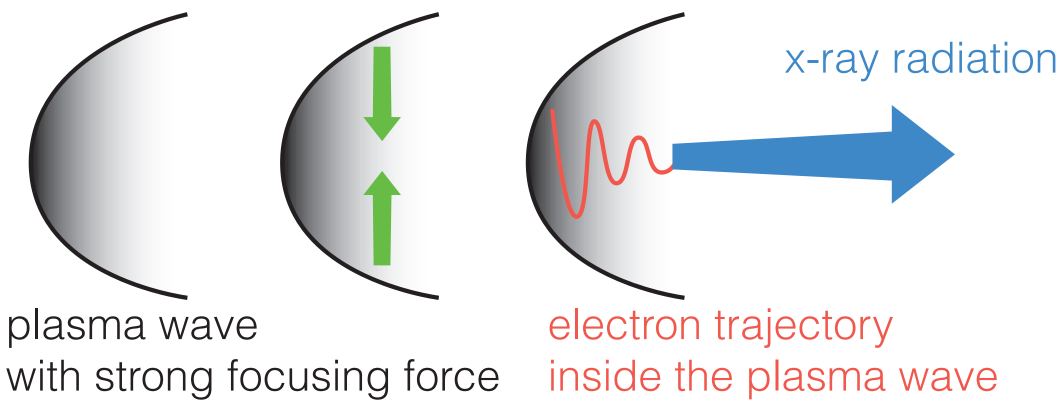
Leemans *et al.* *Phys. Rev. Lett.* **113** 245002 (2014)
E = 16 J, τ = 40 fs, $a0 \approx 173$, $n_e = 7.0 \times 10^{17}$ cm^{-3}

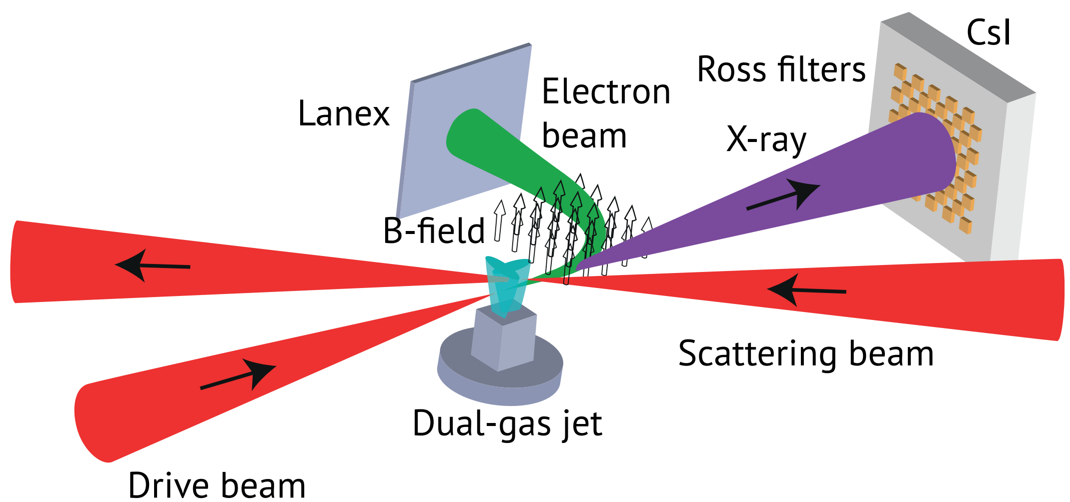
Status….
… and some challenges

Status: Towards applications

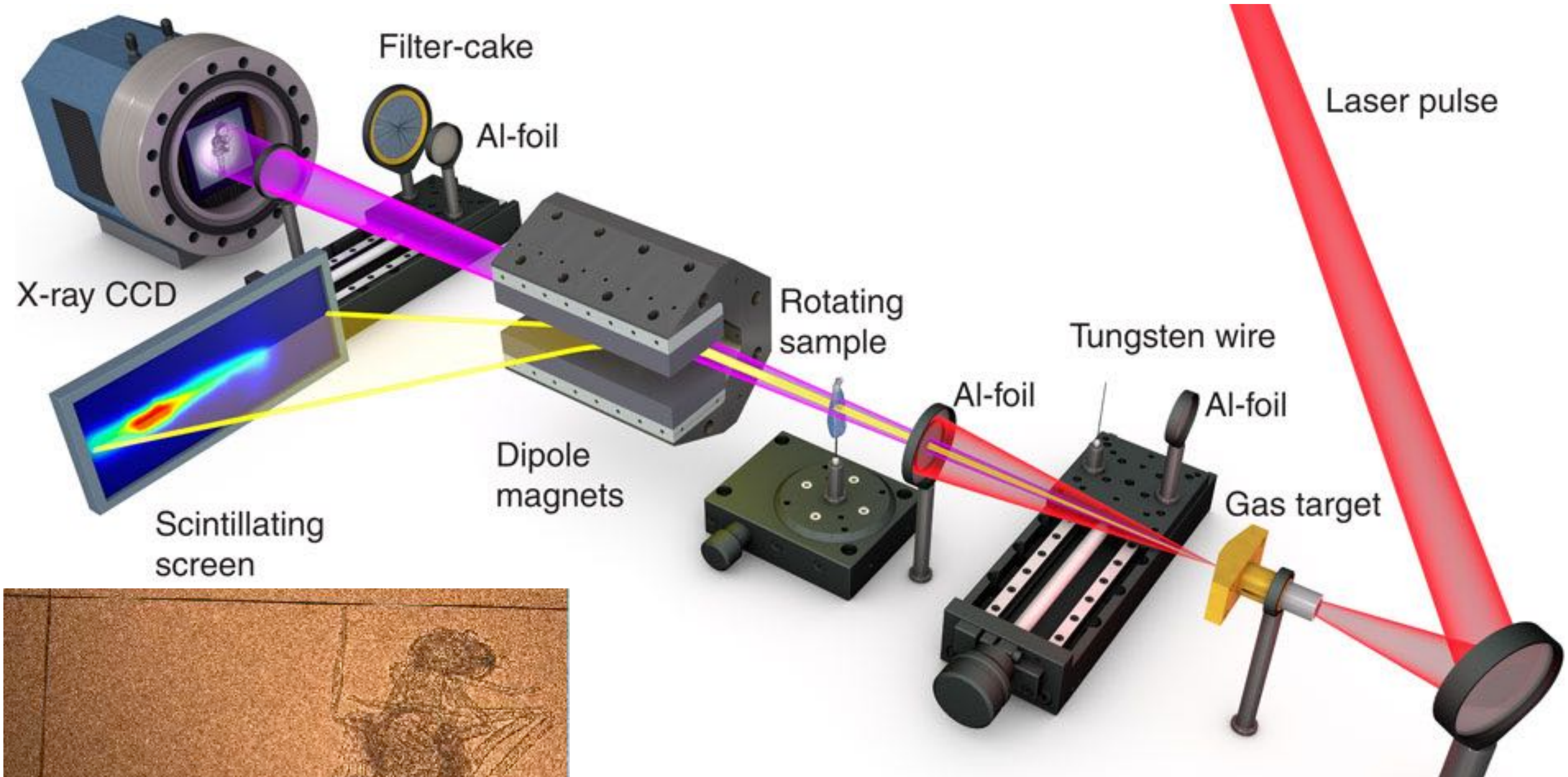
- 100 eV radiation from undulators
  - Fuchs et al. *Nat. Phys.* **5** 826 (2009)
- 10 - 150 keV radiation from betatron motion
  - Kneip et al. *Nat. Phys.* **6** 980 (2010)
  - Cippiccia et al. *Nat. Phys.* **7** 861 (2011)
- 1 MeV from Thomson scattering
  - Powers et al. *Nat. Photon.* **8** 28 (2013)
  - Khrennikov et al. *Phys. Rev. Lett.* 114 195003 (2015)
- Proof-of-principle imaging with betatron radiation sources
  - flies, fish, human bone







Imaging with betatron radiation



Wenz *et al. Nature Comm.* **6** 7568 (2015)

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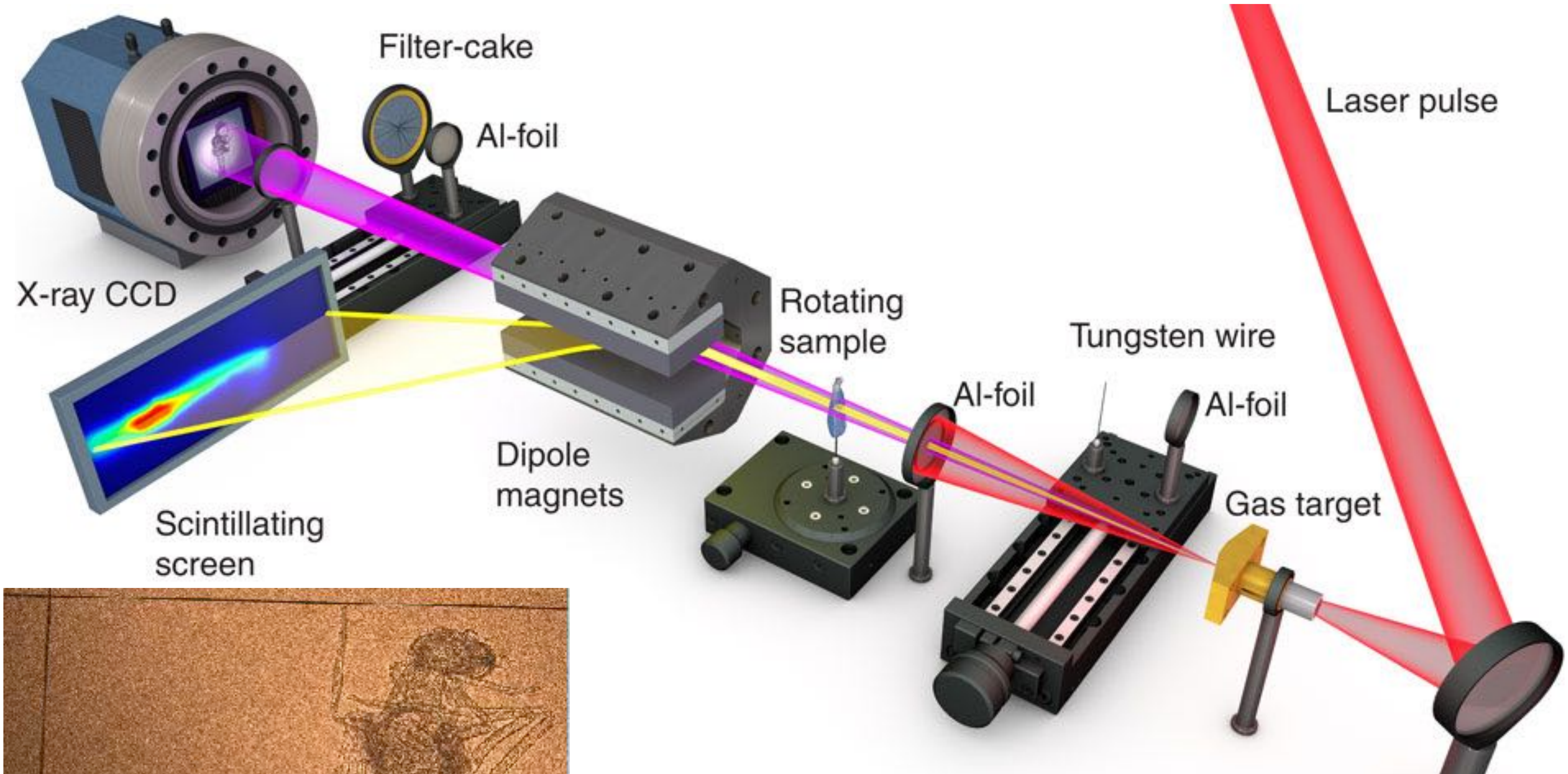

Wenz *et al. Nature Comm.* **6** 7568 (2015)

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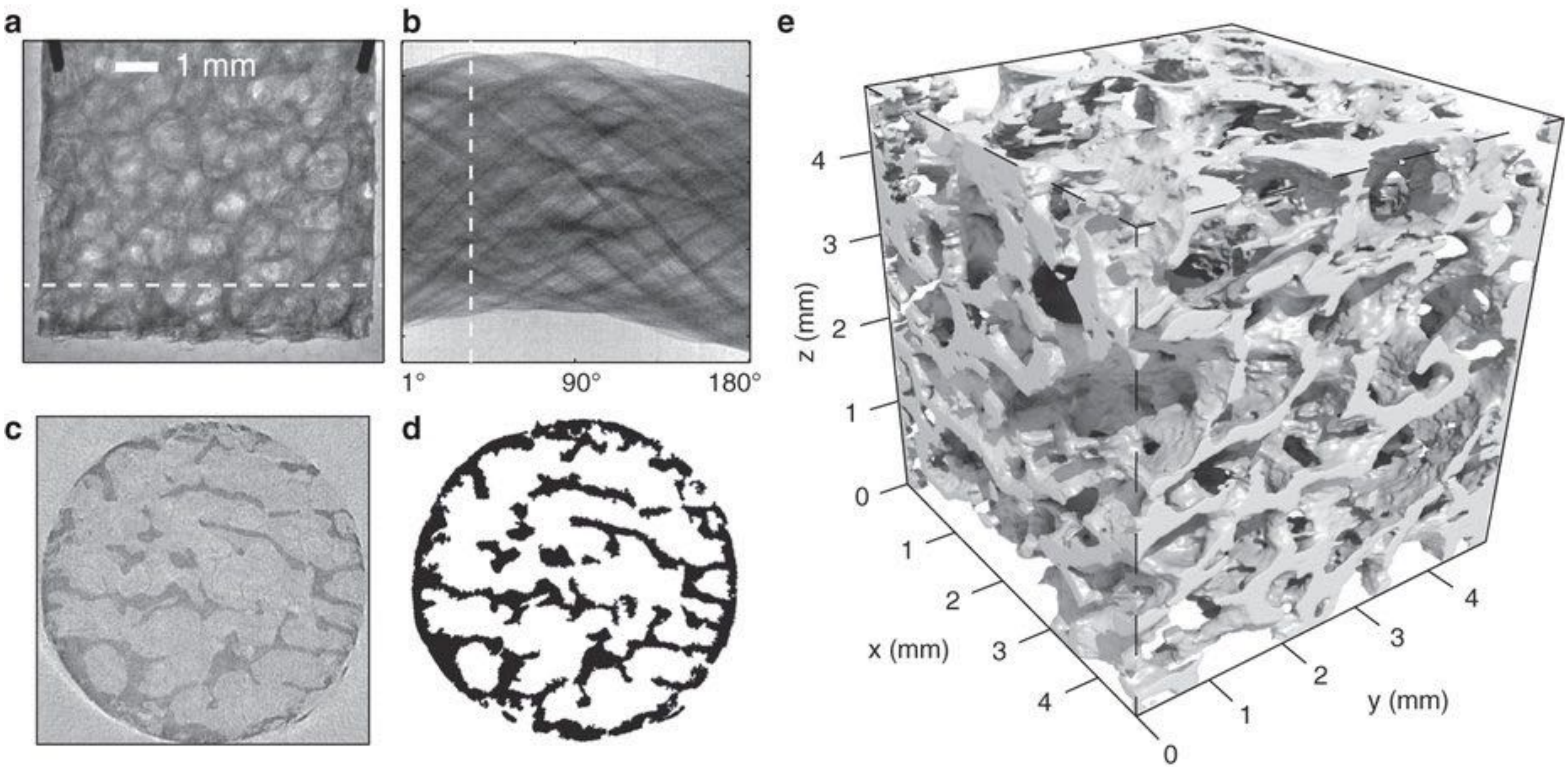

J.M. Cole *et al. Sci. Rep.* **5** 13244 (2015)

Key challenges

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Requires novel ways to drive wakefield

Comparison with European XFEL

Parameter	Typical values from plasma	Requirements of European XFEL	Conclusion
Beam energy E	< 4 GeV	17.5 GeV	😐
Energy spread $\Delta E / E$	1 - 5 %	0.005%	✗
Bunch charge	10 - 100 pC	1000 pC	😐
Bunch duration	< 5 fs	200 fs	✓
Rep. rate	< 10 Hz	27 kHz	✗
Norm emittance ε_n	0.1 - 2 mm mrad	1.4 mm mrad	✓
Jitter: energy	1 - 5%		✗
Jitter: charge	5 - 50%		✗
Jitter: pointing	0.5 - 3.0 mrad		✗

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Jitter: energy	1 - 5%		✗
Jitter: charge	5 - 50%		✗
Jitter: pointing	0.5 - 3.0 mrad		✗

Power in e-beam: 470 kW

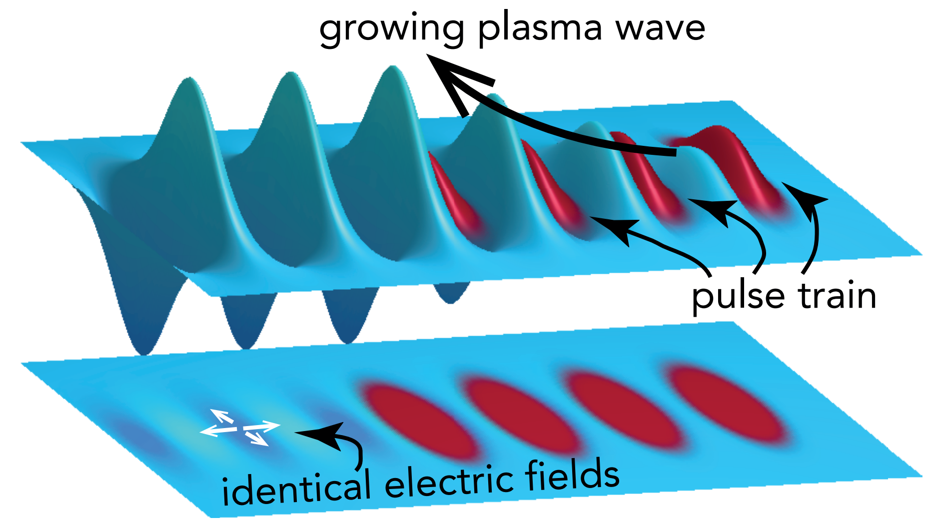
If drive laser has "wall-plug" efficiency of 0.1% then need >400 MW just to power the laser!

Multi-pulse laser wakefield acceleration

MP-LWFA: Advantages

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- MP-LWFA: Use a train of many pulses separated by plasma period to resonantly excite wakefield
  - Not a new idea. Considered theoretically (in 1D) in 1990s
- Some advantages
  - Moves energy storage from laser material to the plasma
  - Allows drive energy to be supplied over many (10 - 100) plasma periods
  - Opens possibility of using new laser technologies (thin-disk, fibre lasers, OPCPA) capable of **multi-kHz operation @ > 10% efficiency**
  - Opportunities for additional control

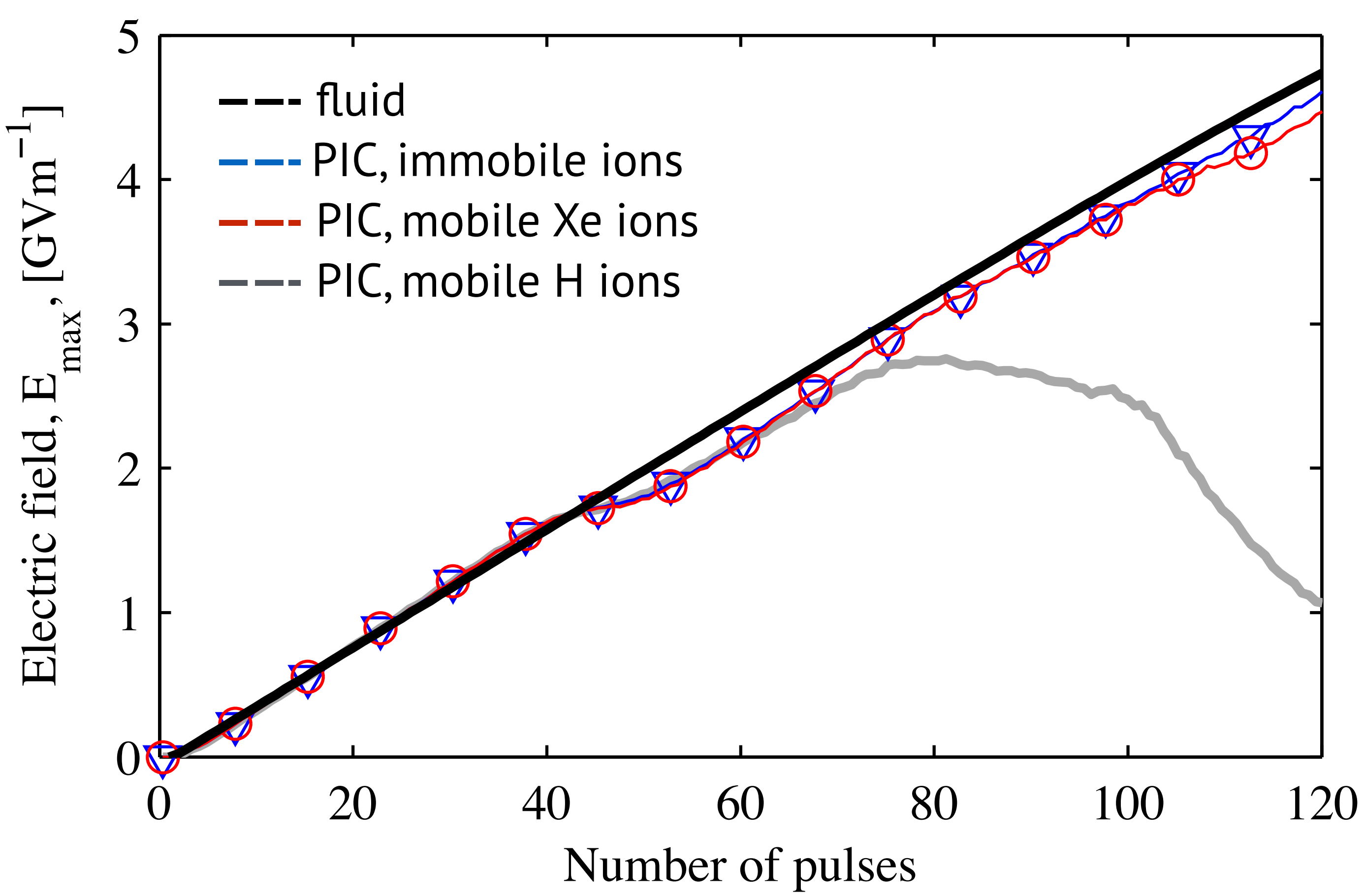


Multi-pulse LWFA
Only 4 laser pulses shown. In reality would use 10 - 100!

MP-LWFA

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

- Fluid and PIC simulations show gradients of 4.7 GV/m for train of 100 pulses
- For $L_{acc} = L_d/2$ = 260 mm, energy gain is 0.75 GeV

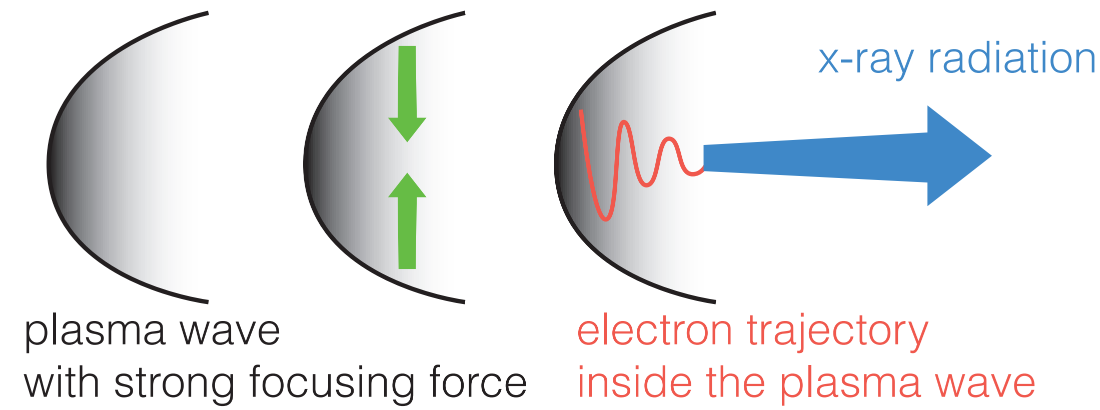


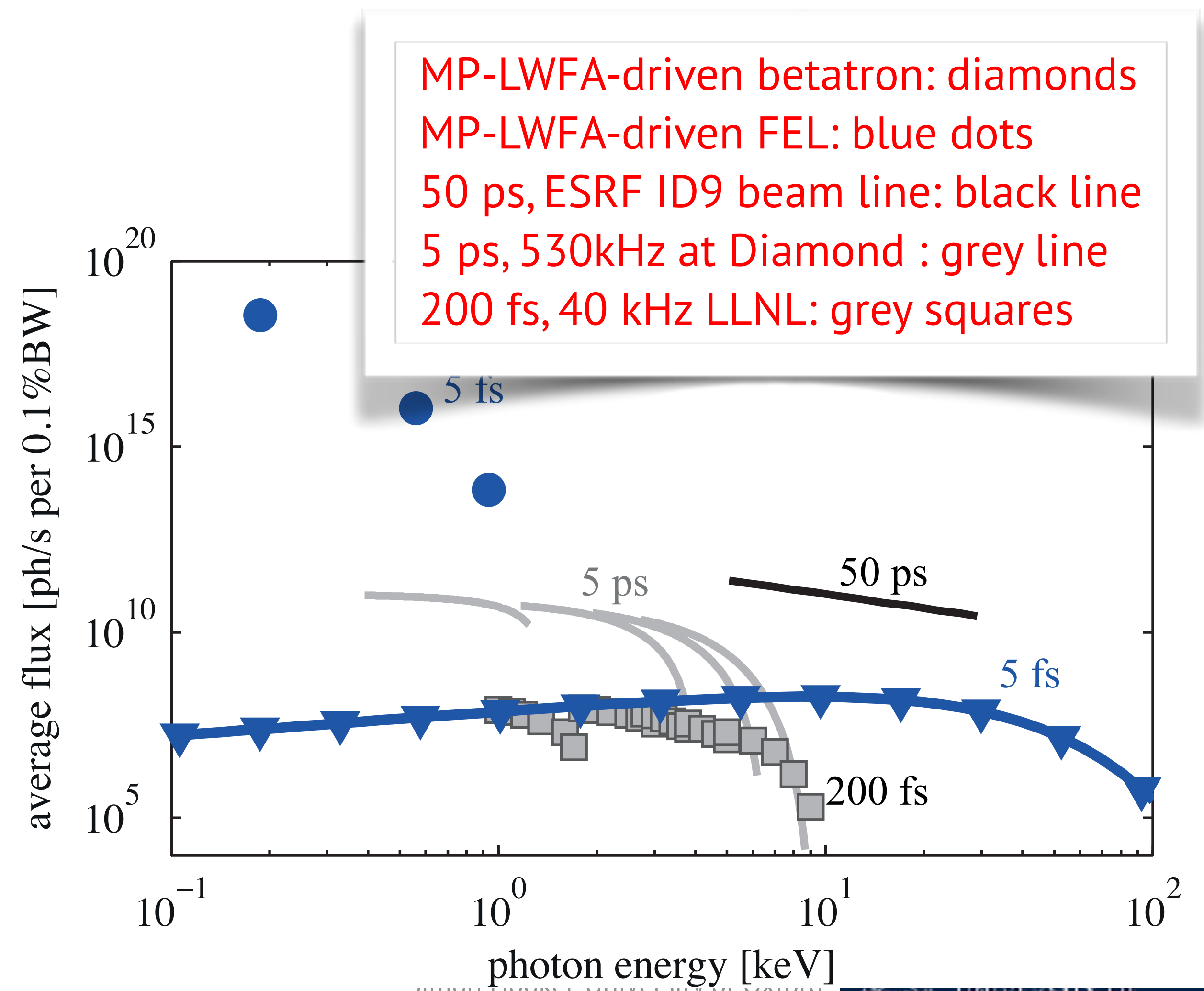
Laser-plasma parameters
E = 10 mJ / pulse
τ = 100fs
w0 = 40 μm
a0 = 0.05
ne = 1.75 × 10^{17} cm-3

MP-LWFA-driven radiation sources

S.M. Hooker *et al. J. Phys. B* **47** 234003 (2013)

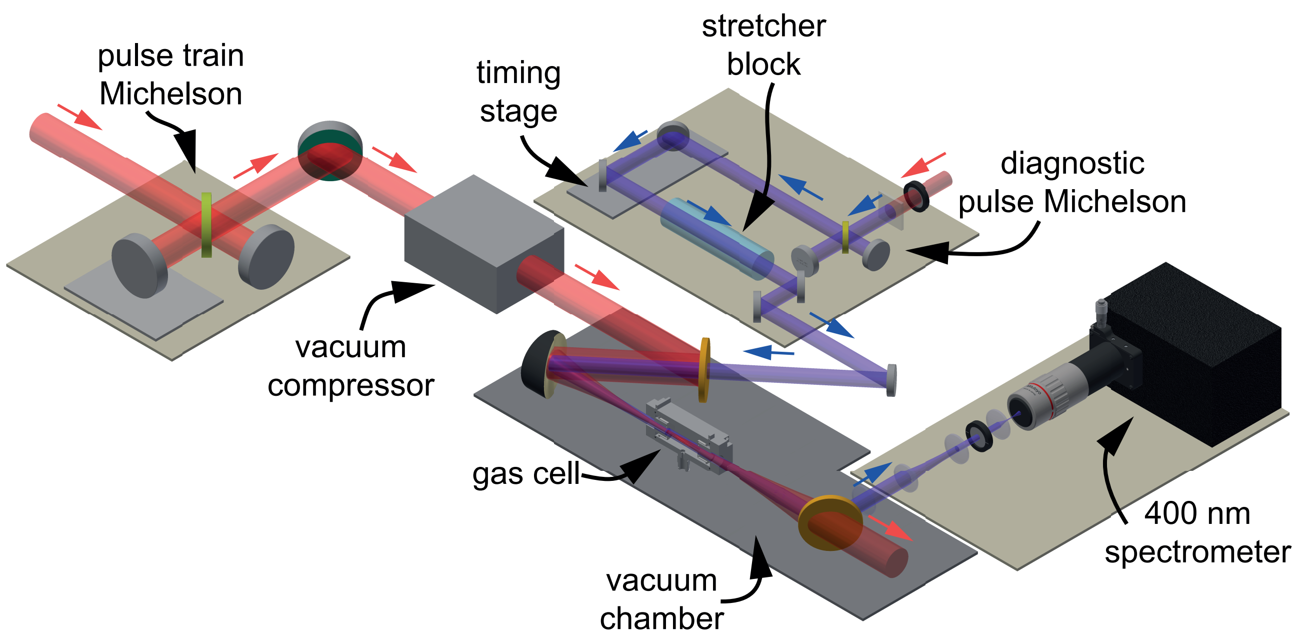
- Betatron radiation
  - **Average** photon flux @ 10keV is ≈ 2 × 10^8 photons s^{-1}, per 0.1% BW
  - **Greater than existing short-pulse 3rd gen sources (but 100 x better resolution)**
- FELs
  - Simulations show SASE saturation reached in soft X-ray range (λ_{FEL} = 6.9 nm) in 4 m TGU
  - Peak FEL power comparable to km-scale FELs but **much higher repetition rate than non-superconducting machine**



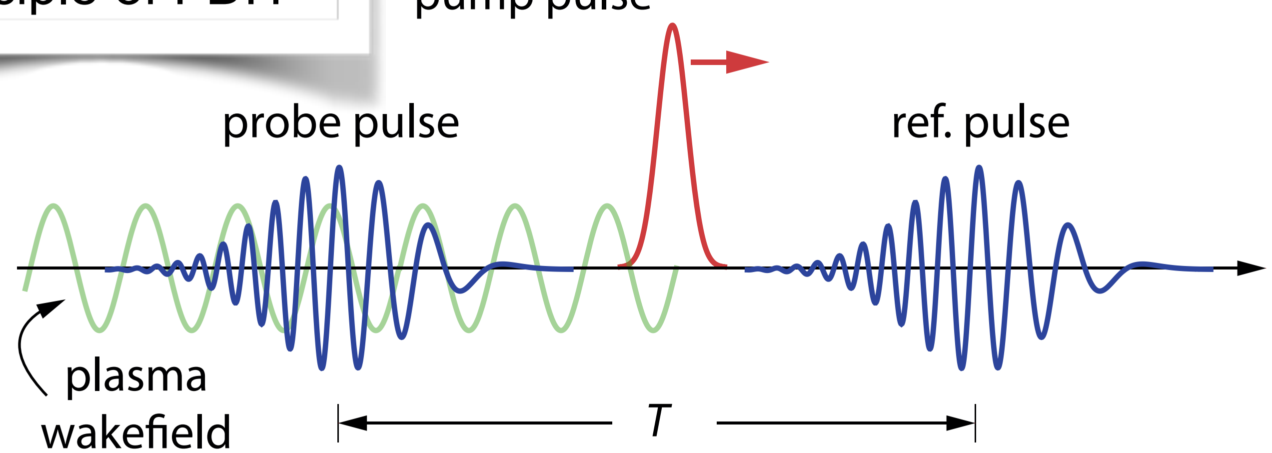


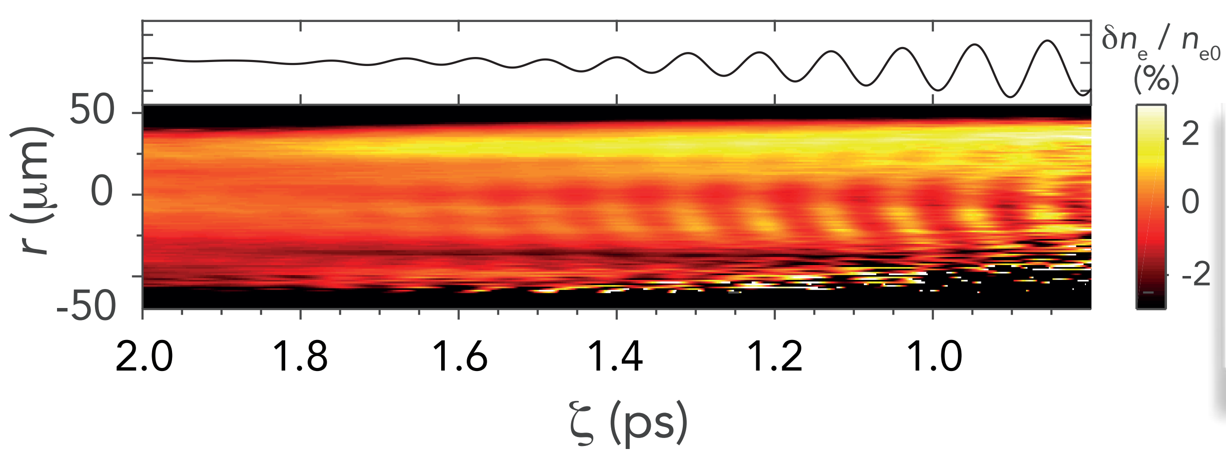
First demonstration of MP-LWFA concept

J. Cowley *et al. Phys. Rev. Lett.* **119** 044802 (2017)



Principle of FDH





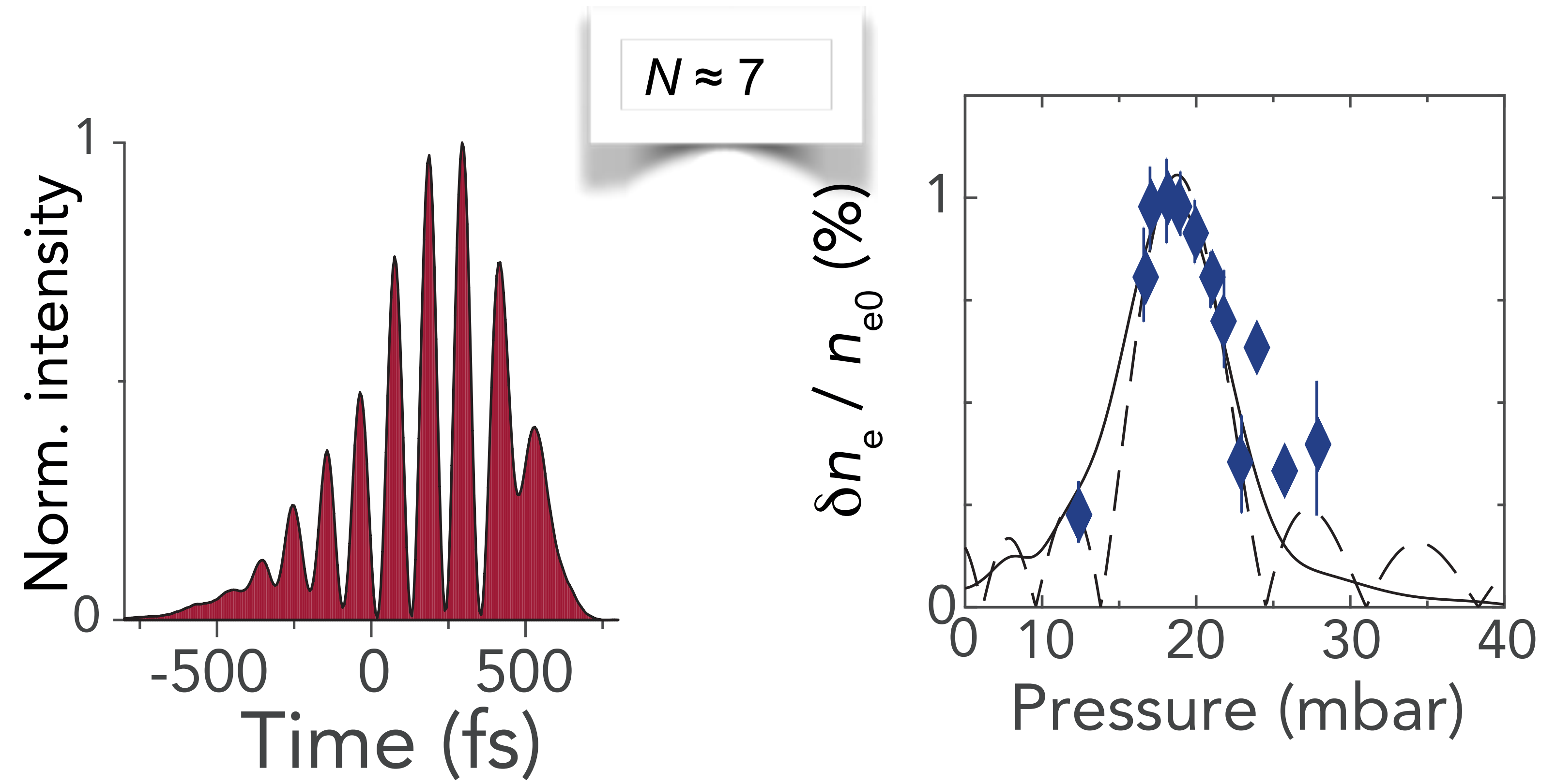
Recovered wakefield (single pulse)

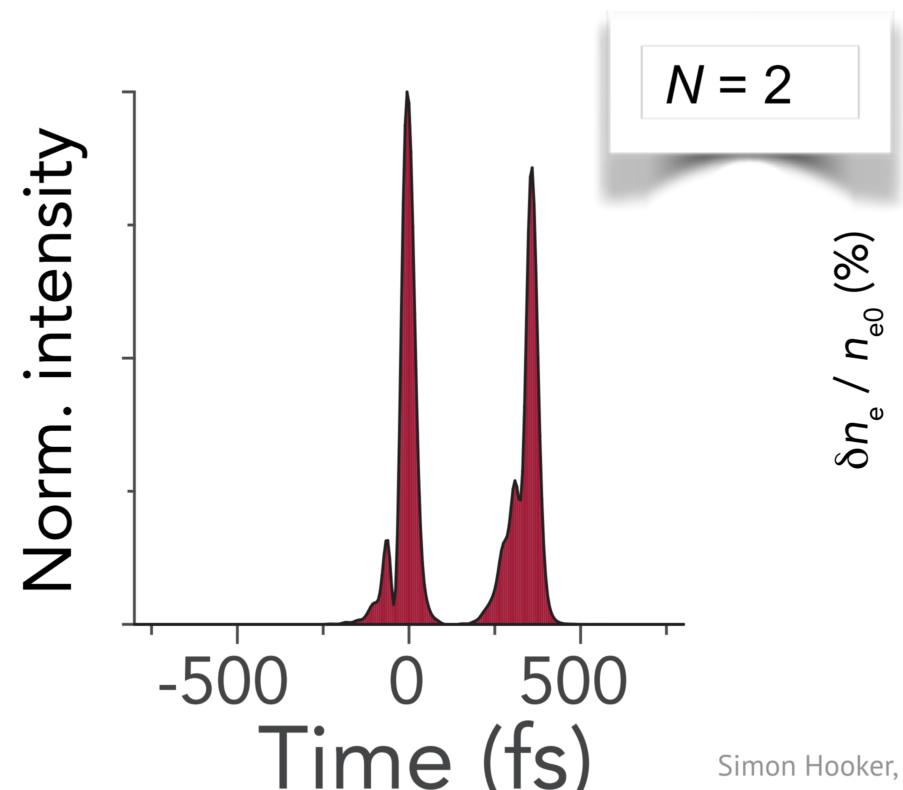
- Single, chirped pulse from Ti:sapphire laser converted to train of pulses by passing through Michelson interferometer
- Focused into gas cell to drive wakefield
- Wakefield probed by frequency domain holography
  - Interference between co-propagating probe pulse and a reference pulse gives phase shift of probe
  - Probe & ref pulses frequency chirped, so frequency ↔ time

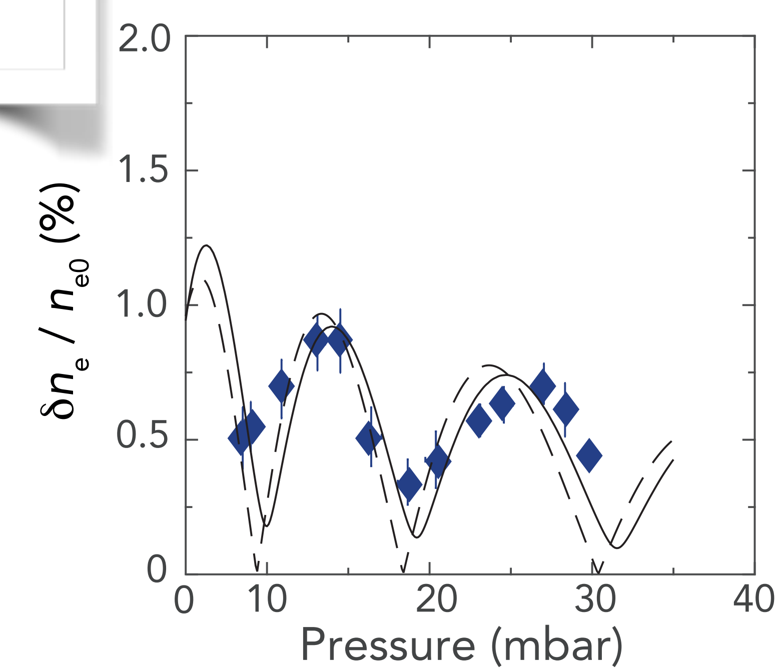
Summary of results

J. Cowley *et al.* *Phys. Rev. Lett.* **119** 044802 (2017)

- Pulse train ($N \approx 7$) experiments
  - Clear resonant excitation when plasma period (~ $P^{-1/2}$) matches pulse spacing
- "Energy recovery" ($N = 2$)
  - Wakefield damped by trailing laser pulse when out of resonance
  - Trailing pulse reduced wake amplitude by (44 ± 8)%

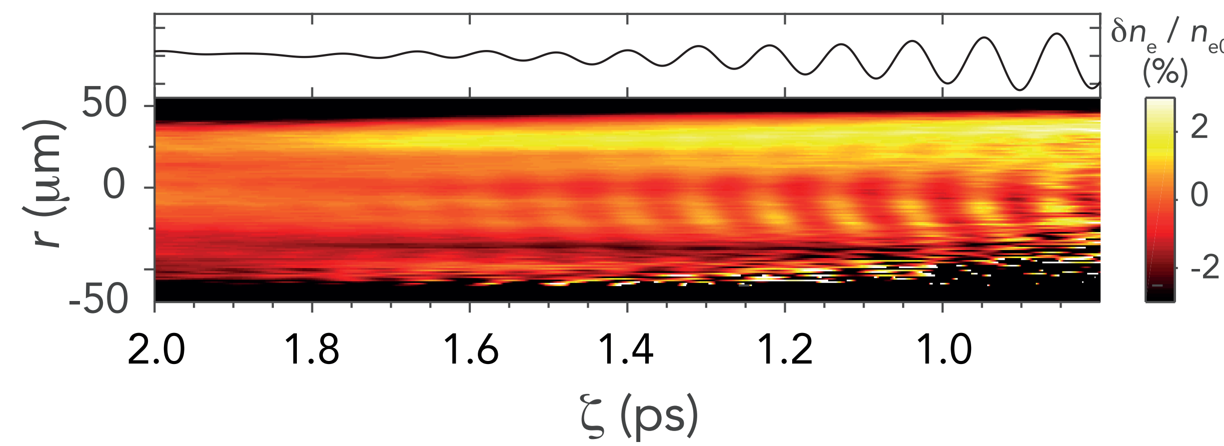


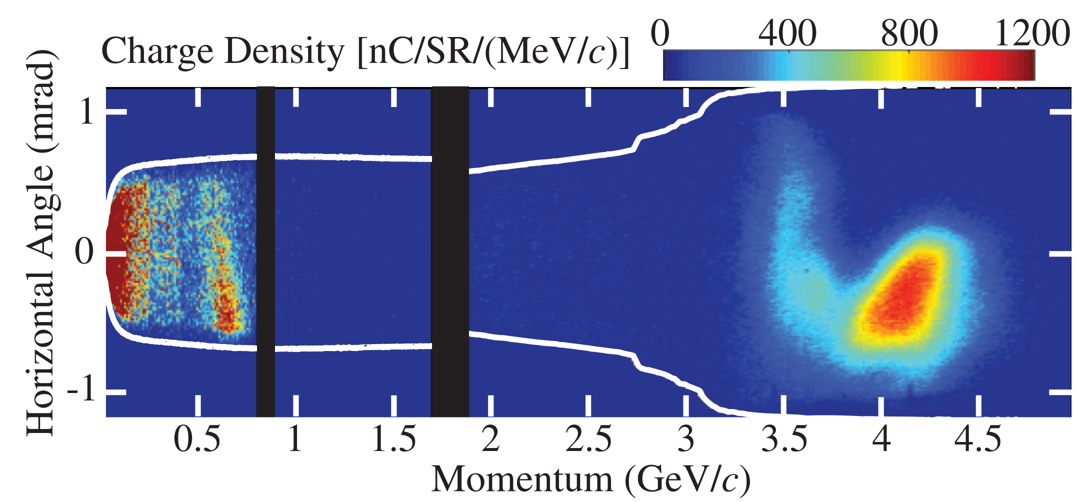


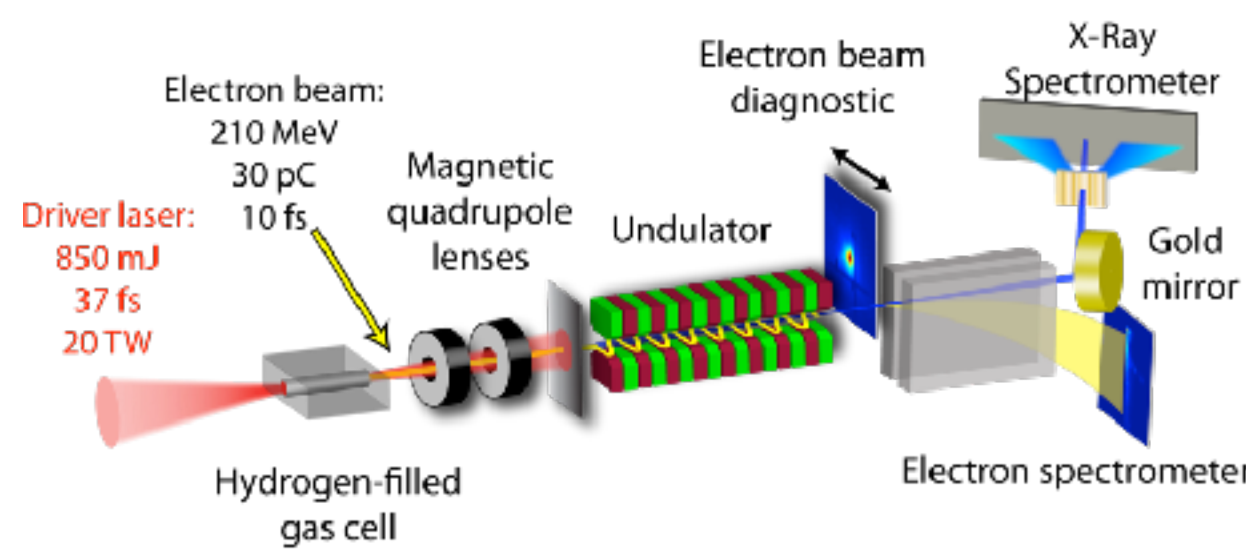


Summary

- Laser-driven plasma accelerators have made enormous progress in last three decades
- GeV-scale electron beams can now be generated from accelerator stages only a few cm long
- Attention is now turning to near-term applications
- Future challenges for laser-driven plasma accelerators are to:
  - Improve bunch parameters
  - Reduce shot-to-shot pulse jitter
  - Operate at higher repetition rate
  - Increase efficiency of driving lasers







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