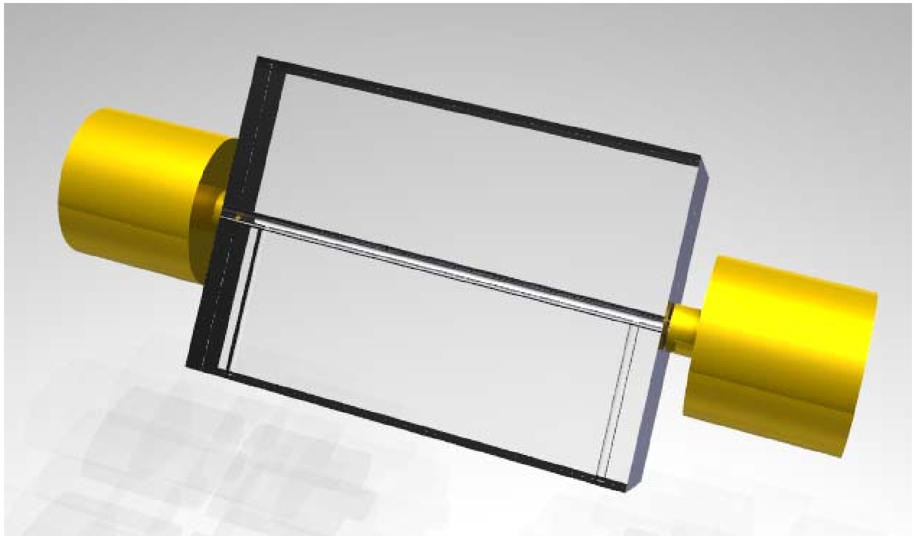
Laser-Driven Plasma Accelerators



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S. Mangles, Z. Najmudin et al.

P. Foster, P. Rajeev, P.A. Norreys, John Collier et al

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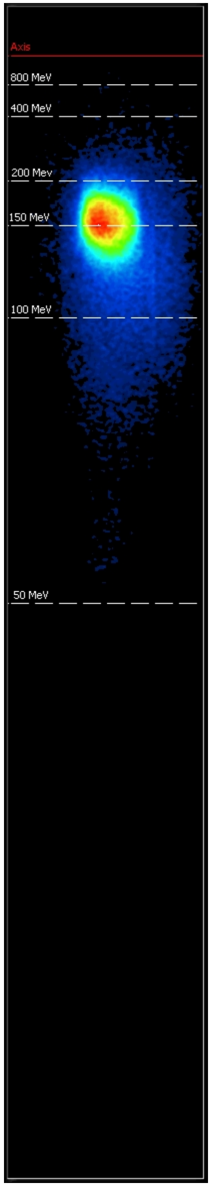
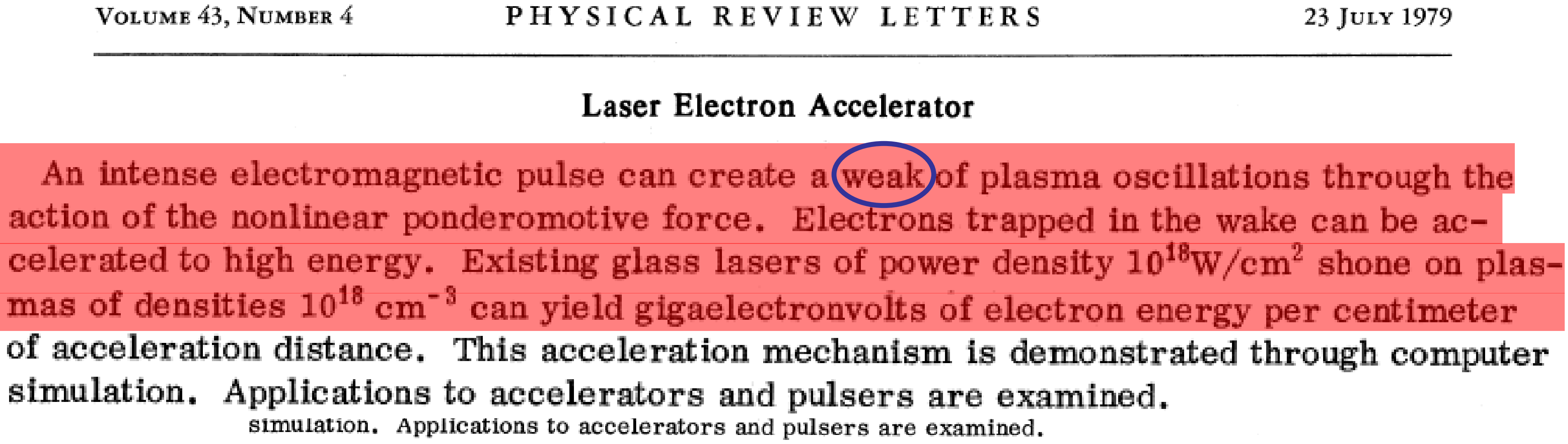
Outline



- Laser-driven plasma accelerators
  - – Overview of operation
  - – Early experimental results
  - – Scaling to higher energies
- Electron acceleration in a plasma waveguide
  - – Generation of GeV beams
- Present status, future directions and potential applications
  - – Controlled injection
  - – Radiation generation
  - – Increased beam energy

Plasma accelerators driven by TW lasers

Tajima & Dawson *Phys Rev. Lett.* **43** 267 (1979)



VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

Laser Electron Accelerator

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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Introduction

Accelerators have many applications

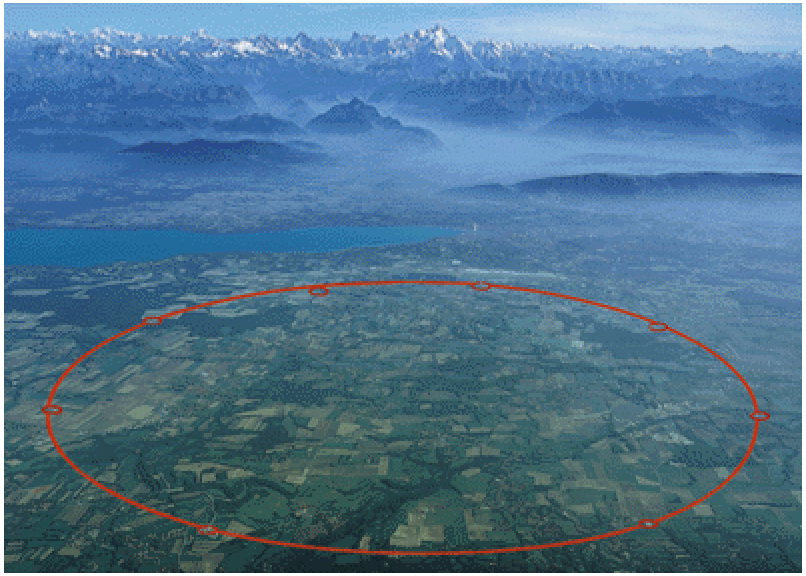
- Synchrotrons (a few GeV)
- FELs (a few GeV to a few 10s of GeV)
- Particle physics (up to a few TeV)

Conventional radio-frequency accelerators are highly developed, so why bother with plasma accelerators?

Why might plasma accelerators be interesting?

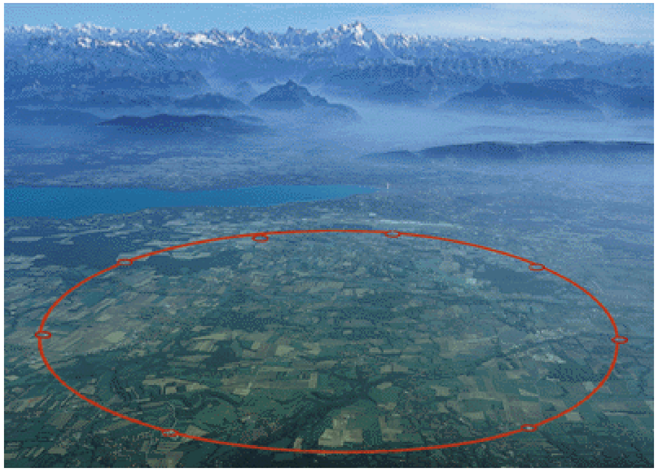
- Big accelerators are:
  - big
  - expensive

Diamond
Length: 150 m
Beam energy (electrons): 3 GeV
Cost: £370M



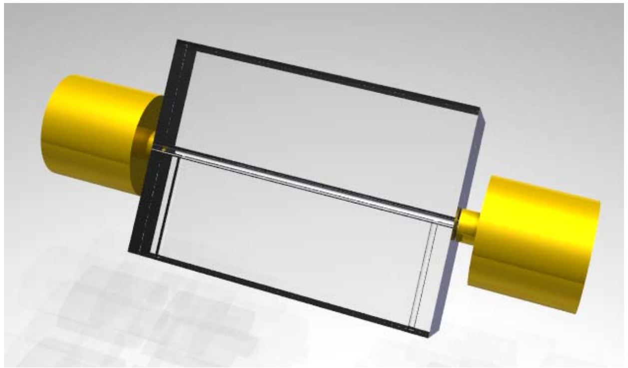
CERN LHC
Circumference: 27 km
Beam energy (protons): 7 TeV
Cost: £2G

Why might plasma accelerators be interesting?



- The acceleration gradient in a plasma accelerator is <u>much</u> bigger:
  - In a conventional particle accelerator acceleration gradient limited by electrical breakdown to:

$$E_z \approx 10 - 100 \text{ MV m}^{-1}$$

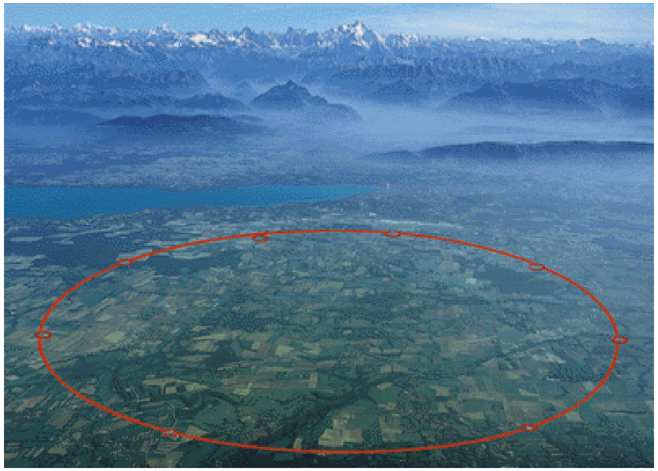


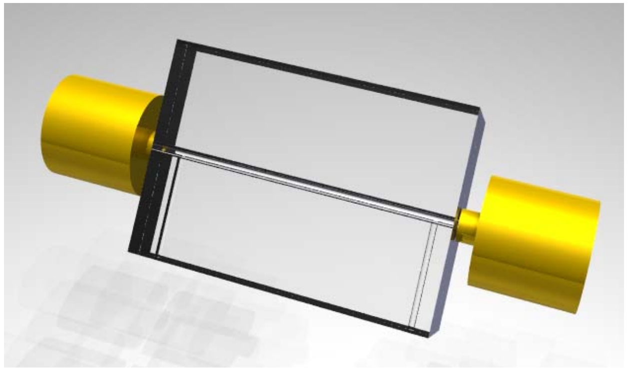
  - A plasma accelerator can reach acceleration gradients of order:

$$\boxed{E_z \approx 100 \text{ GV m}^{-1}}$$

i.e. 3 to 4 orders of magnitude larger

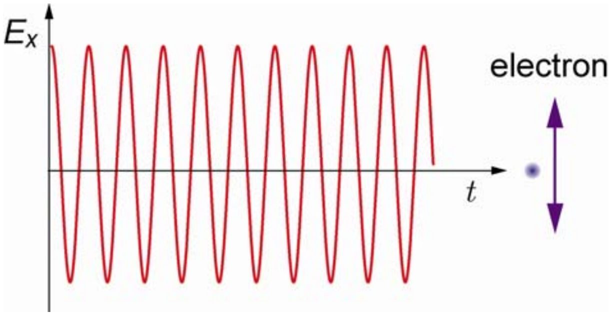
Why might plasma accelerators be interesting?





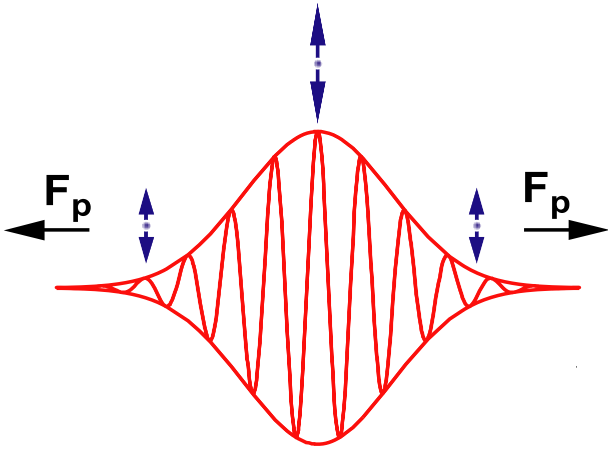
- Plasma accelerators offer new possibilities:
  - Oscillation period of accelerating field is ~ 100 fs:
  - Allows generation and acceleration of femtosecond duration bunches

The ponderomotive force



An ionized electron ***quivers*** in the E-field of the laser with a ***ponderomotive energy***:

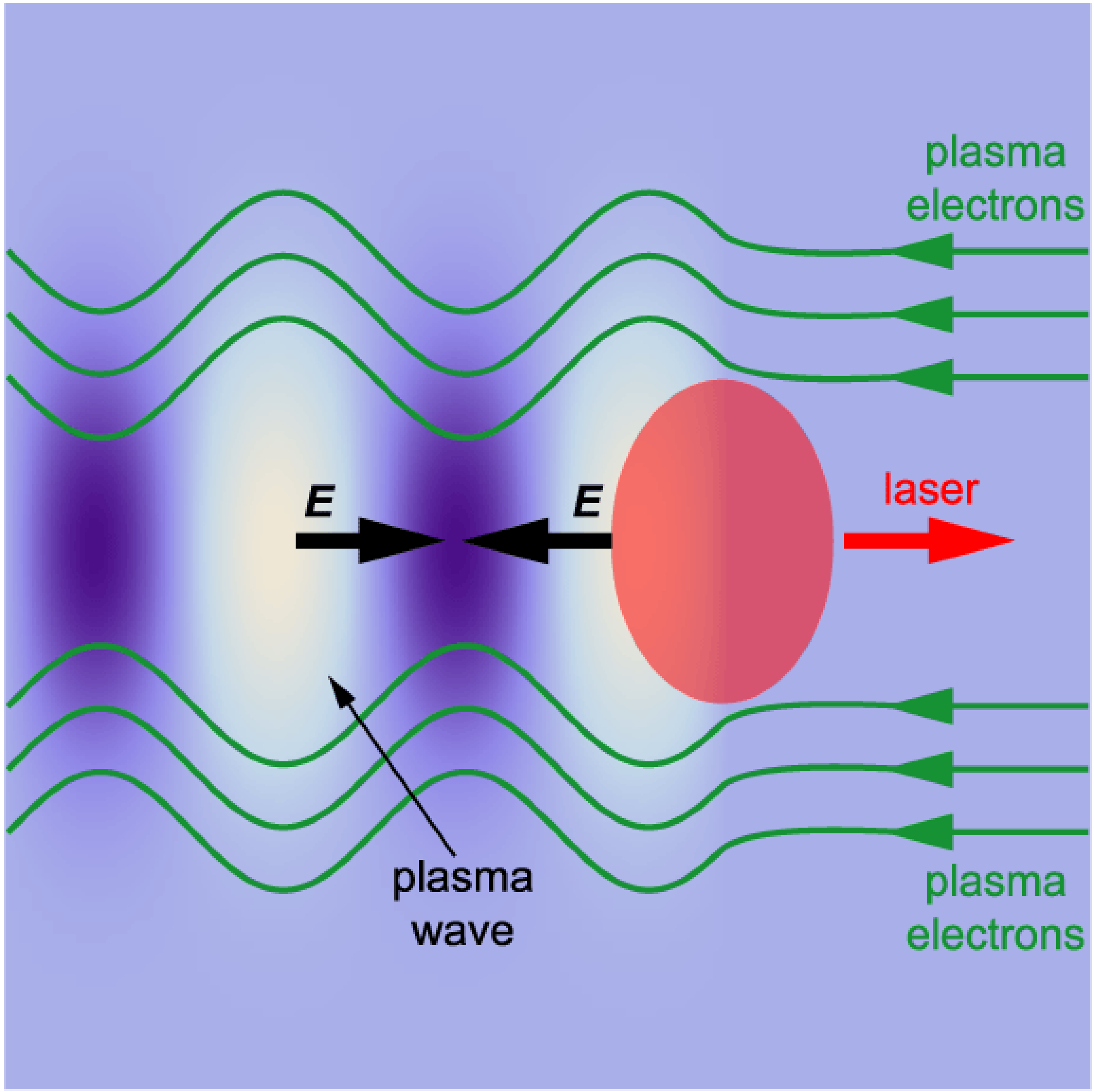
$$\boxed{U_p = \overline{\frac{1}{2} m_e v^2} = 0.57 \; I_{18} \lambda_{\mu\text{m}}^2 \; m_e c^2}$$



Spatial variation in the ponderomotive energy gives rise to a force, the ***ponderomotive force***:

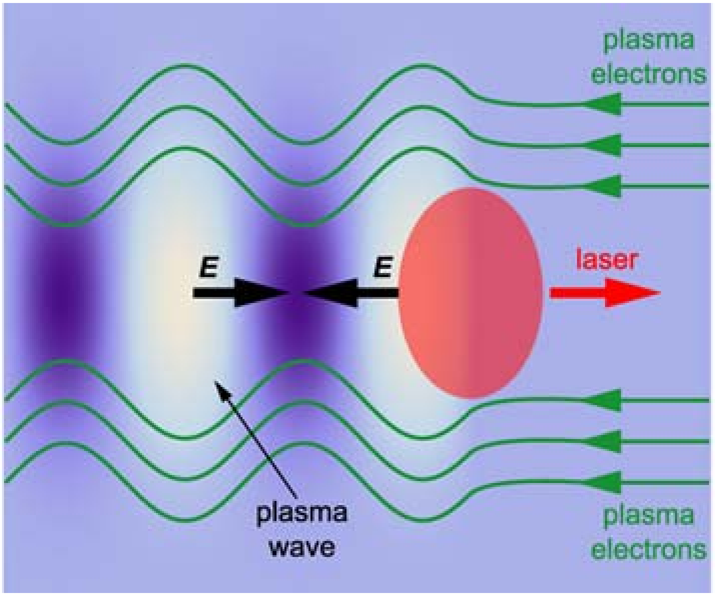
$$\boxed{\mathbf{F}_p = -\nabla U_p}$$

Excitation of wakefield



The ponderomotive force in a laser pulses with intensity of order 1018 W cm-2 expels electrons from the region of the pulse to form a trailing [plasma wakefield.]

Orders of magnitude



The electric field within the plasma can reach the ***wave-breaking limit***:

$$\boxed{E_{\mathrm{wb}}^{\text{non rel.}} = \frac{m_e \omega_p c}{e}}$$

$$\boxed{\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}}}$$

Example :

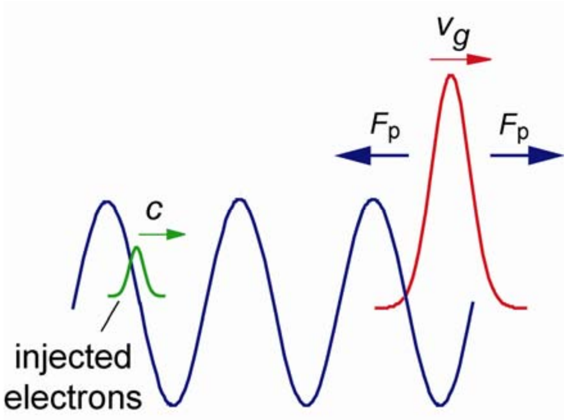
$$n_{\mathrm{e}} = 10^{18}\ \mathrm{cm}^{-3}$$

$$\omega_{\mathrm{p}} = 5.6 \times 10^{13}\ s^{-1}$$

$$T_{\mathrm{p}} = 110\ \mathrm{fs}$$

$$E_{\mathrm{wb}}^{\text{non rel.}} = 95\ \mathrm{GV\,m^{-1}}$$

Limitations



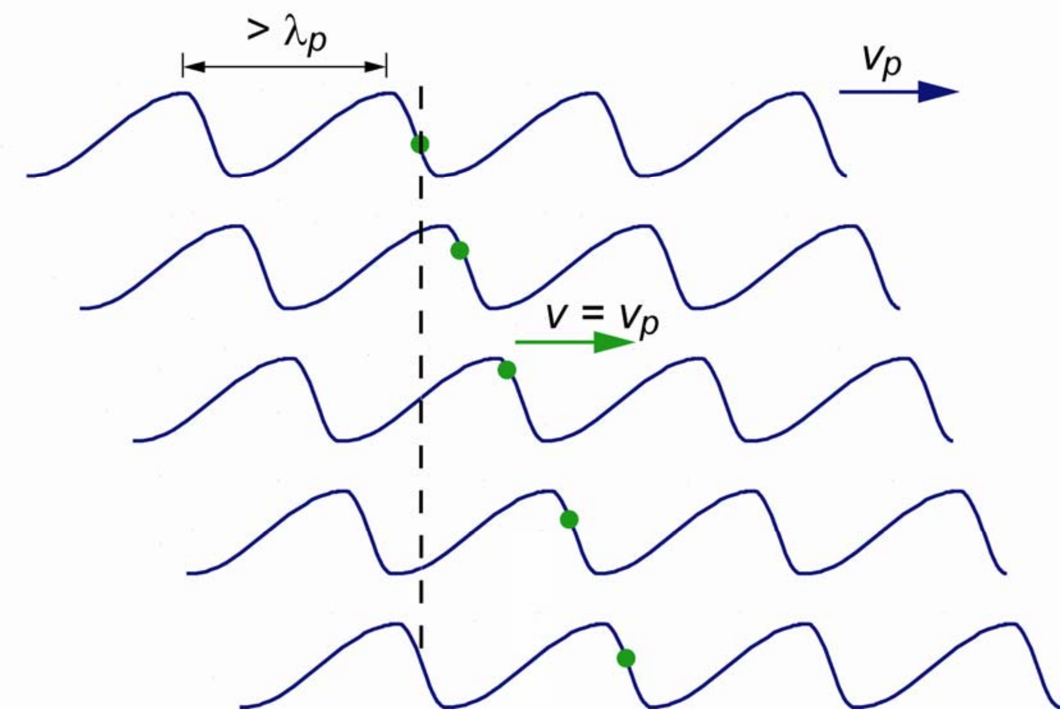
Several processes limit the length over which acceleration can occur:

- Defocusing of the pump beam
- Dephasing between electrons and plasma wave

In addition, we need some way of injecting electrons into the plasma wake…

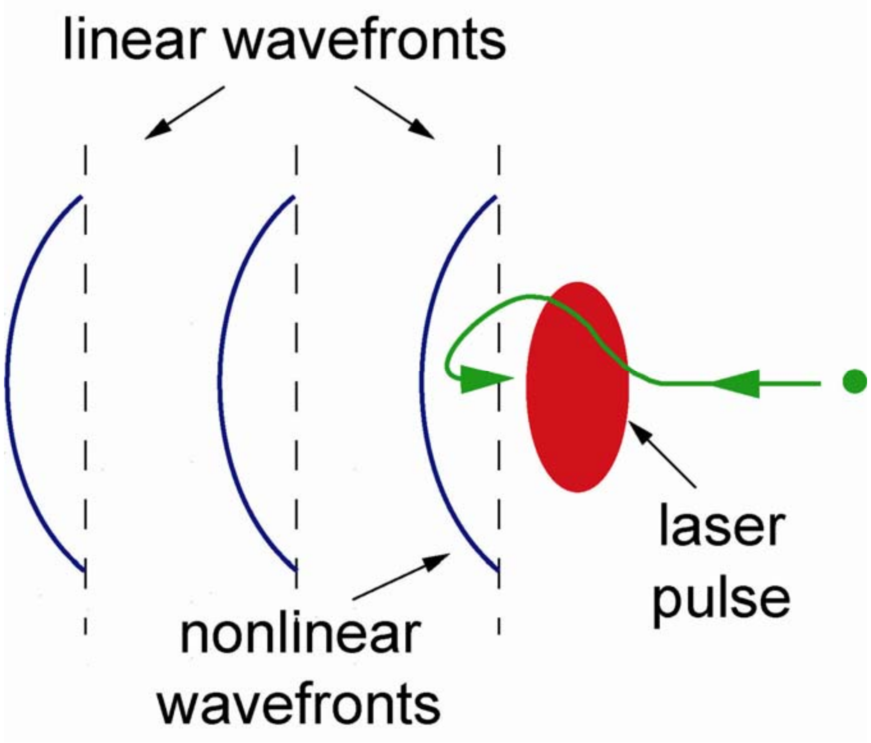
Electron injection: External

Electron injection: Internal



- Plasma waves of large amplitude become nonlinear and develop a “sawtooth” profile
- It is now possible for an initially stationary electron to reach $v > v_p$ and hence be trapped
- This is known as ***wavebreaking***

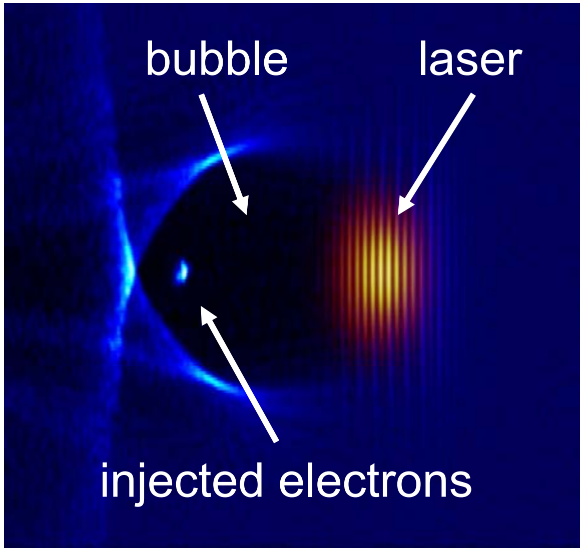
Electron injection: Internal

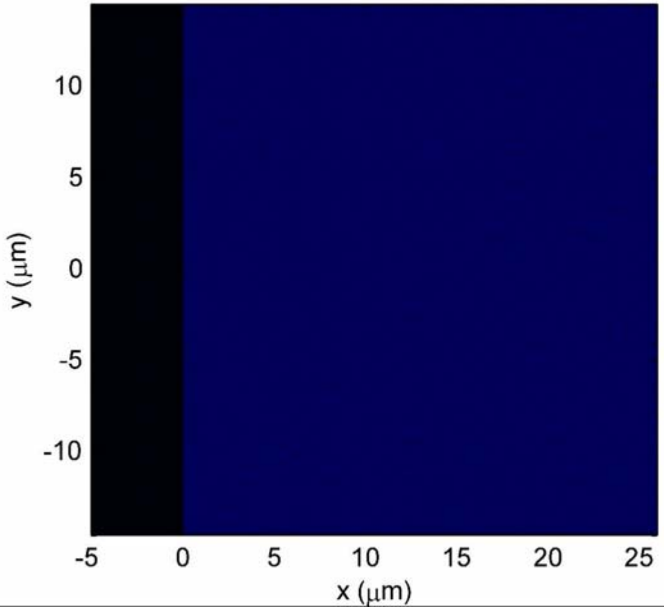


- Nonlinear plasma waves develop curved phase fronts
- This allows electrons to be injected transversely
- This is known as ***transverse wavebreaking***

Electron injection: Self-injection

At sufficiently high driving intensities the “bubble” or “blow-out” regime is reached

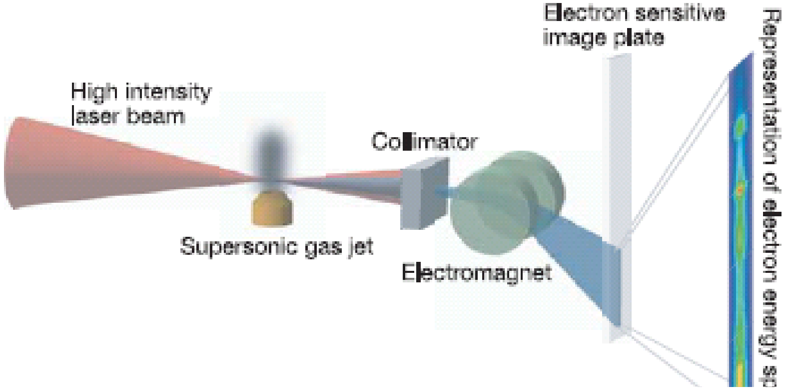




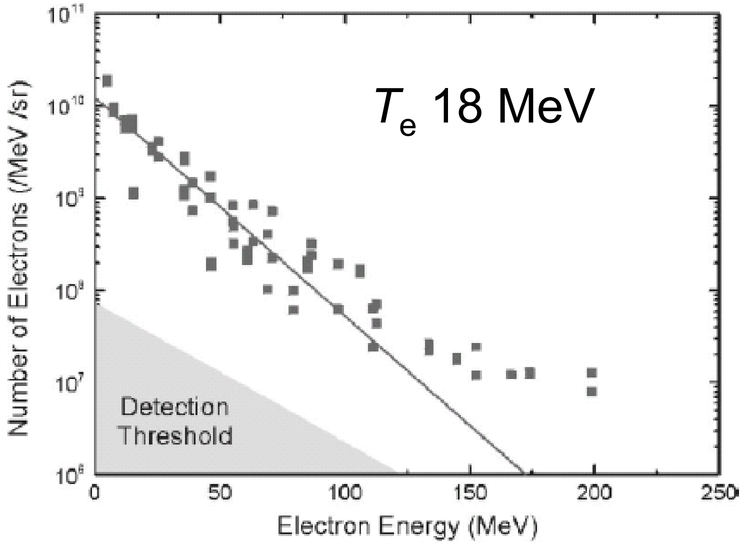
Most experiments to date operate in this regime

Early results

Z. Najmudin *et al.* Phys. Plasma **10** 2071 (2003)
S. D. Mangles et al. *Nature* 431 02939 (2004)



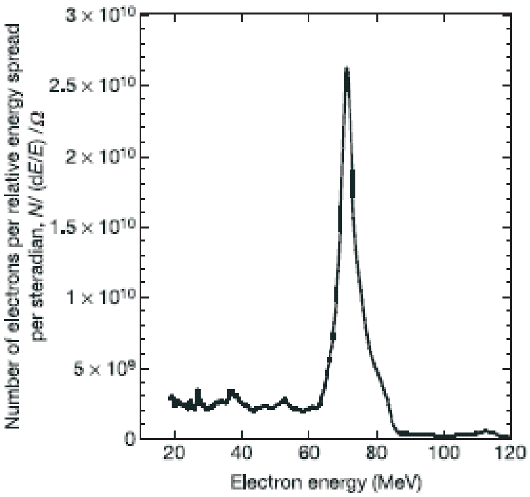
- Early experiments on laser-driven plasma accelerators show continuous, quasi-thermal energy spectrum.
- Electrons injected from background plasma
- Maximum electron energy ~ 100 MeV

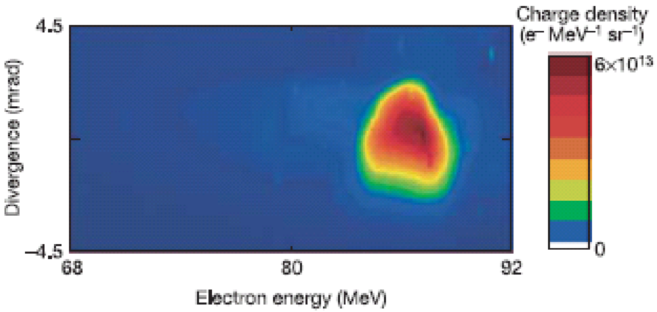


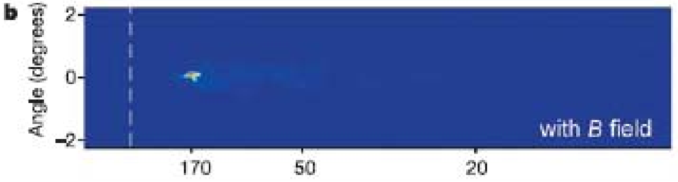
Laser parameters

- Energy 1 J
- Pulse duration 30 fs

Quasi-monoenergetic beams







Typical output parameters:

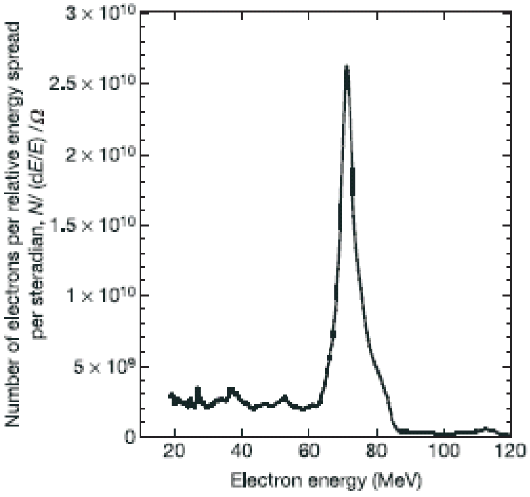
- Output energy: 100 - 170 MeV
- Energy spread: 2.5 - 8%
- Bunch charge: 20 - 500 pC

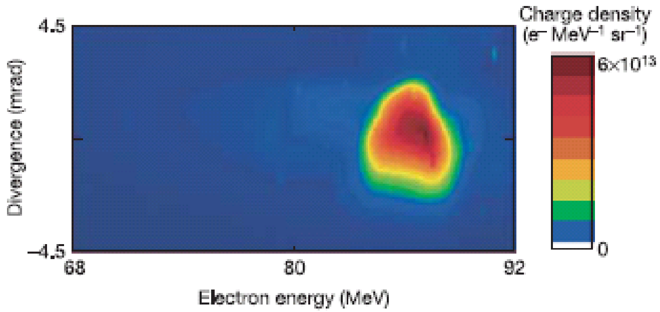
Plasma parameters:

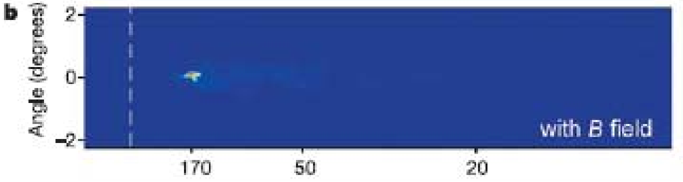
- Plasma density of ~ 10^{19} cm^{-3}
- Length of gas jet ~ 1 - 2 mm

C. G. R. Geddes et al. *Nature* **431** 02900 (2004)
S. D. Mangles et al. *Nature* **431** 02939 (2004)
J. Faure et al. *Nature* **431** 02963 (2004)

Quasi-monoenergetic beams







Quasi-monoenergetic bunch production relies on 4-step process:

- Self-focusing and self-modulation of laser pulse to excite non-linear wakefield
- Self-injection of background electrons (transverse wave breaking)
- Termination of self-injection (beam loading)
- Acceleration of electrons over distance approx. equal to dephasing length.

Plasma accelerators: Scaling to higher energies

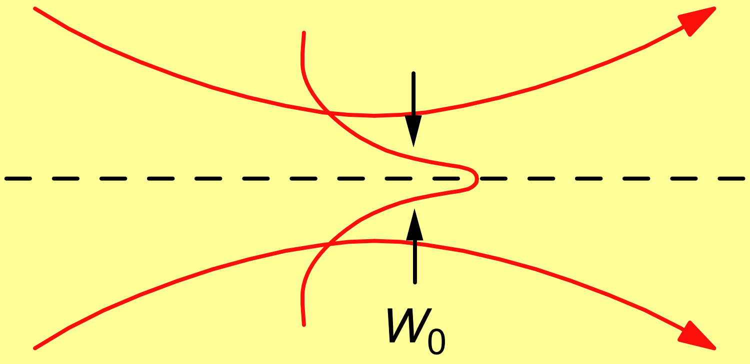
Accelerating field: $E_z \propto \omega_p \propto \sqrt{n_e}$

Dephasing length: $L_{deph} \approx \frac{\lambda_p^3}{\lambda^2} \propto \frac{1}{n_e^{3/2}}$

Energy gain: $\Delta W = E_z L_{\mathrm{deph}} \propto \frac{1}{n_e}$

Factor 10 increase in energy requires:

- Factor 10 decrease in electron density → ~10^{18} cm^{-3}
- Factor 30 increase in length → ~30 - 60 mm



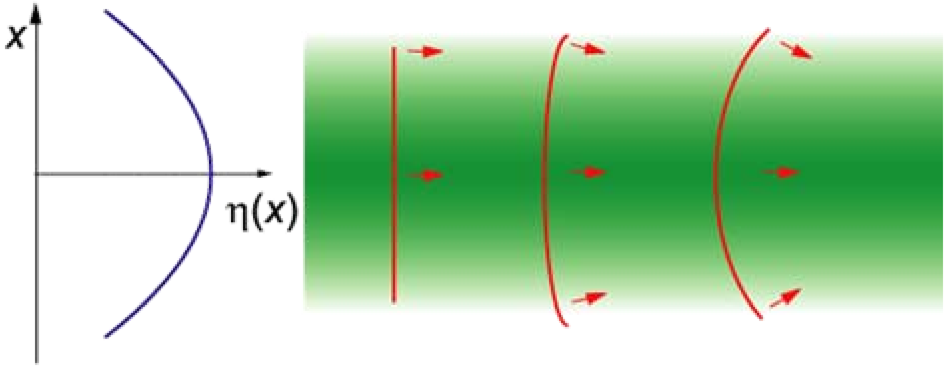
Diffraction limits the interaction length to the order of the ***Rayleigh range***:

$$Z_R = \frac{\pi W_0^2}{\lambda}$$

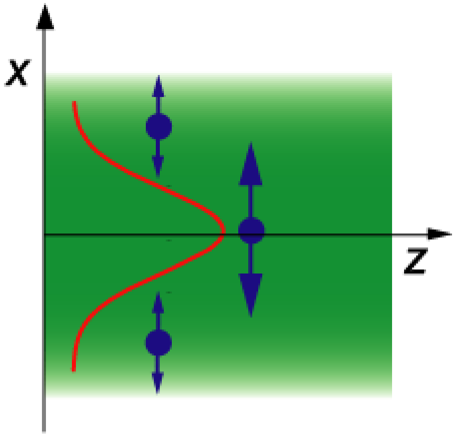
Eg. W_0 = 10 μm; λ = 1 μm

$\Rightarrow Z_R$ = 0.3 mm

Gradient refractive index guiding



A propagating beam will be focused if the refractive index ***decreases*** with distance from axis.



Relativistic self-focusing: transverse variation of <u>intensity</u> yields refractive index profile:

$$\eta = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2} \approx 1-\frac{1}{2}\frac{n_e e^2}{\gamma(r) m_e \varepsilon_0 \omega^2}$$

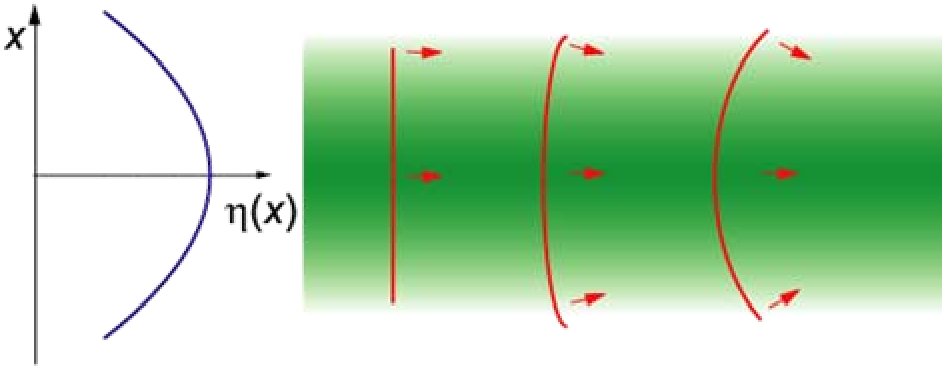
This leads to self-focusing for beams above a critical power:

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

Example

n_e = 10^{18} cm^{-3}, λ = 800 nm: P_c = 8 TW

Gradient refractive index guiding



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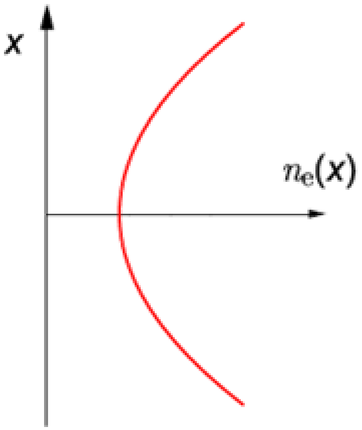


Plasma channel: transverse variation of <u>electron density</u> yields refractive index profile:

$$\boxed{\eta = \sqrt{1-\left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \varepsilon_0 \omega^2}}$$

A parabolic electron density profile supports matched guiding of Gaussian beams with a constant spot size:

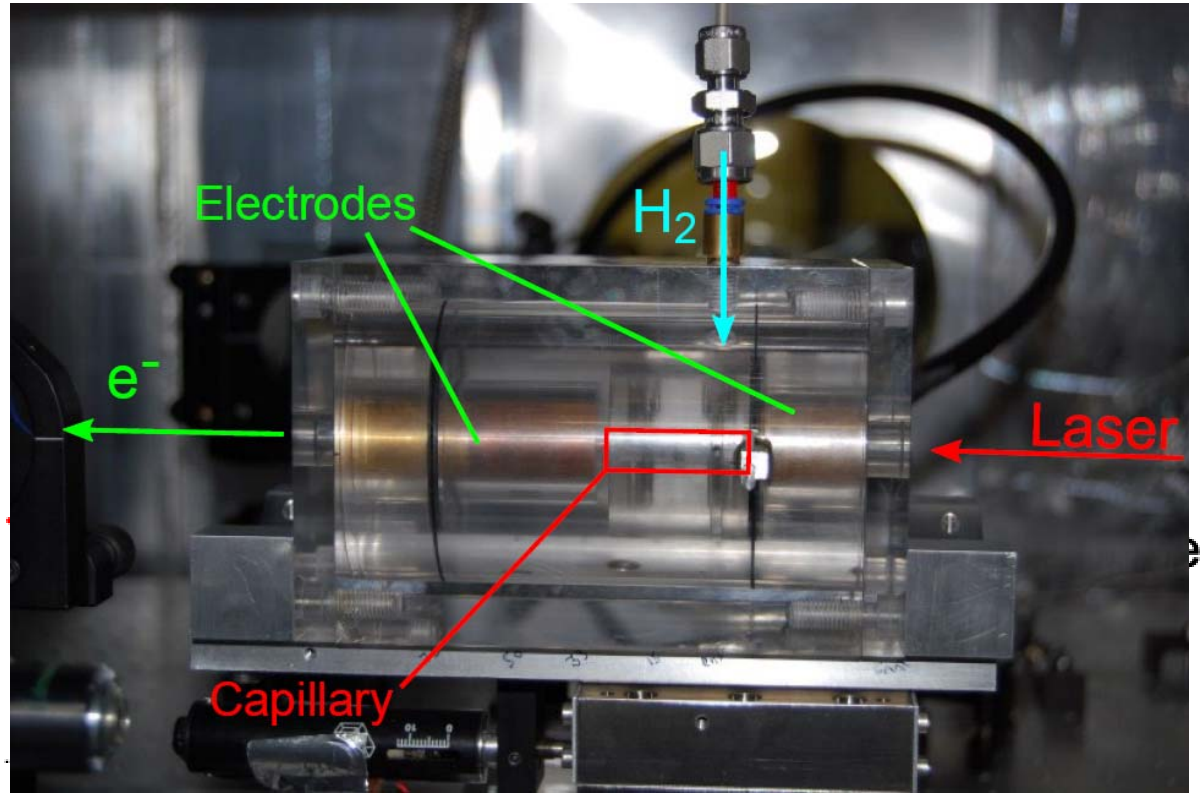
$$N_e(r) = N_e(0) + \Delta N_e\left(r/r_{ch}\right)^2$$

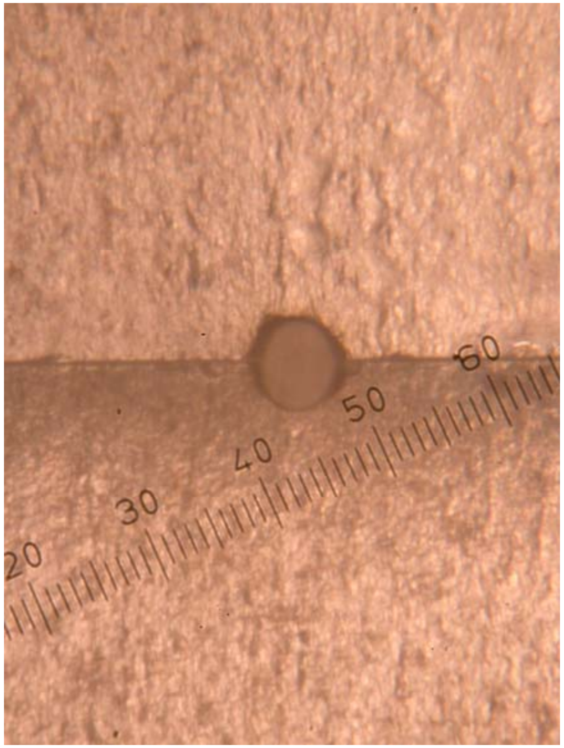
$$\boxed{W_M = \left(\frac{r_{ch}^2}{\pi r_e \Delta n_e}\right)^{1/4}}$$

Gas-filled capillary discharge waveguide

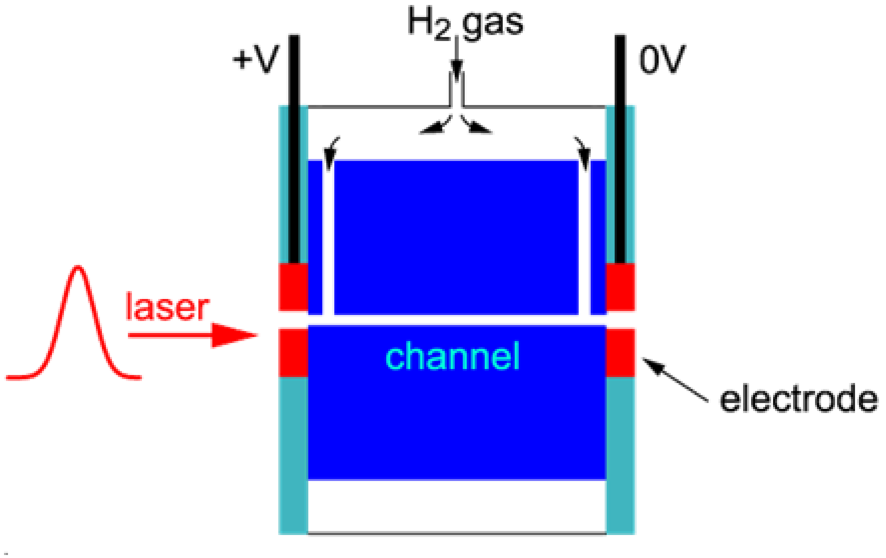
D. J. Spence et al. *Phys. Rev. E* **63** 015401(R) (2001)

A. Butler et al. *Phys. Rev. Lett.* **89** 185003 (2002).



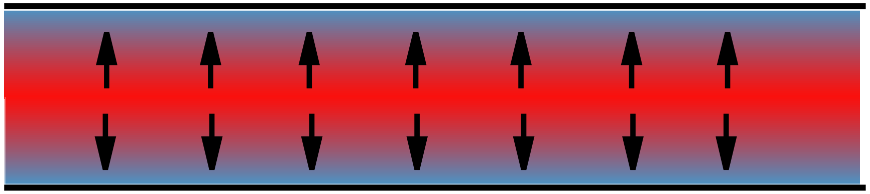


Gas-filled capillary discharge waveguide



Mechanisms responsible for channel formation described in detail in:

- N. A. Bobrova *et al. Phys. Rev. E* **65** 016407 (2002)
- B. H. P. Broks *et al. Phys. Rev. E* **71** 016401 (2005)
- B. H. P. Broks *et al. J. Phys. D* **39** 2377 (2006)
- B. H. P. Broks *et al. Phys. Plasm.* **14** 023501 (2007)

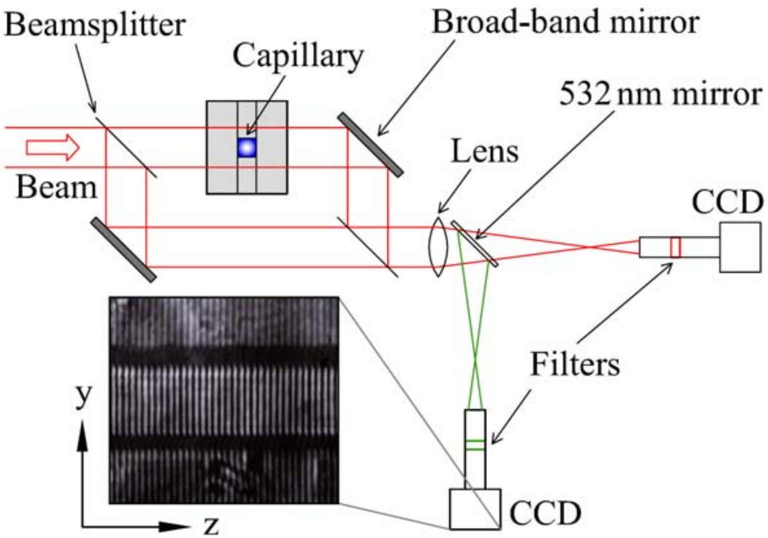


Plasma channel formed by heat conduction to capillary wall.

Channel is fully ionized and stable.

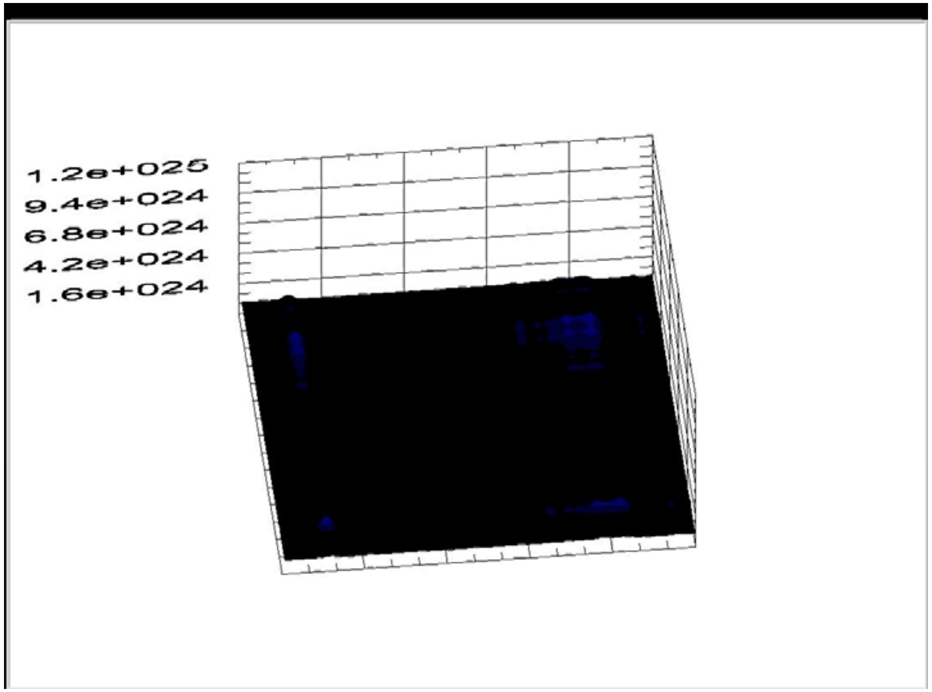
Capillary discharge waveguide: Interferometry

A. J. Gonsalves et al. *Phys. Rev. Lett.* **98** 025002 (2007)



Phase shift of probe beam :

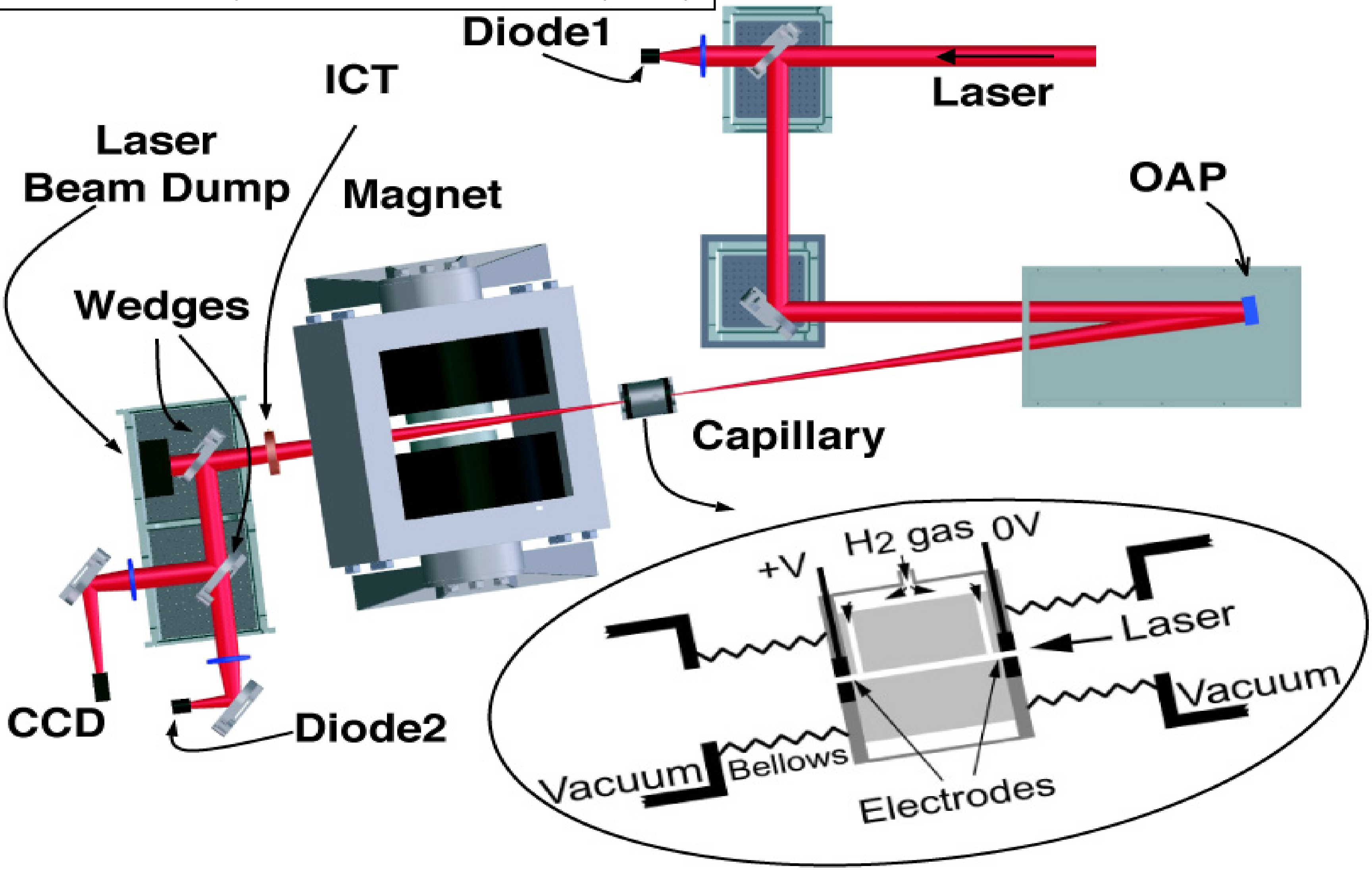
$$\Phi_p(y,z) = -r_e \lambda \int_{-X/2}^{X/2} n_e(x,y,z)dx$$



Oxford/LBNL experiments: Set-up

W. P. Leemans et al. *Nature Physics* **2** 696 (2006)

K. Nakamura et al. *Phys. Plasmas* **14** 056708 (2007)

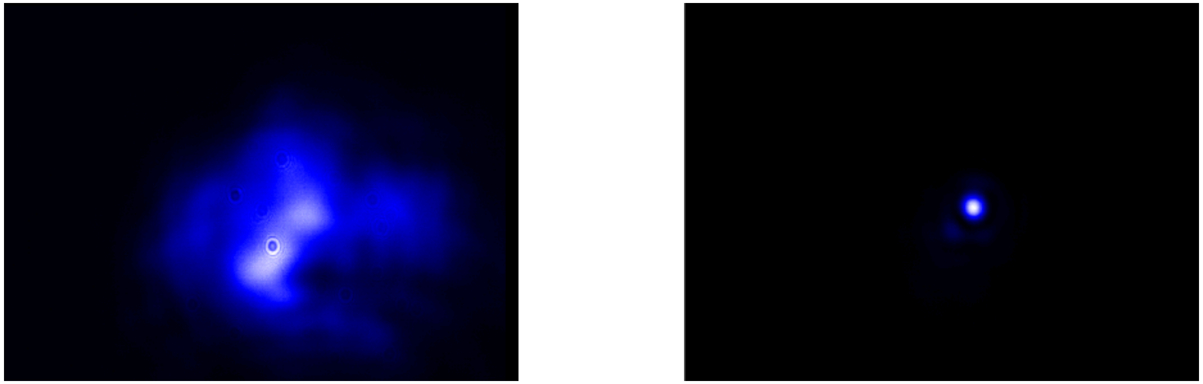


Oxford/LBNL experiments
Guided beam (low power)

W. P. Leemans et al. *Nature Physics* **2** 696 (2006)

K. Nakamura et al. *Phys. Plasmas* **14** 056708 (2007)

capillary exit plane



no capillary

with capillary

~ 100 mJ/pulse

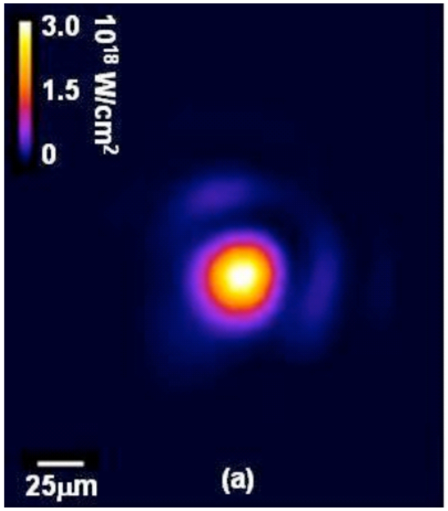
Oxford/LBNL experiments
Guided beam

W. P. Leemans et al. *Nature Physics* **2** 696 (2006)

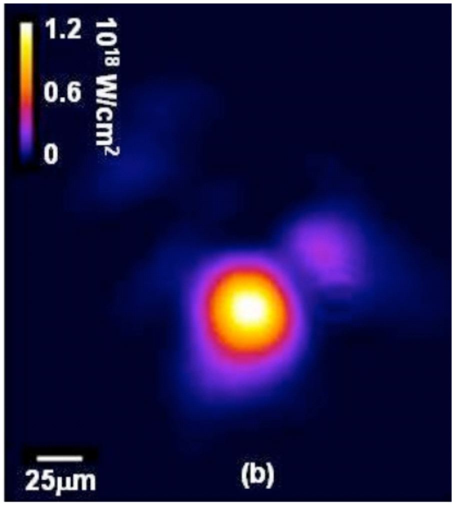
K. Nakamura et al. *Phys. Plasmas* **14** 056708 (2007)

Guiding achieved over 33 mm:

- Capillary 190 um
- Input laser power 40 TW
- Peak input intensity > 10^{18} W cm^{-2}
- Plasma: 3 × 10^{18} cm^{-3}
- Spot size at entrance 26 μm
- Spot size at exit 33 μm



Entrance

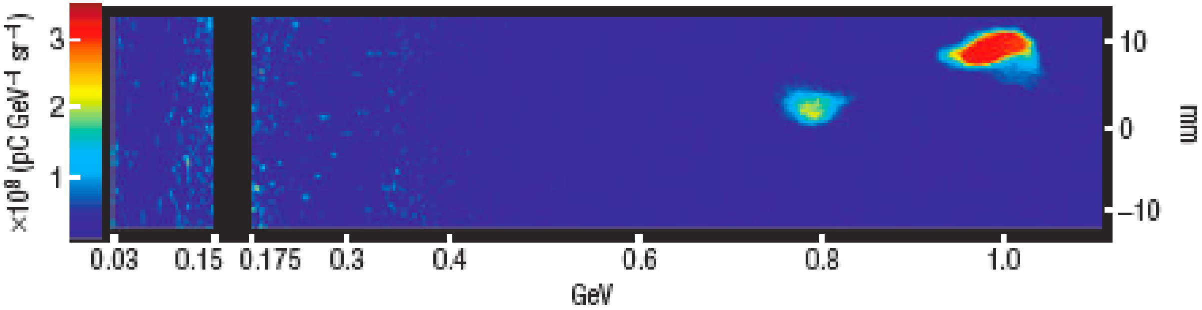


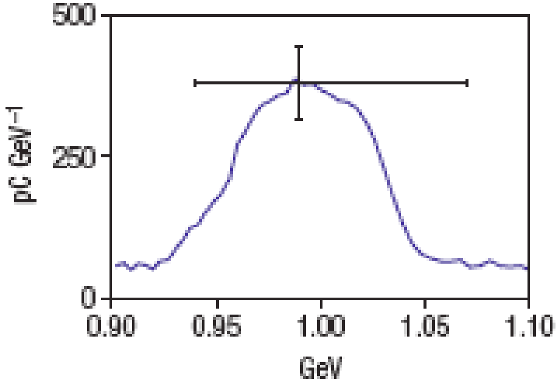
Exit

Oxford/LBNL experiments
1 GeV beams

W. P. Leemans et al. *Nature Physics* **2** 696 (2006)

K. Nakamura et al. *Phys. Plasmas* **14** 056708 (2007)





Experiment conditions:

- Capillary: 33 mm, 312 μm diam.
- Density 4.3 ×10^{18} cm^{-3}
- Laser: 40 TW: 1.5 J, 37 fs

E = (1.0 +/- 0.06) GeV
ΔE = 2.5% r.m.s
$\Delta\theta$ = 1.6 mrad r.m.s.
Q = 30 pC

In recent experiments with the Astra-Gemini laser by the Imperial College et al, 0.8 GeV beams were generated by relativistically-guided (200 TW) laser pulses [Kneip et al. *Phys. Rev. Lett.* **103**, 035002 (2009)]

Present status

- Laser-driven plasma accelerators have made very significant advances in the last few years.
- It is now possible to generate monoenergetic electron beams with energies comparable to those used in synchrotrons.
- In the near-term we can expect controlled and stable laser-accelerated beams with parameters suitable for applications.

Likely near-term parameters

Energy:	few GeV
ΔE:	~1%
σ_x	~ 5 μm
$\sigma^{/}_{x}$	~ 1 mrad
Bunch duration:	~ 10 fs
Bunch charge:	10-100 pC
Repetition rate:	10 Hz

Future themes

Current research on laser-driven plasma accelerators may be divided into several themes:

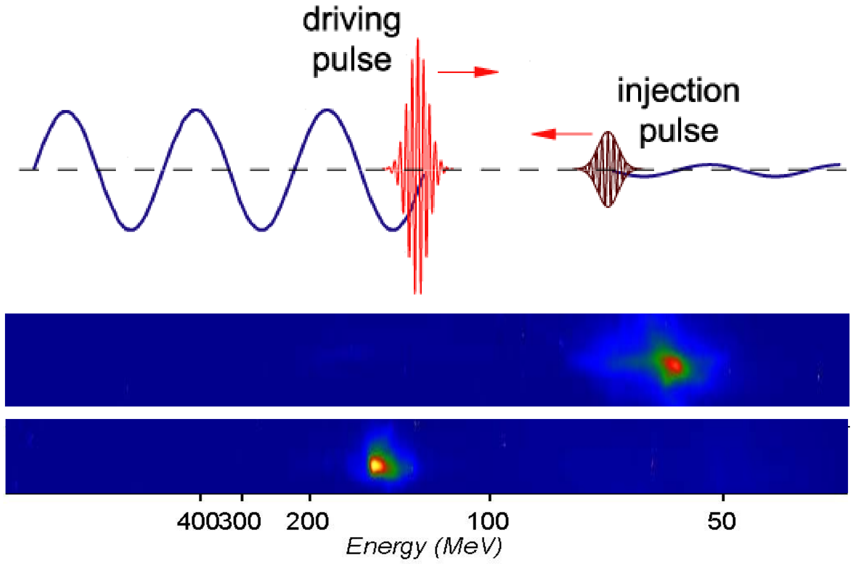
- Improved shot-to-shot stability
  - Imperative for applications
- Increased beam energy
- Better (single-shot) diagnostics
  - emittance
  - bunch duration (~ 10 fs?)
- Development of applications

- In current experiments the generated beams have relatively poor shot-to-shot stability
  - jitter in E ~ 5%
  - jitter in Q ~ 50%
  - beam pointing ~ 5 mrad
- Some of these are caused by fluctuations in the laser and plasma conditions
  - Require engineering solutions
- Controlling the injection offers potential for significant improvements

Improved stability: controlled injection

Colliding pulse (LOA)

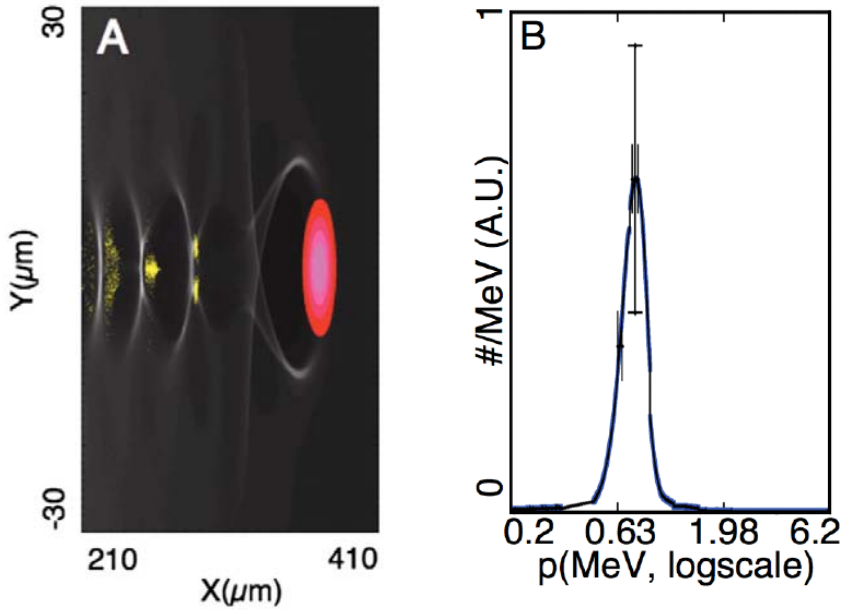
J. Faure et al. *Nature* **444** 737 (2006)



- Plasma electrons heated stochastically at collision, allowing some to be injected
- Energy tuned from 50 – 300 MeV by changing collision point

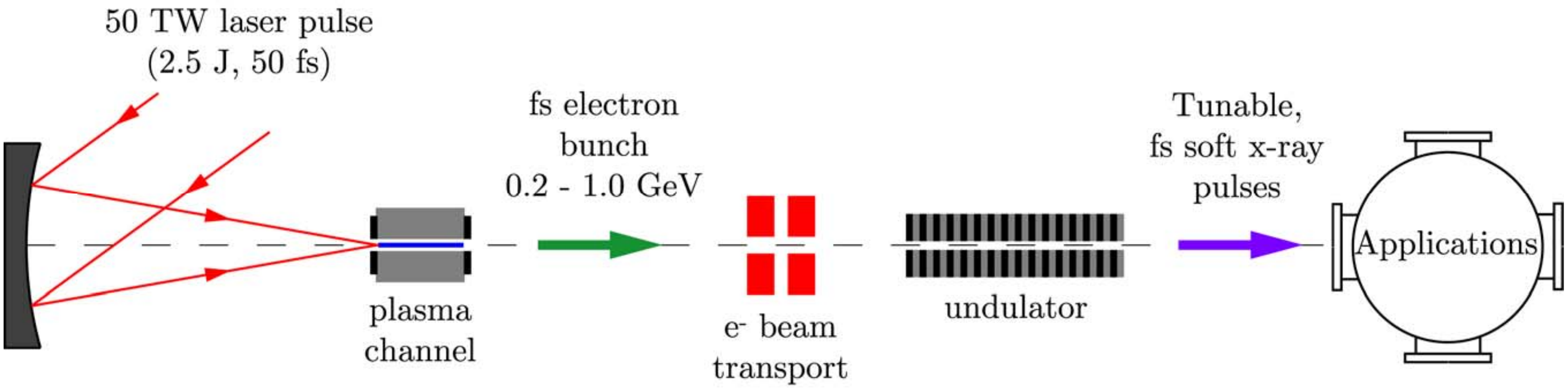
Density down-ramp (LBNL)

C. Geddes et al. *PRL* **100** 215004 (2008)



- Velocity of wake slowed, trapping easier
- Low absolute energy spread of ~ 0.2 MeV/c at a momentum of 0.76 MeV/c

Near-term applications: Radiation generation

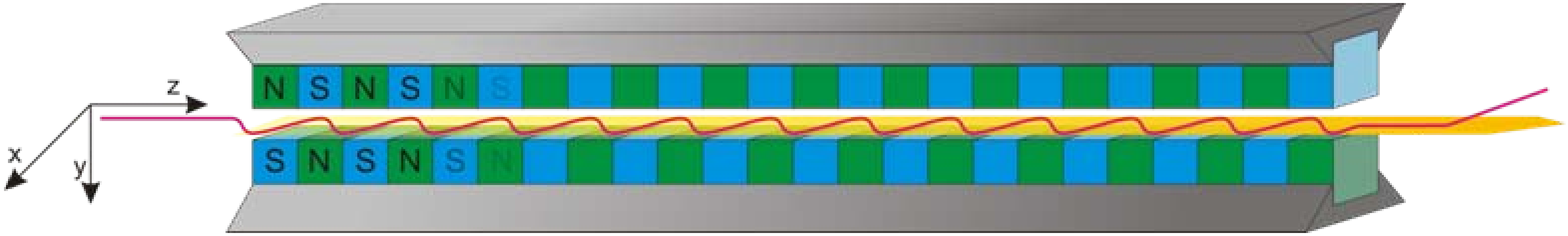


Laser-driven accelerators could be used to drive very compact, tunable sources of:

- Femtosecond electron bunches: 0.1 - 1 GeV
- Femtosecond x-rays:
  - Bending magnet: 5 keV (0.2 nm)
  - 10 mm period undulator: 1 keV (1 nm)

all intrinsically synchronized to a femtosecond visible laser system

Undulator radiation

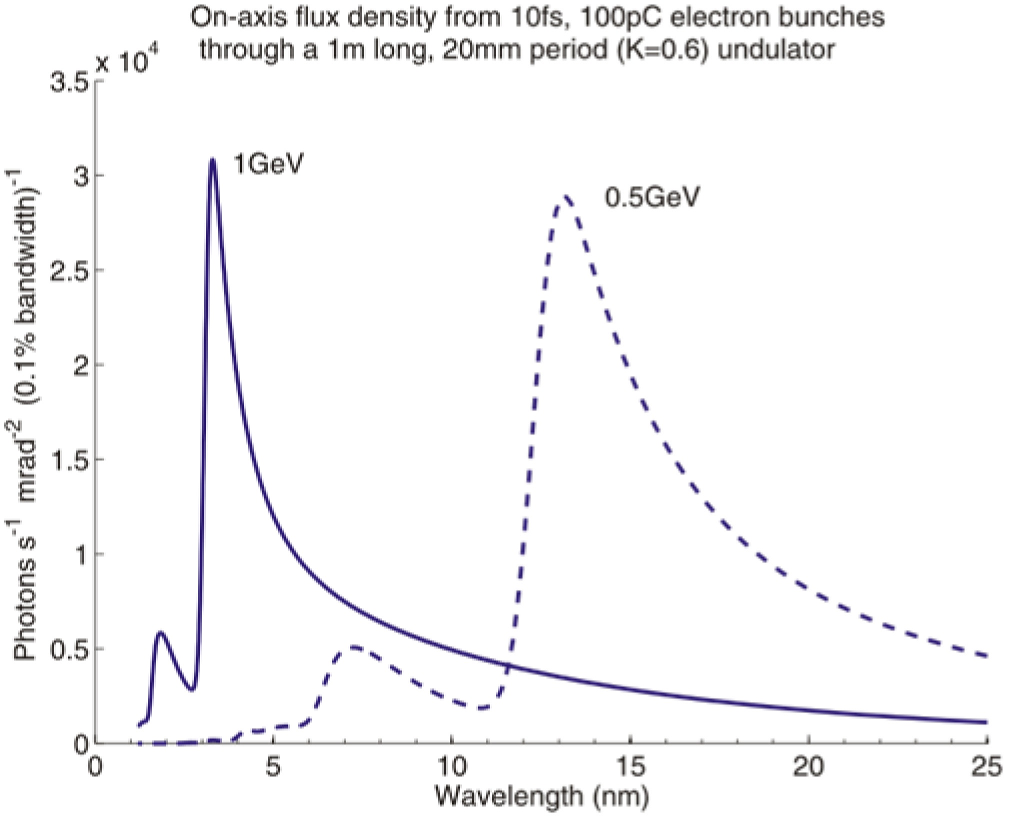


Undulator equation:

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

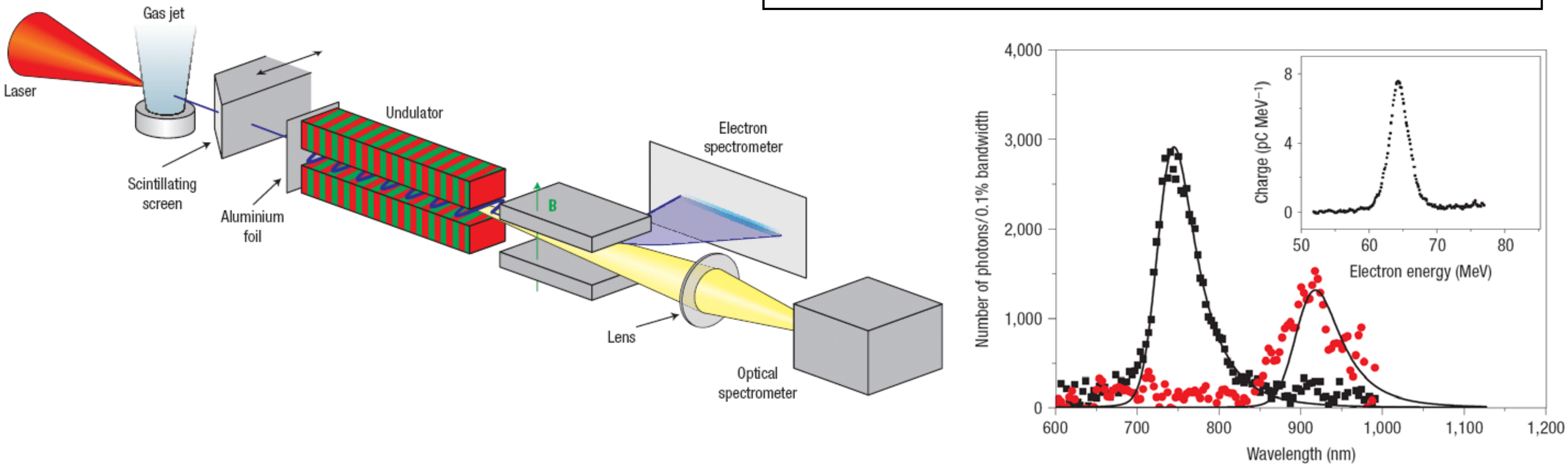
where,

$$K = \frac{eB_0\lambda_u}{2\pi m_e c}$$



Near-term applications: Radiation generation

Schlenvoigt et al. *Nature Physics* **4** 130 (2008)



Generation of undulator radiation demonstrated for first time by Jena-Strathclyde collaboration

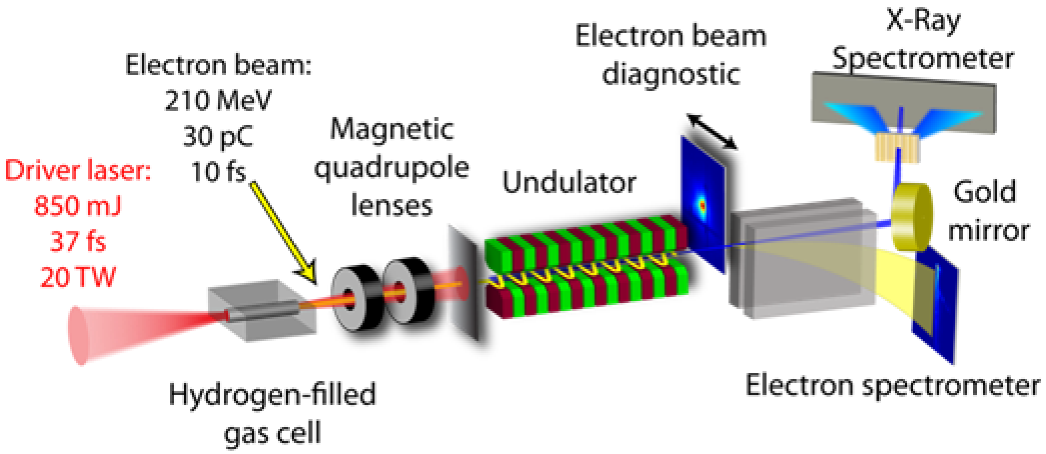
- Electron beam: 55 – 75 MeV
- Undulator:λ_p = 20 mm, N = 50, K = 0.6
- Peak brilliance est. to be 6×10^{16} ph/s/mrad^2/mm^2/0.1%

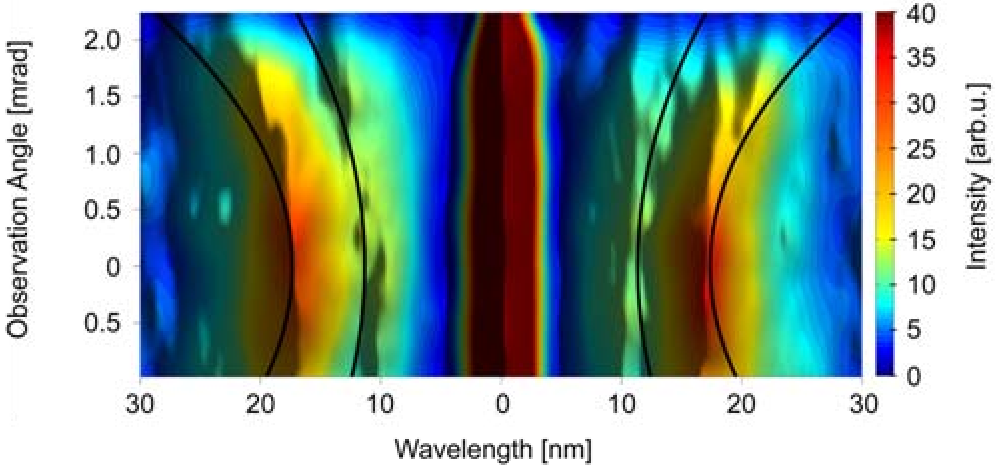
Near-term applications: Radiation generation

Fuchs et al. *Nature Physics* (2009)

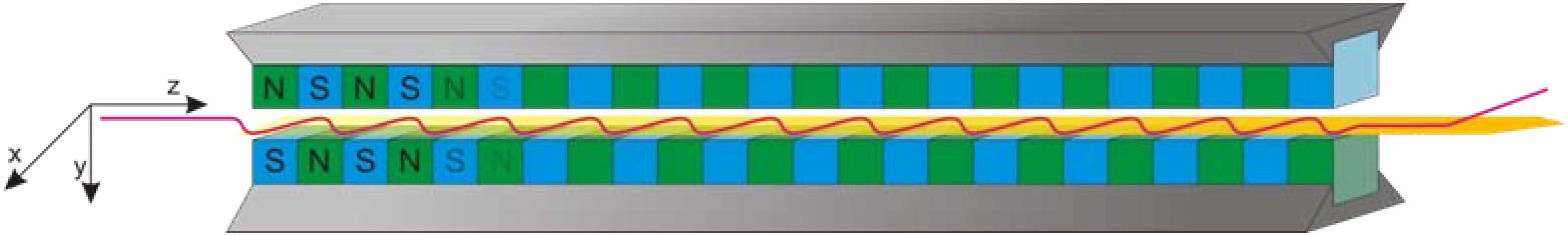
Recently extended to soft x-ray wavelengths by MPQ-Oxford collaboration

- Electron beam: 210 MeV
- Undulator: $\lambda_p = 5$ mm
- Radiation at 18 nm & 9 nm (2nd harmonic)
- Peak brilliance est. to be 2×10^{17} ph/s/mrad^2/mm^2/0.1%
- Preliminary tuning demonstrated





Free-electron lasers



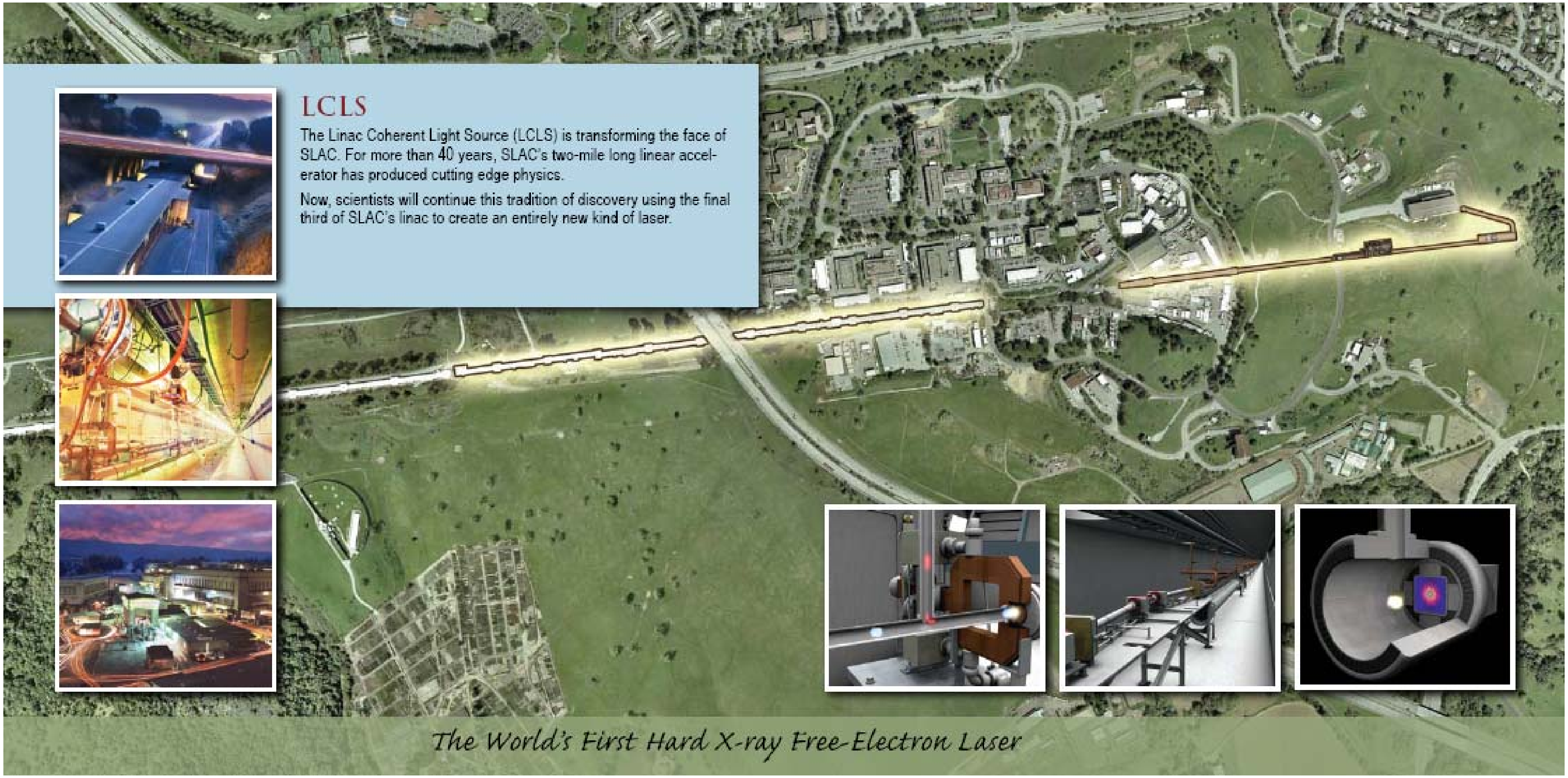
- Spontaneous radiation causes electron **microbunching** on scale of radiation wavelength
- Leads to coherent emission of radiation; **self-amplification**
- Exponential gain in power output:

$$P \propto \exp\left(\frac{z}{L_G}\right)$$

where,

$$L_G = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$$

Free-electron lasers



LCLS

The Linac Coherent Light Source (LCLS) is transforming the face of SLAC. For more than 40 years, SLAC's two-mile long linear accelerator has produced cutting edge physics.

Now, scientists will continue this tradition of discovery using the final third of SLAC's linac to create an entirely new kind of laser.

The World's First Hard X-ray Free-Electron Laser

- The LCLS FEL uses the last one-third of the two-mile SLAC accelerator
- Recently demonstrated lasing at 0.15 nm
- Project cost ~$350M ($300M saved by using SLAC)

FELs: Key electron bunch parameters

- Pierce parameter, ρ, characterizes strength of coupling between electrons and radiation field

$$\frac{\sigma_\gamma}{\gamma} < \rho = \frac{1}{2\gamma}\left[\frac{I_p}{I_A}\left(\frac{\lambda_u K f_K}{2\sqrt{2}\pi\sigma_b}\right)^2\right]^{1/3}$$

Parameter	Plasma accelerator	TESLA XFEL
Energy (GeV)	0.5 – 1	10 - 20
Energy spread σ_γ/γ (%)	1 – 5	0.02
Bunch charge (pC)	100 – 250	1000
Bunch duration (fs)	10	80
Peak Current I_p (kA)	10	12
Norm. emittance (mm mrad)	1 – 10	1.4

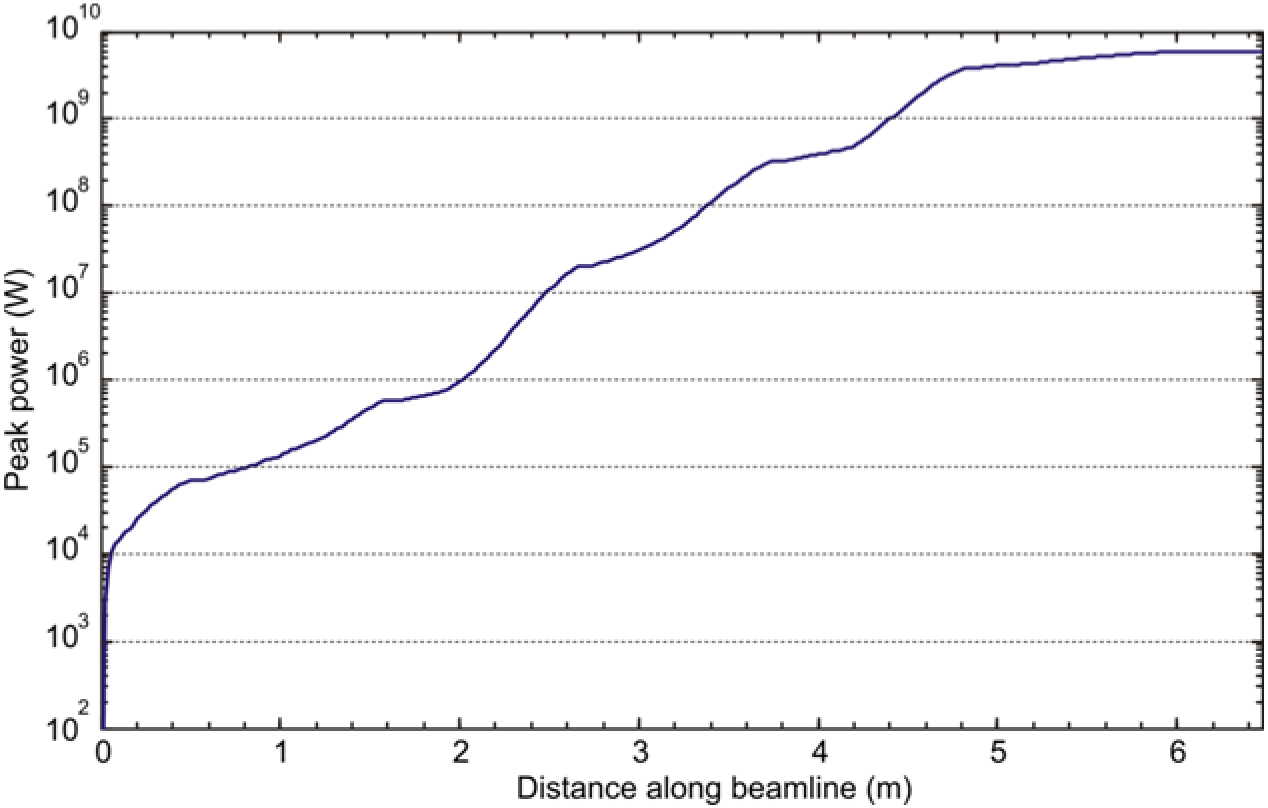
FELs: GENESIS Simulations

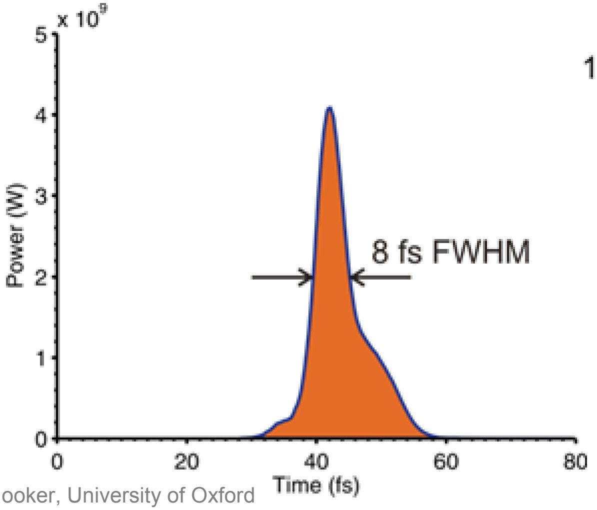
Generation of 50nm radiation

Electron parameters:
E = 400 MeV

ΔE = 1%
Q = 250 pC
τ = 10 fs rms
ε = 1 mm mrad normalized

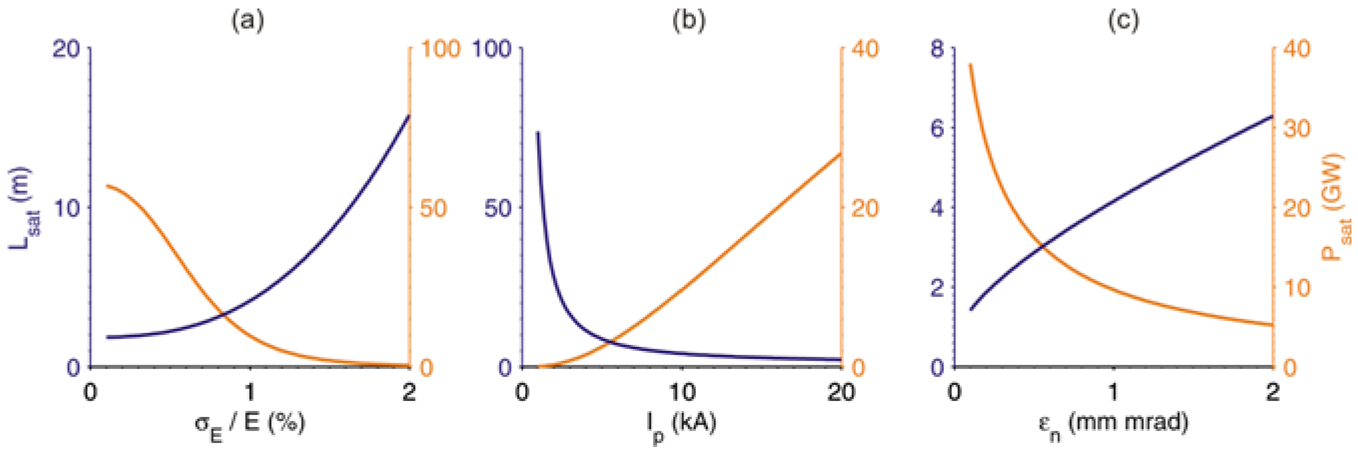
Undulator:
2 cm period
K = 2





FELs: GENESIS Simulations

- Variation of saturation length and power at 50 nm (Xie scaling):

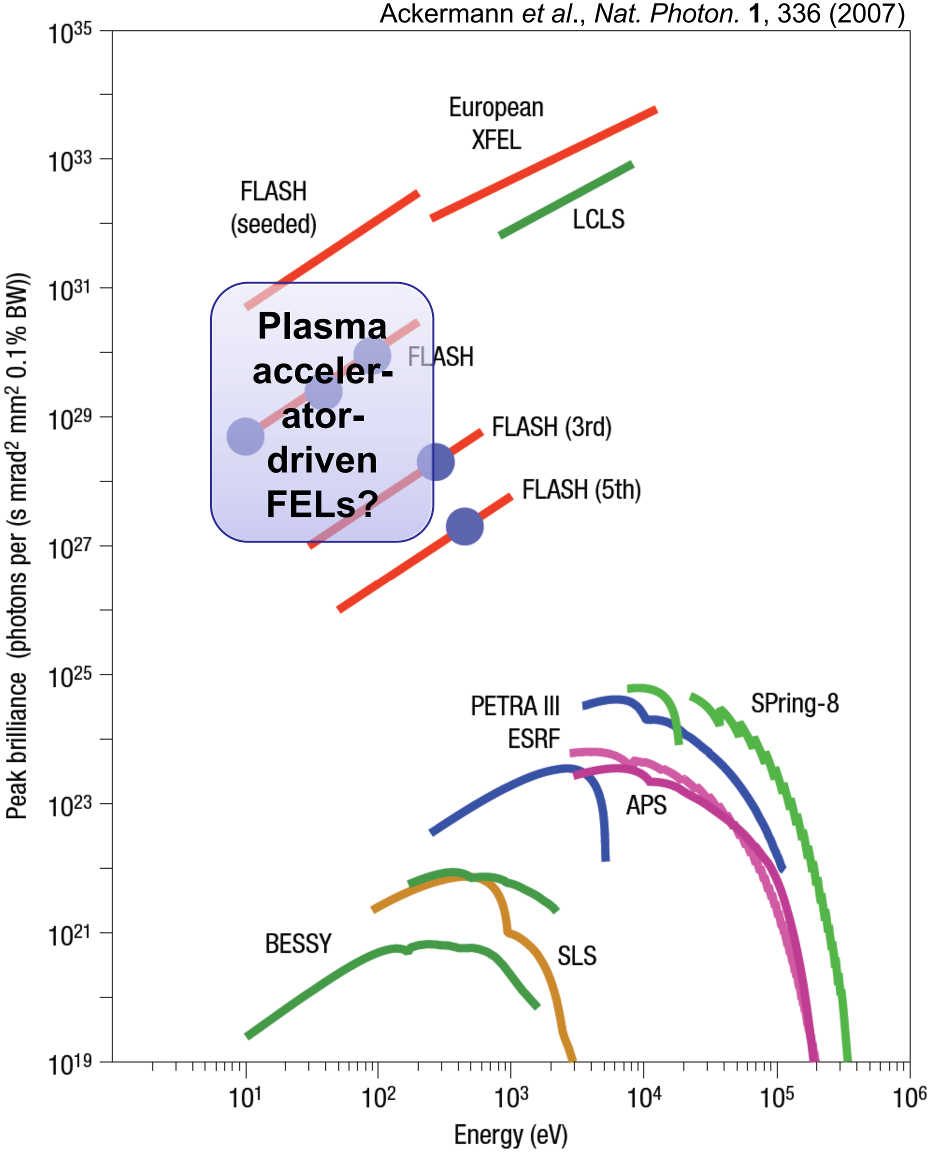


- Further simulations (Q = 250 pC, ε_n = 1 mm mrad):

Rad.	**Undulator**		**Electrons**			**Output characteristics**				
λ (nm)	λ_u (mm)	K	E (MeV)	σ_E/E (%)	τ_e (fs)	**L_{sat} (m)**	**P_{sat} (GW)**	N γ /pulse	τ_r (fs)	B.W. (%)
50	20	2.0	400	1	10	**5.1**	**4.2**	$7.8\ 10^{12}$	4.3	2.7
10	15	1.9	750	1	10	**18.3**	**1.6**	$1.1\ 10^{12}$	7.8	12.6
10	15	1.9	750	0.5	10	**4.8**	**50.0**	$1.1\ 10^{13}$	3.3	1.3
5	10	2.2	950	0.5	5	**5.1**	**283.0**	$7.6\ 10^{12}$	1.7	0.7

FELs: Comparison to conventional sources

Ackermann *et al.*, *Nat. Photon.* **1**, 336 (2007)



Long-term: TeV accelerators

The challenges for a laser-driven plasma accelerator operating at TeV energies are daunting…

	1 GeV	**1 TeV (ILC class)**
No. electrons	2 × 10^{8}	2 × 10^{10}
Energy in e^-	0.03 J	3.2 kJ
Laser energy	1.5 J	160 kJ
Rep. rate	10 Hz	14 kHz
Mean laser power	15 W ↓ 0.1%	2.2 GW
Electrical energy	15 kW	2.2 TW

Long-term: TeV accelerators

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No. electrons	2×10^8	2×10^{10}	2×10^{10}
Energy in e^-	0.03 J	3.2 kJ	3.2 kJ
Laser energy	1.5 J	160 kJ	16 kJ
Rep. rate	10 Hz	14 kHz	14 kHz
Mean laser power	15 W	2.2 GW	220 MW
Electrical energy	15 kW	2.2 TW	2.2 GW

0.1%

20%

10%

Indeed, in USA the BELLA (laser-driven) and FACET (beam-driven) projects have been funded (~$50M) to investigate potential for scaling to collider-type energies

Summary

- Laser-driven plasma accelerators have made significant advances in last 5 years.
- Now possible to generate monoenergetic electron beams with energies comparable to those used in synchrotrons.
- It is likely that in the next few years these will be used to drive incoherent sources of tunable, femtosecond x-rays.
- It remains to be seen if the brightness of the electron beam is sufficient to drive very compact FELs.
- Extending to TeV (esp. high pulse rep. rate) level is challenging and will require significant advances in both plasma accelerators and laser technology