Laser wakefield accelerators

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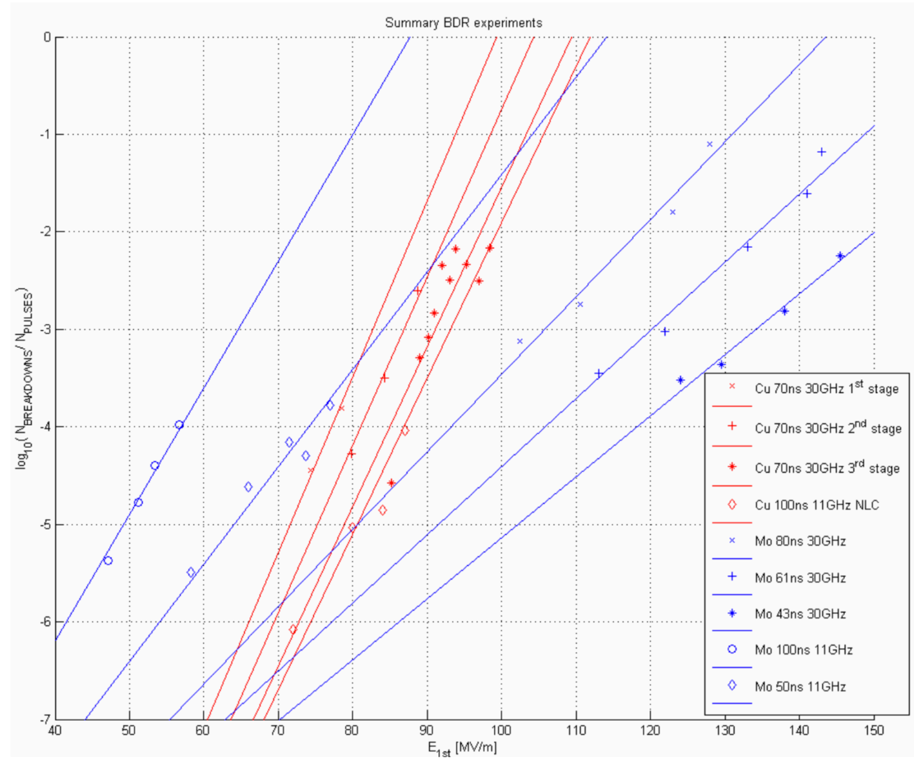
Why plasma-based accelerators?

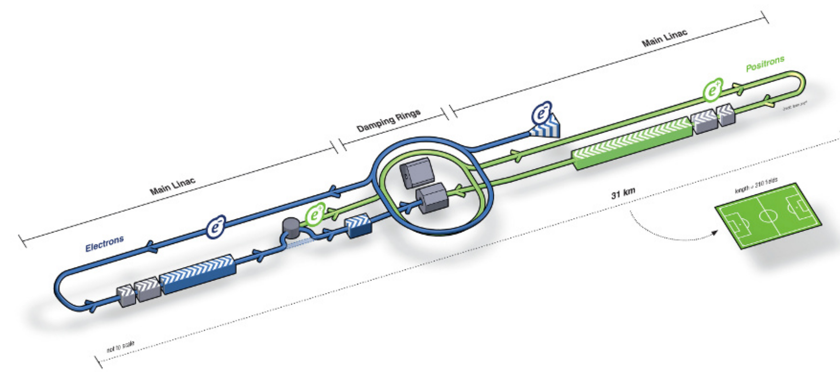
Aim: accelerate electrons to high energies, require large electric fields

Problem: the electric fields in conventional accelerators are limited to 10-150 MVm^{-1} by electrical breakdown, meaning accelerators are large

e.g. the International Linear Collider will be 10s of km long and cost £ billions.

Solution: avoid electrical breakdown by using a plasma





…are not a new idea

SOVIET PHYSICS USPEKHI VOLUME 10, NUMBER 6 MAY-JUNE 1968

621.384.6

ACCELERATION OF CHARGED PARTICLES IN A PLASMA

Ya. B. FAĬNBERG

Physico-technical Institute, Ukrainian Academy of Sciences, Kharkov

Usp. Fiz. Nauk 93, 617–631 (December, 1967)

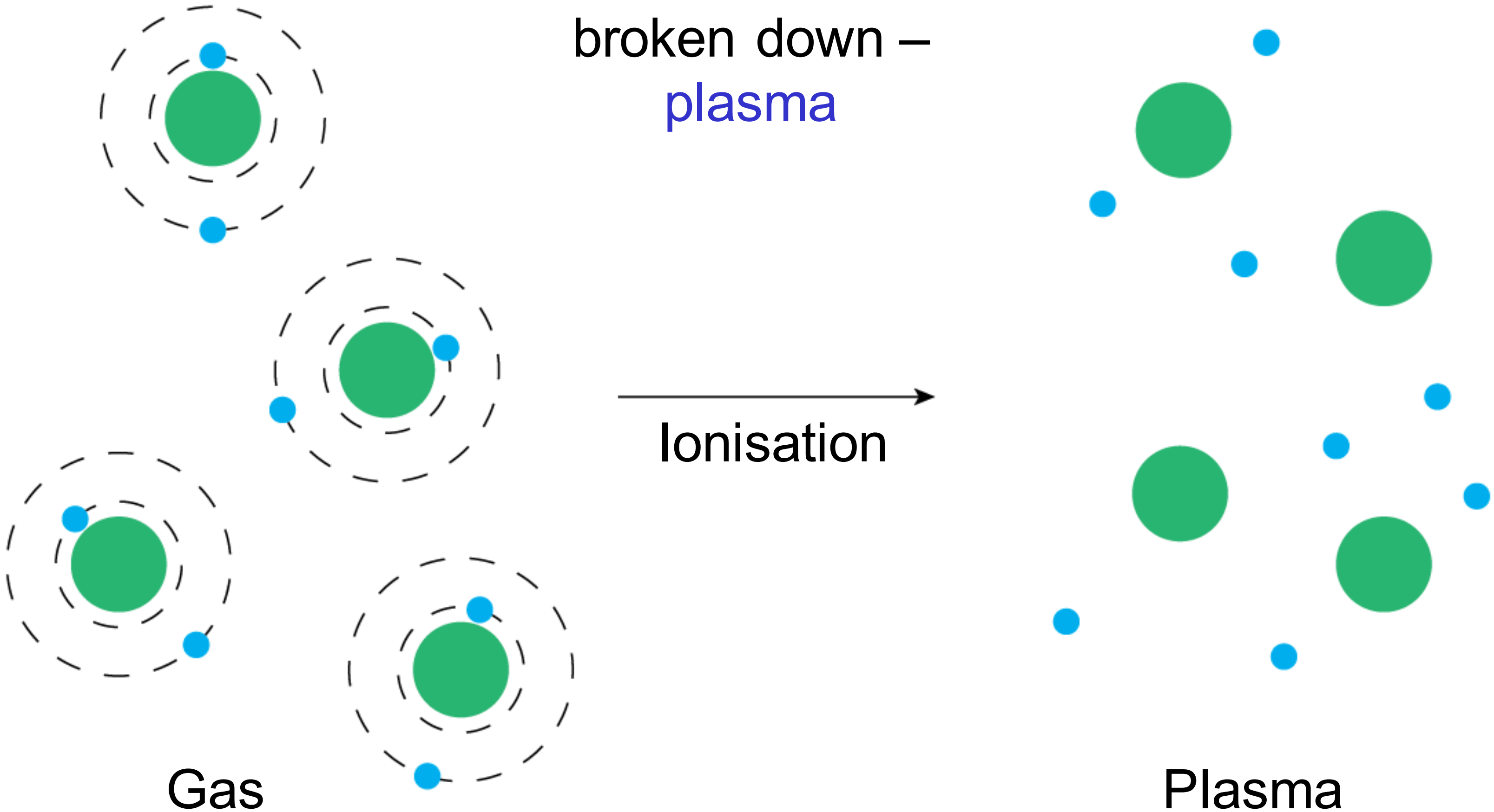
of physics Veksler very quickly realized the possibilities that might be made available by the use of an electron-ion plasma for the acceleration of charged particles. In one of the new principles of acceleration

Fainberg, 1968

[1] V. I. Veksler, Proc. CERN Symp. 1, 80 (1956), FIAN Reports, 1951, 1952.

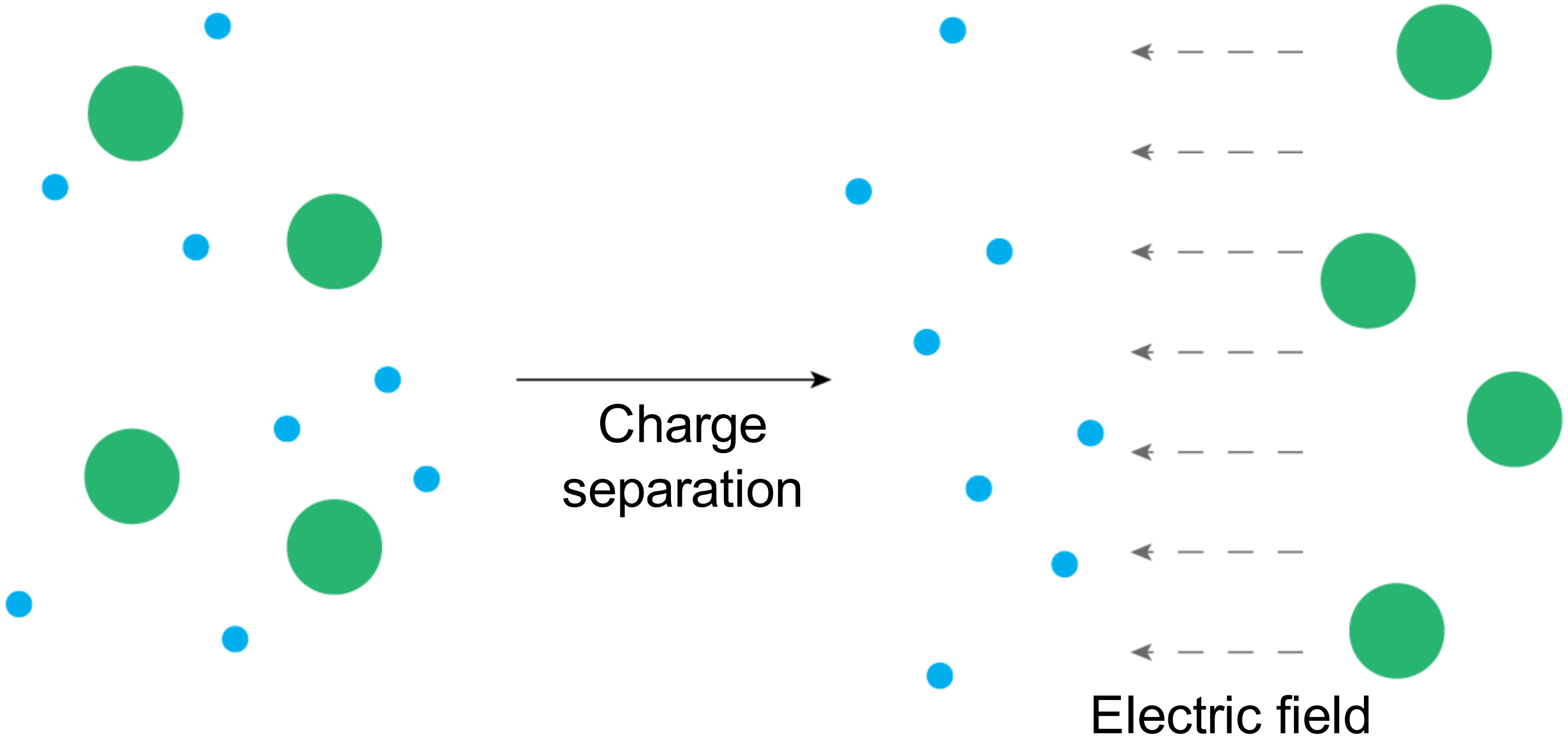
Laser wakefield accelerators (LWFAs)

Key idea #1: replace accelerator material with a substance which cannot be broken down – plasma



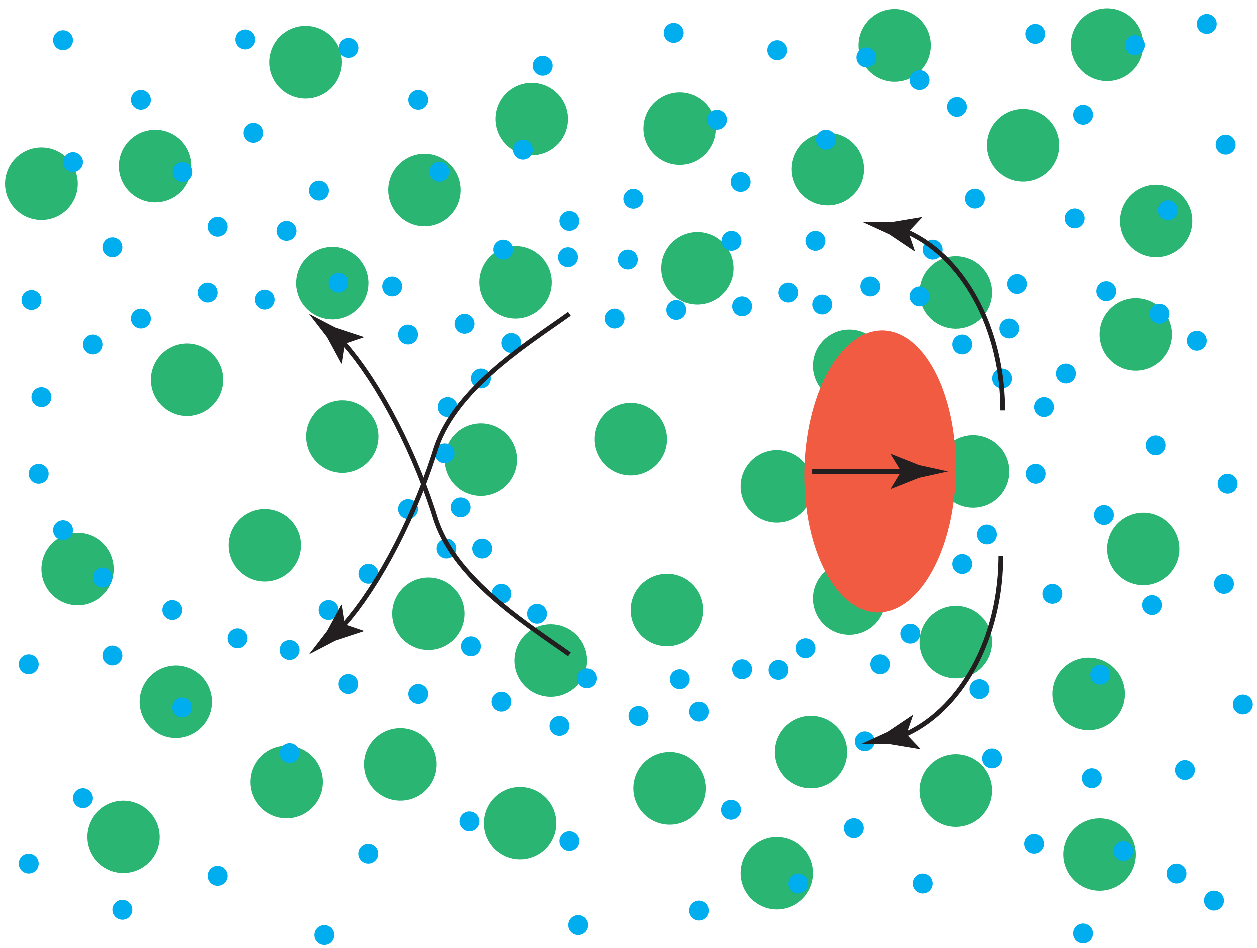
Laser wakefield accelerators

Key idea #2: create large electric fields by separating electrons and ions



Laser wakefield accelerators

Key idea #3: use an intense laser pulse to both ionise and separate charges



…are not a new idea

VOLUME 43, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 1979

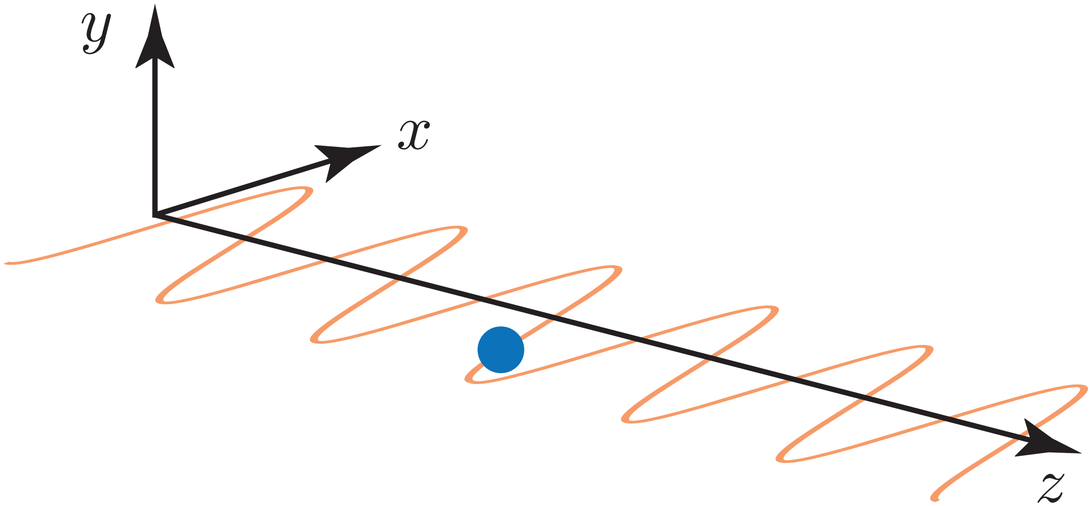
Laser Electron Accelerator

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.

Tajima *et al*, PRL, 1979

Electron motion in a plane laser field



Laser fields

$$\mathbf{E} = E_0 \sin(kz - \omega t)\hat{\mathbf{x}}$$

$$\mathbf{B} = \frac{E_0}{c} \sin(kz - \omega t)\hat{\mathbf{y}}$$

$$a_0 \equiv \frac{eE_0}{m_e c \omega}$$

Electron momentum

$$\frac{p_x}{m_e c} = a_0 \cos(\omega s)$$

$$\frac{p_z}{m_e c} = \frac{a_0^2}{2} \cos^2(\omega s)$$

Role of a_0

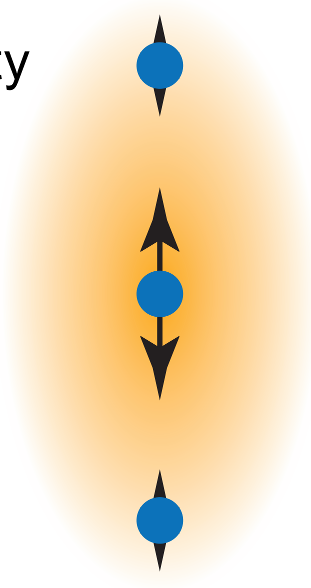
$$\frac{p_x}{m_e c} = a_0 \cos(\omega s)$$ ‘Quiver velocity’ or ‘normalised momentum’

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} \Rightarrow |\mathbf{A}| = \frac{E_0}{\omega} = \frac{m_e c a_0}{e}$$ ‘Normalised vector potential’

$$I = \frac{1}{2}\epsilon_0 c E_0^2 \qquad a_0 \approx 0.855\,\lambda[\mu\mathrm{m}]\sqrt{I[10^{18}\mathrm{Wcm}^{-2}]}$$ ‘Intensity’

If $a_0 > 1$ then $p_x > m_e c$ in a single optical cycle and the plasma electrons are always relativistic.

Ponderomotive force



Nonuniform laser intensity distribution

Large quiver velocity — a_0 large

Small quiver velocity — a_0 small

$$W_{\mathrm{kin}} = \frac{1}{2} a_0^2 m_e c^2$$

$$\mathbf{F}_p \propto \nabla a_0^2 \propto \frac{1}{m^2}$$

Pushes electrons away from regions of high laser intensity down ‘potential’ gradient

Force smaller for heavier particles, ions accelerate much less

Establishes charge separation

Wake generation (nonrelativistic)

Electron fluid momentum equation

$$m_e\left(\frac{\partial \mathbf{v}}{\partial t}+\boxed{(\mathbf{v}\cdot\nabla)\,\mathbf{v}}\right)=-e(\mathbf{E}+\boxed{\mathbf{v}\times\mathbf{B}})$$

$$\mathbf{v}\approx \mathbf{a}c \qquad \mathbf{B}=\frac{m_e c}{e}\nabla\times\mathbf{a}$$

Velocity drive term is ponderomotive force $-\frac{1}{2}m_e c^2\nabla|\mathbf{a}|^2$

To get to linear wake equation, need to add:

$$\frac{\partial n_e}{\partial t}+\nabla\cdot(n_e\mathbf{v})=0 \quad \text{(fluid continuity)}$$

$$\nabla\cdot\mathbf{E}=-\frac{e(n_e-n_i)}{\epsilon_0} \quad \text{(Gauss' law)}$$

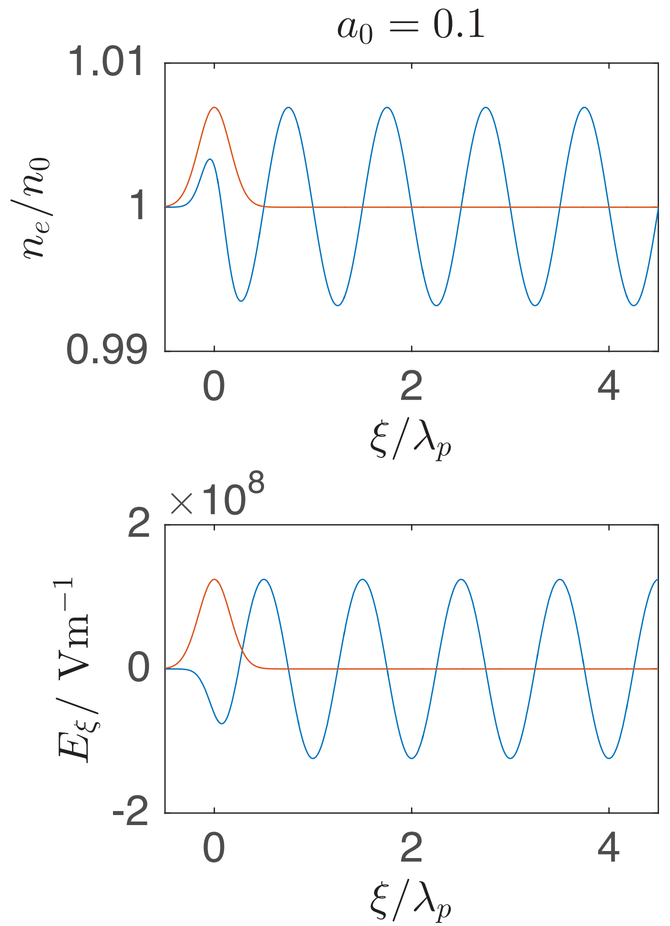
Wake generation (nonrelativistic)

Arrive at the non-relativistic equation of motion for the electron density

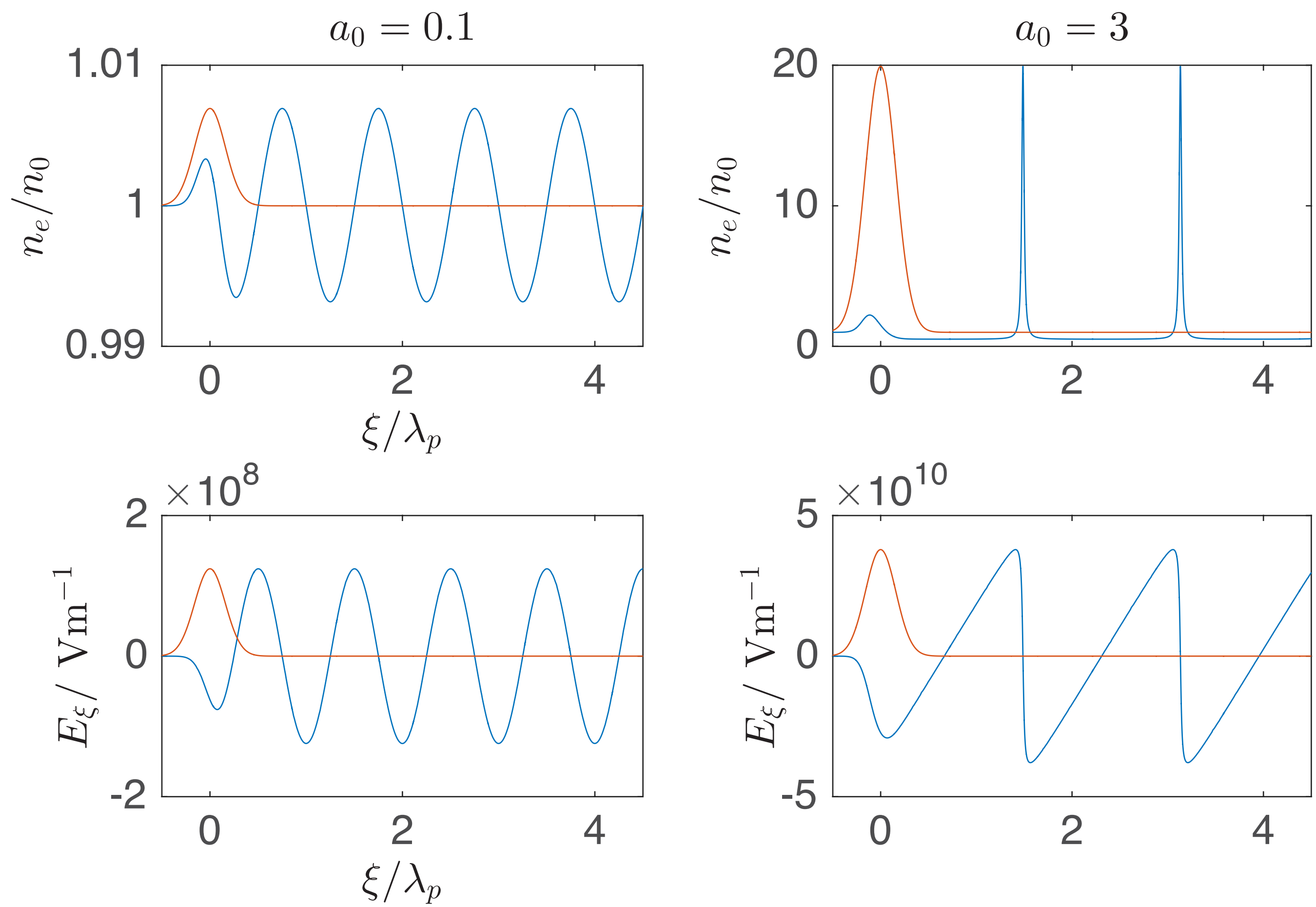
$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right) \delta n_e = \frac{1}{2} n_0 c^2 \nabla^2 |\mathbf{a}|^2$$

$$n_e = n_0 + \delta n_e \qquad \omega_p = \sqrt{\frac{n_e e^2}{m_e \epsilon_0}}$$

- Simple harmonic oscillator at ω_p
- Natural wavelength λ_p
- Driven by gradient of F_p
- Increases like a^2

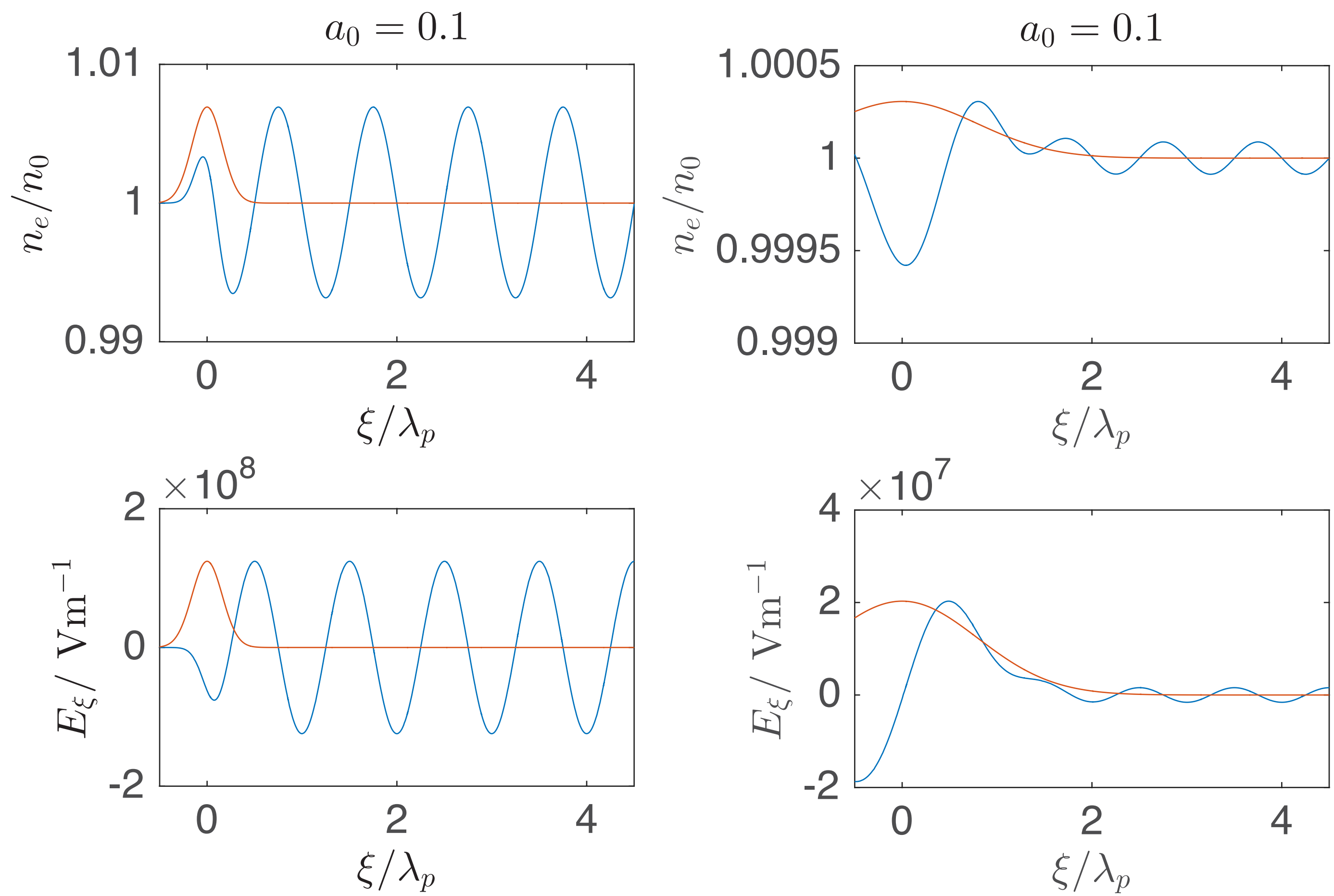


Wake amplitude increases as a_0^2



At relativistic intensities the wavelength increases, the electric field assumes a 'sawtooth' profile

Wake amplitude decreases with pulse length



When $T_L > \lambda_p$ the wake excitation efficiency drops dramatically.

Wavebreaking

As a_0 increases, the maximum electric field asymptotes towards the 'wavebreaking threshold', beyond which the plasma wave breaks.

In 1D characteristic field $E_{\mathrm{max}} = \sqrt{\frac{n_e m_e c^2}{\epsilon_0}}$

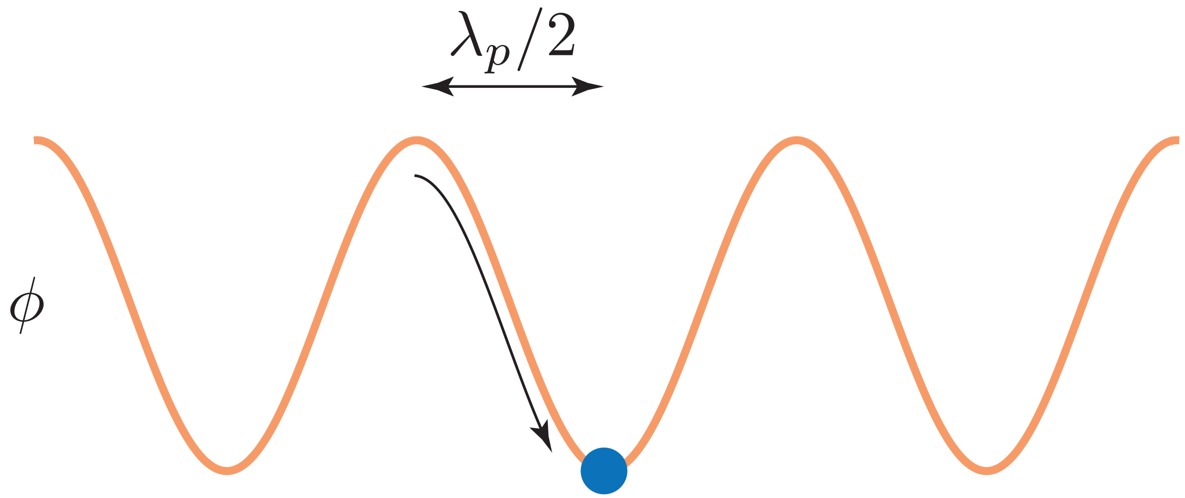
When $n_e = 10^{18}$ cm^{-3} (~0.1 atm), E_{max} = 100 GVm^{-1}

Very large, even at moderate plasma densities

Promise of shrinking linear accelerator components

Electron energy gain limit

Electrons stop accelerating when the longitudinal field switches direction



Electromagnetic dispersion relation $\omega^2 = \omega_p^2 + c^2k^2 \quad \omega \gg \omega_p$

Group velocity of laser pulse & wake $v_g = c\sqrt{1 - \omega_p^2/\omega^2}, \quad \gamma_g = \dfrac{\omega}{\omega_p}$

Electron energy gain limit

If electron much above γ_g (i.e. 5 - 20 MeV) then travelling at ~c

Enters decelerating phase after travelling $\lambda_p/2$ relative to the wake:

$$L_{\text{dephase}} = \boxed{\frac{\lambda_p}{2}} \times \boxed{\frac{1}{c - v_g}} \times \boxed{v_g}$$

millimetres – centimetres

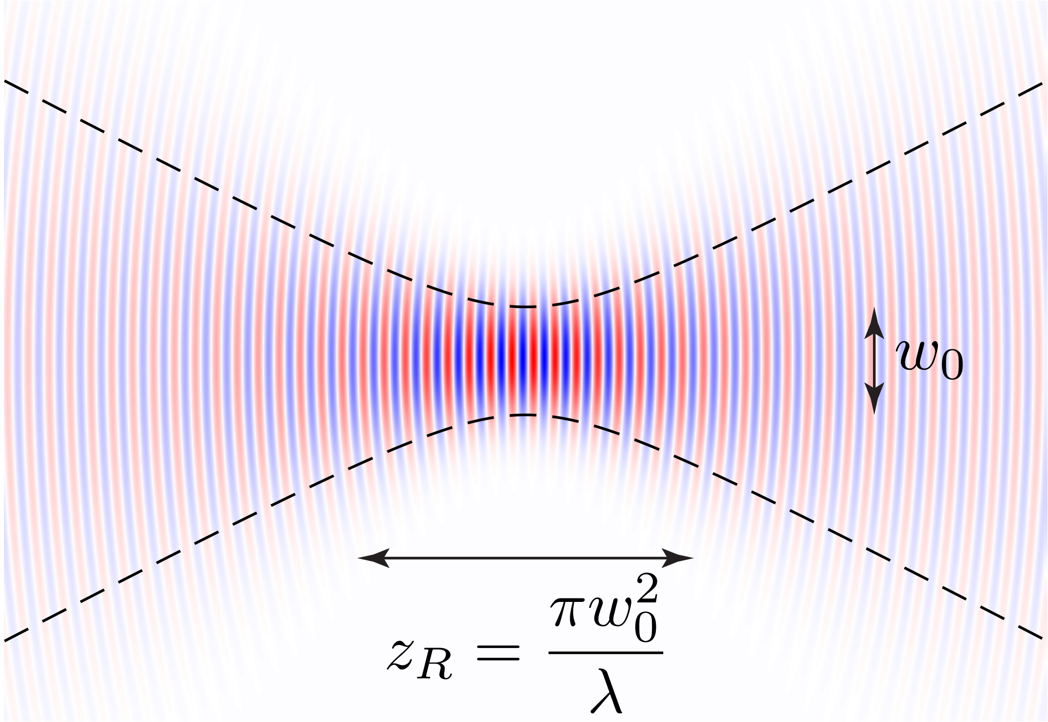
Distance relative to wake | Time taken | Distance travelled by laser

Electron energy after dephasing length $W_{\text{max}} = 2m_e c^2 \frac{\omega^2}{\omega_p^2} \propto \frac{1}{n_e}$

Larger energy gain at **lower** density
Weaker electric fields BUT wake travels **faster**

Laser pulse must propagate over $L_{dephase}$

Laser pulse stays intense over longer distance if it is focussed to a larger focal spot size

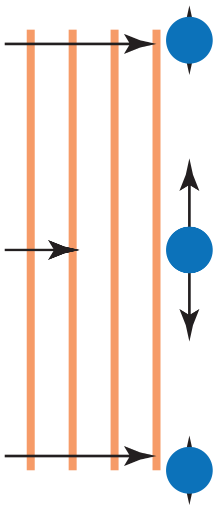


Laser pulse must propagate over $L_{dephase}$

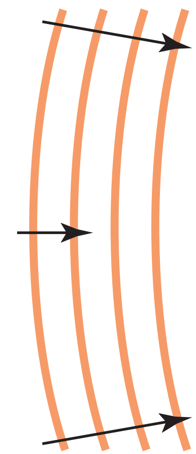
Relativistic plasma motion aids focussing of pulse

$$\omega_p \to \omega_p / \sqrt{\gamma} \qquad v_\phi = \frac{c}{\sqrt{1 - \omega_p^2/\omega^2}}$$

Phase velocity lowest in centre



Electron motion strongest in centre



Results in wavefront curvature and self - focussing

Diffraction

Laser spot size

$$\frac{\mathrm{d}^2 w}{\mathrm{d}z^2} = \frac{\lambda^2}{\pi^2 w^3}\left(1 - \frac{P}{P_c}\right)$$

$$P_c = 17.5\,\mathrm{GW} \times \frac{\omega^2}{\omega_p^2}$$

Self-focussing

Laser wakefield accelerator constraints

High electron energy → Low plasma density $\omega_p << \omega$ → Pulse needs to propagate over longer dephasing length

High electron energy → Large wake amplitude

Large wake amplitude → $a_0 > 1$

Large wake amplitude → $T_L < \lambda_p/2$

Pulse needs to propagate over longer dephasing length → z_R is large → w_0 is large

Pulse needs to propagate over longer dephasing length → $P > P_c$ → ω_p cant be too low

$a_0 > 1$ → Large pulse energy

w_0 is large → Large pulse energy

Bottom line: high power, short pulse lasers required

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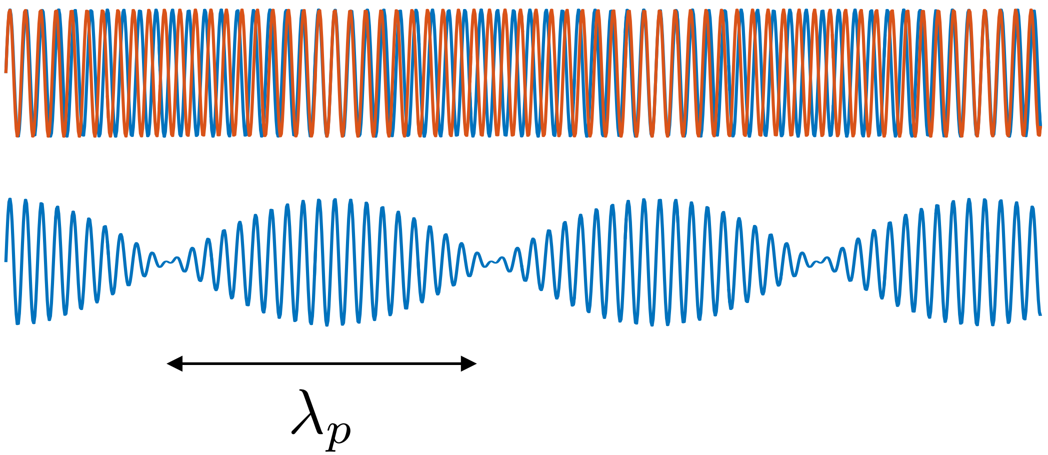
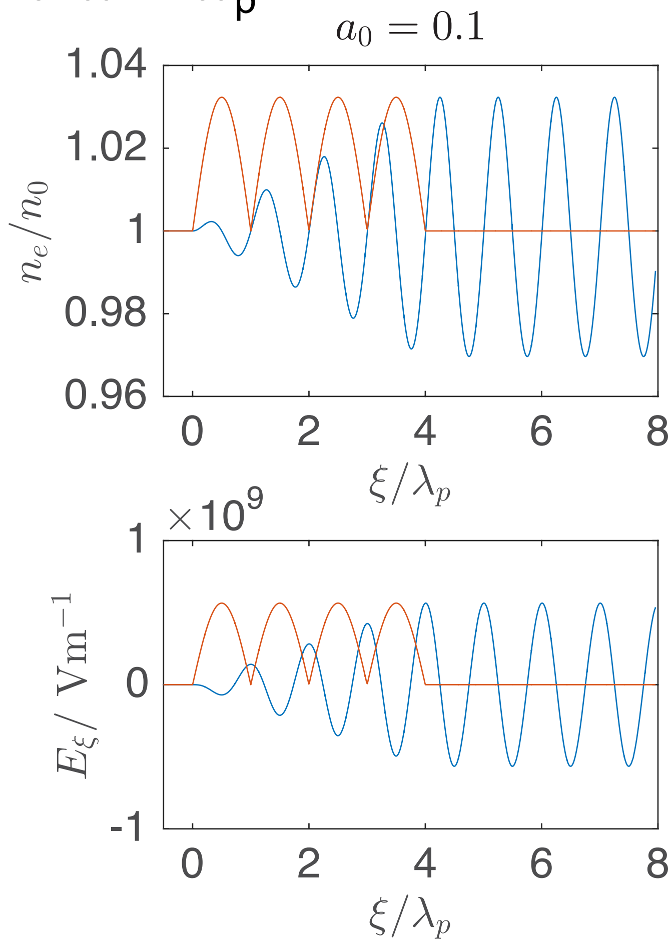
Plasma beatwave acceleration

Initially difficult to produce such short laser pulses.

Solution: interfere two long pulses at ω and ω + ω_p



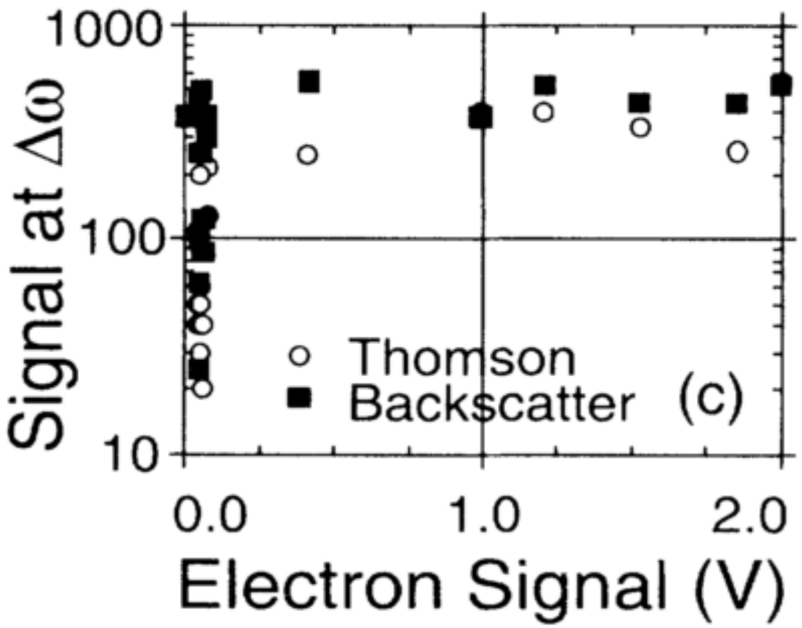


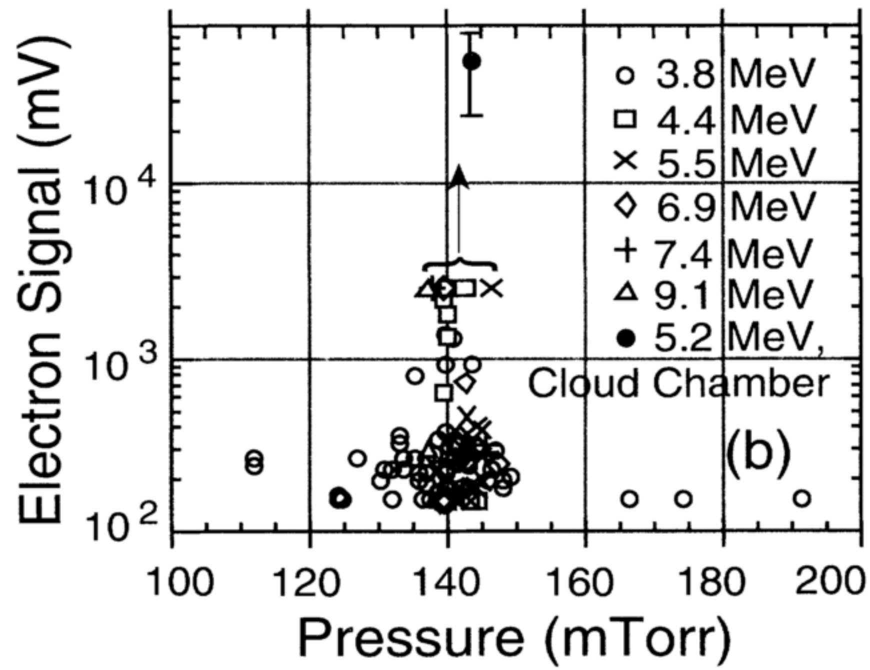
The wake amplitude grows with each passing pulse

When the wave 'breaks' plasma electrons break free from the wave and accelerate

Plasma beatwave acceleration

First experiments observed electrons up to a few MeV





C. Clayton *et al*, Physical Review Letters, 1993

Problem: as plasma wave grows in amplitude, relativistic motion changes plasma wavelength, growth saturates

Self-modulated LWFA

Solution: allow plasma to shape laser pulse naturally

Plasma electrons oscillate at ω in the laser fields, and at ω_p in the plasma fields. Natural currents at frequencies $\omega \pm \omega_p$

Generate light at $\omega \pm \omega_p$

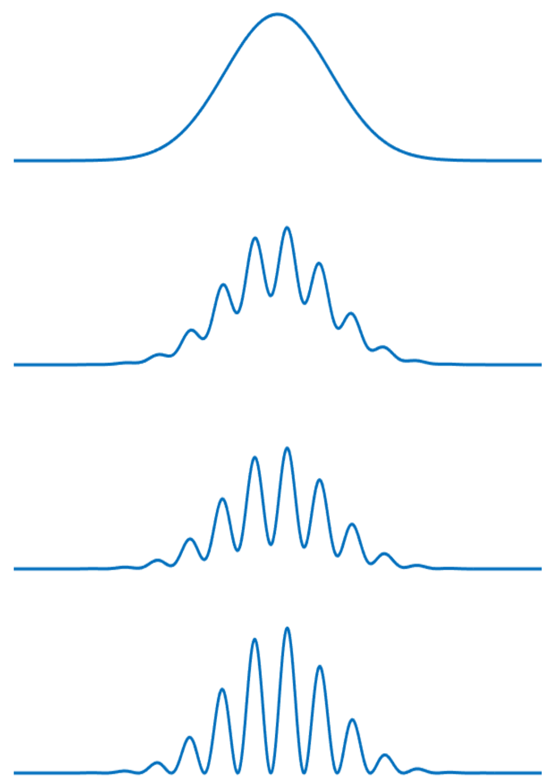
↓

Resonantly drive larger amplitude wake

↓

Density perturbations reinforce pulse modulations

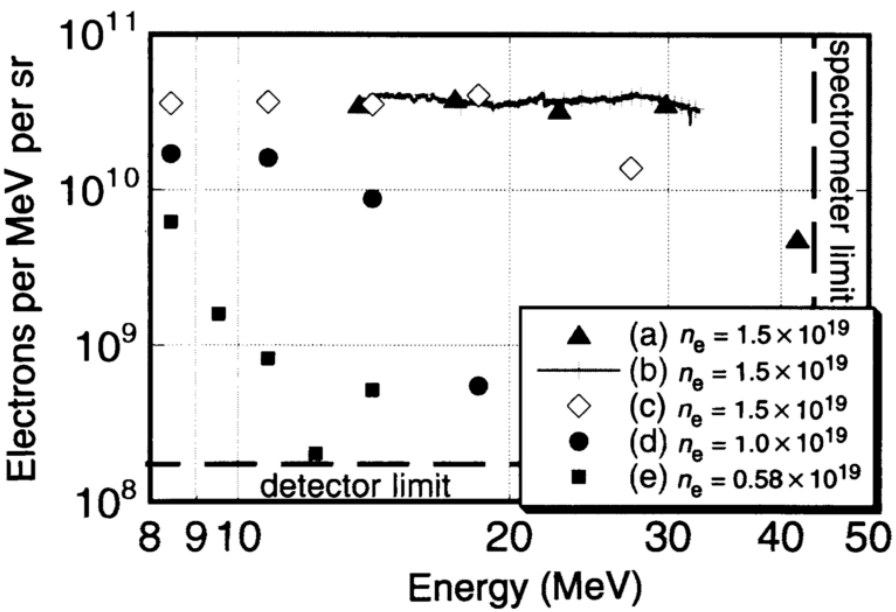
↻

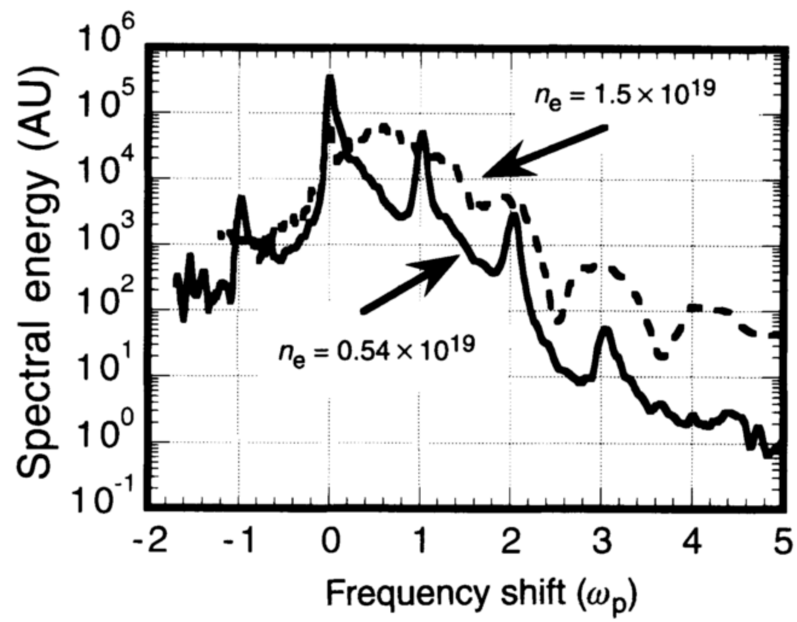


Self-modulated LWFA

Solution: allow plasma to shape laser pulse naturally

Signified by the appearance of peaks in the transmitted laser spectrum





A. Modena *et al*, Nature, 1995

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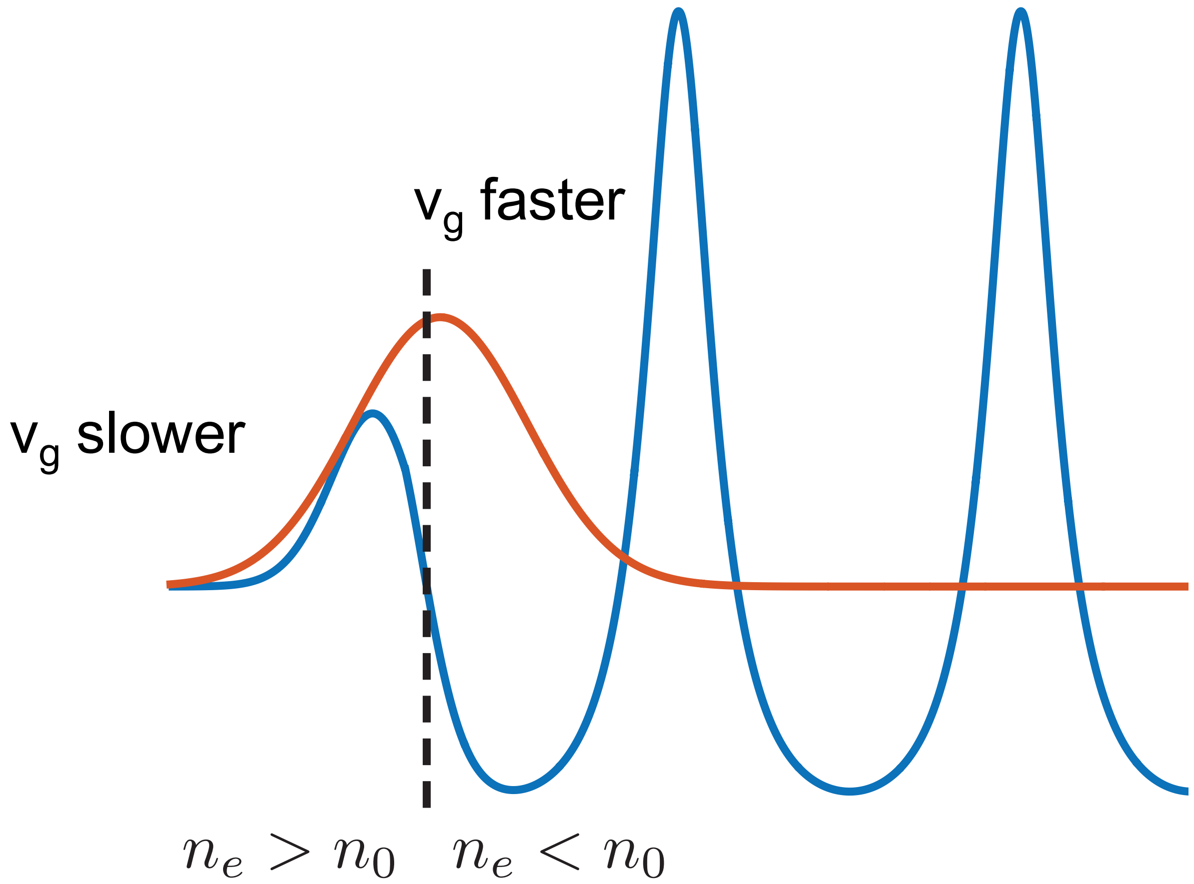
Forced LWFA

$L_{laser} = \lambda_p$. Too long for efficient plasma wave generation, too short for beatwave or self-modulation.



Natural onset of laser pulse compression.

Rear of pulse ‘catches up’ with front of pulse.

Pulse shortens, intensity rises

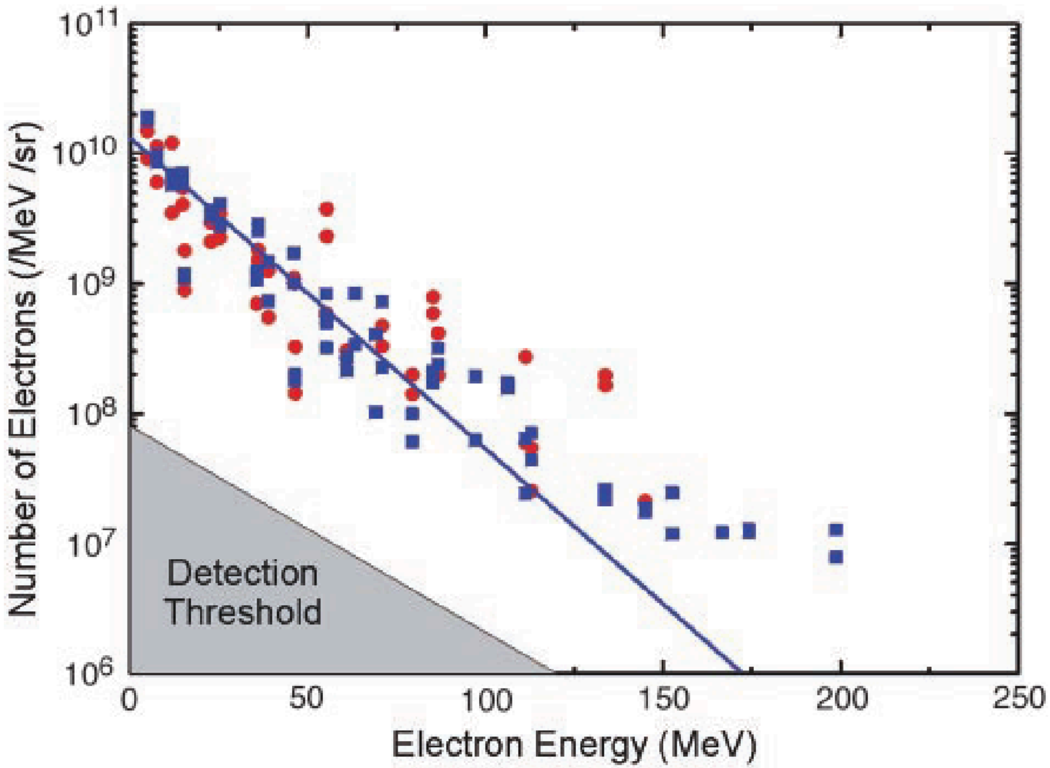
Forced LWFA

$L_{laser} = \lambda_p$. Too long for efficient plasma wave generation, too short for beatwave or self-modulation

Doesn't rely on the intrinsically unpredictable growth of instabilities over many e-folding times

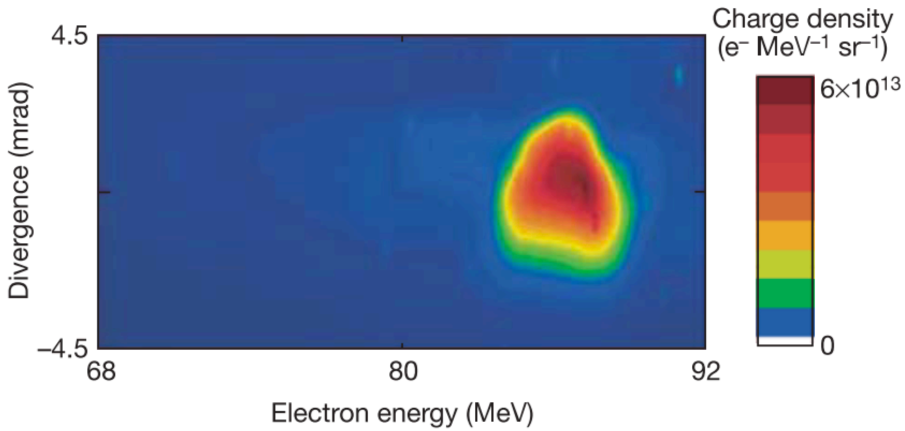
Improved repeatability

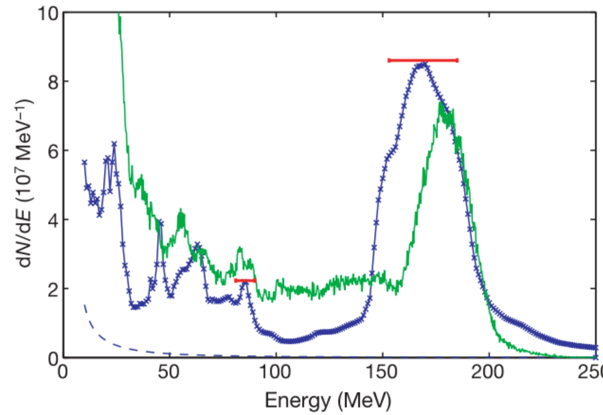
Electron spectra still quasi-thermal

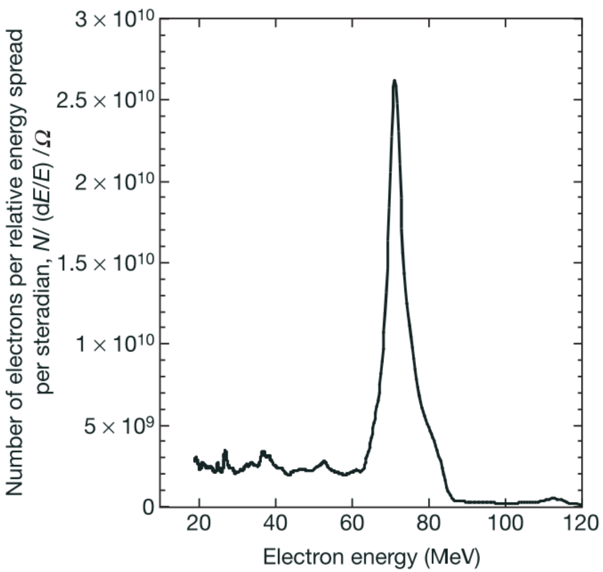


V. Malka *et al*, Science, 2002

LWFA







S.P.D. Mangles *et al*, Nature, 2004
C.G.R. Geddes *et al*, Nature, 2004
J. Faure *et al*, Nature, 2004

3 landmark papers in 2004

Demonstrated that non-thermal electron spectra were achievable

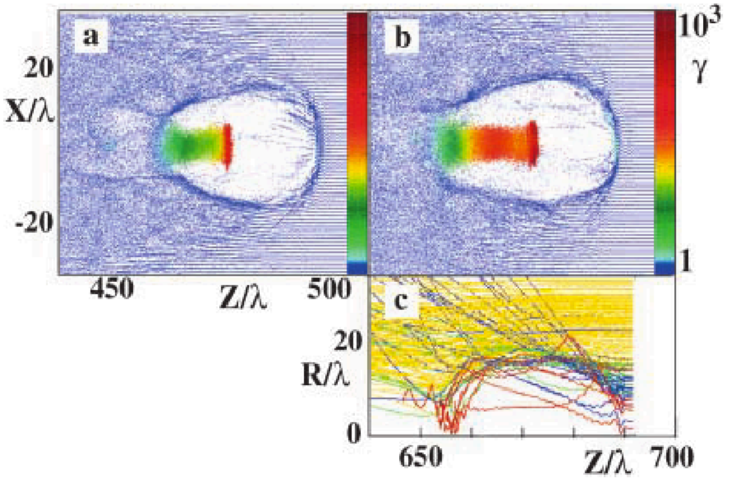
How? Bubble regime

Earlier results based on the gradual growth of periodic plasma waves

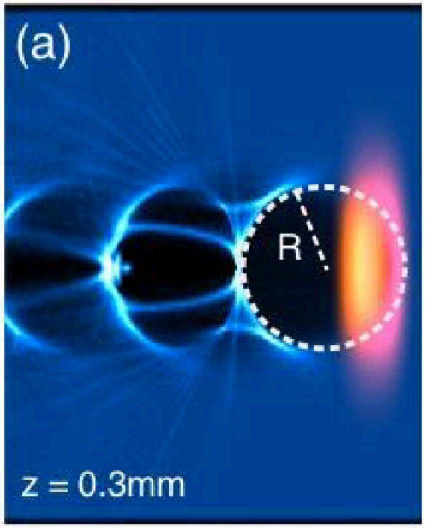
At high enough intensities ($a_0 > 3$, $P > 3P_c$) the wake is destroyed, simulated in 2002

Only a single spherical ion cavity ('bubble') follows the laser pulse

Electrons injected at the rear of the bubble, all feel the same electric field

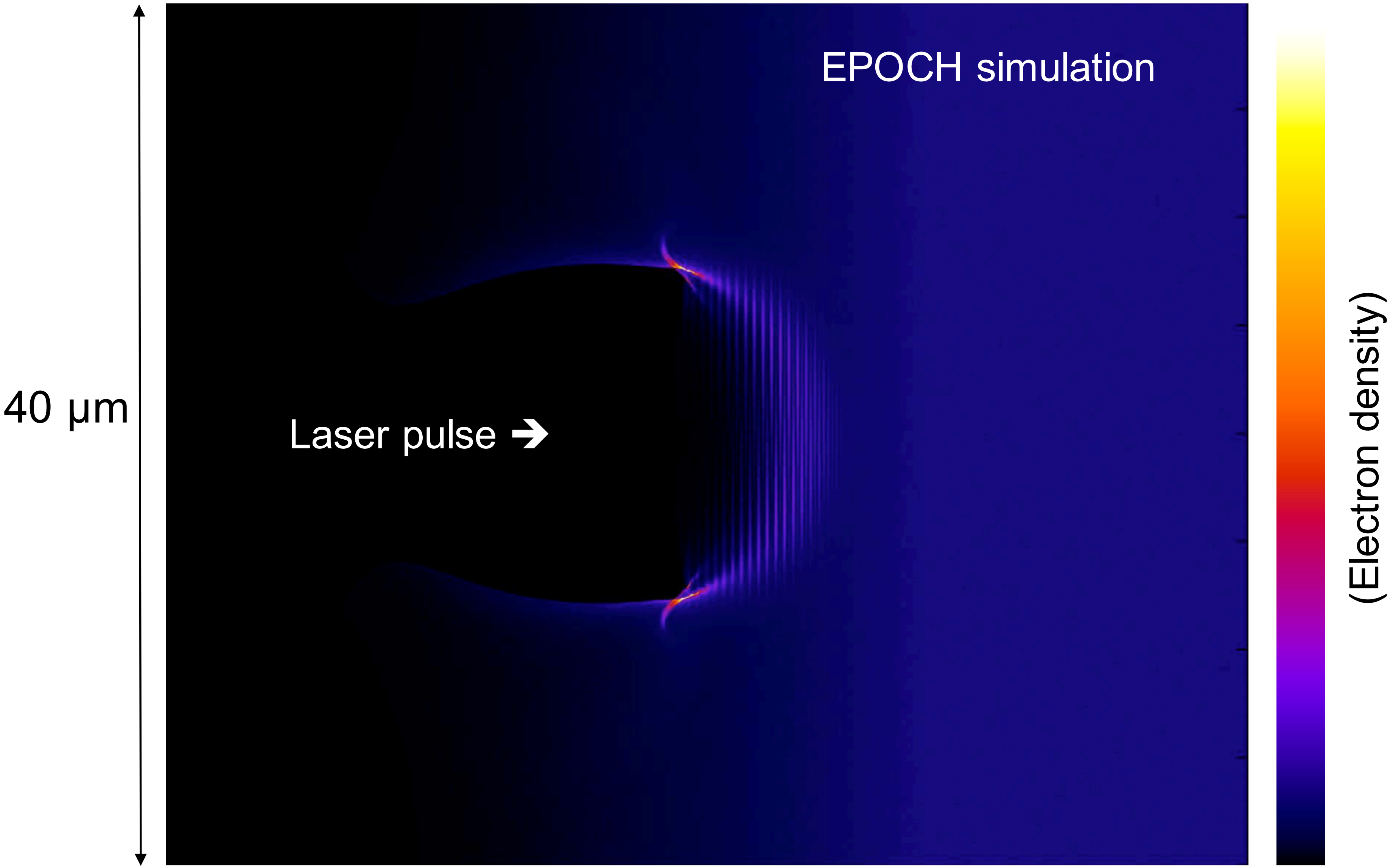


A. Pukhov *et al*, Applied Physics B, 2002

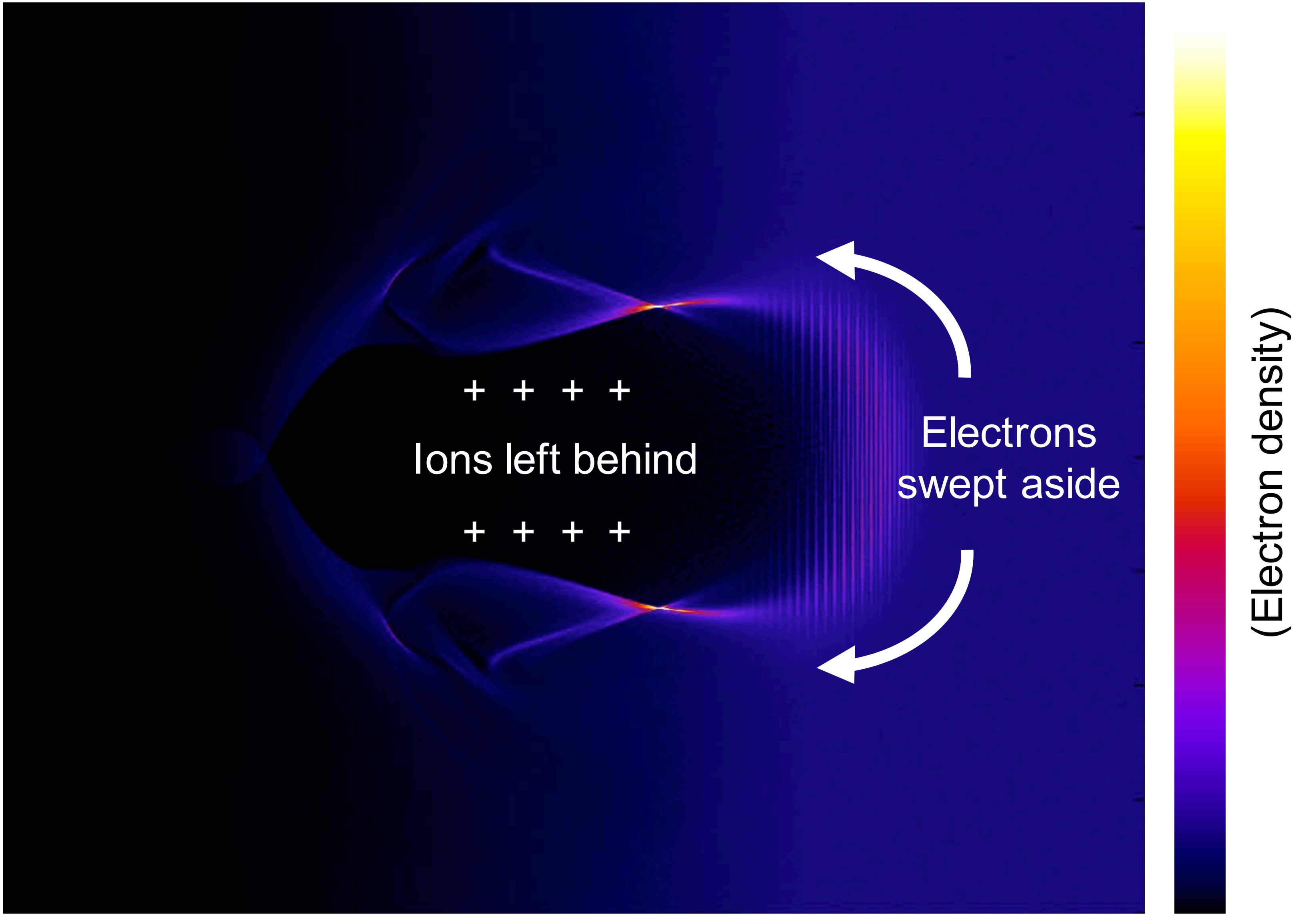


W. Lu *et al*, PRSTAB, 2007

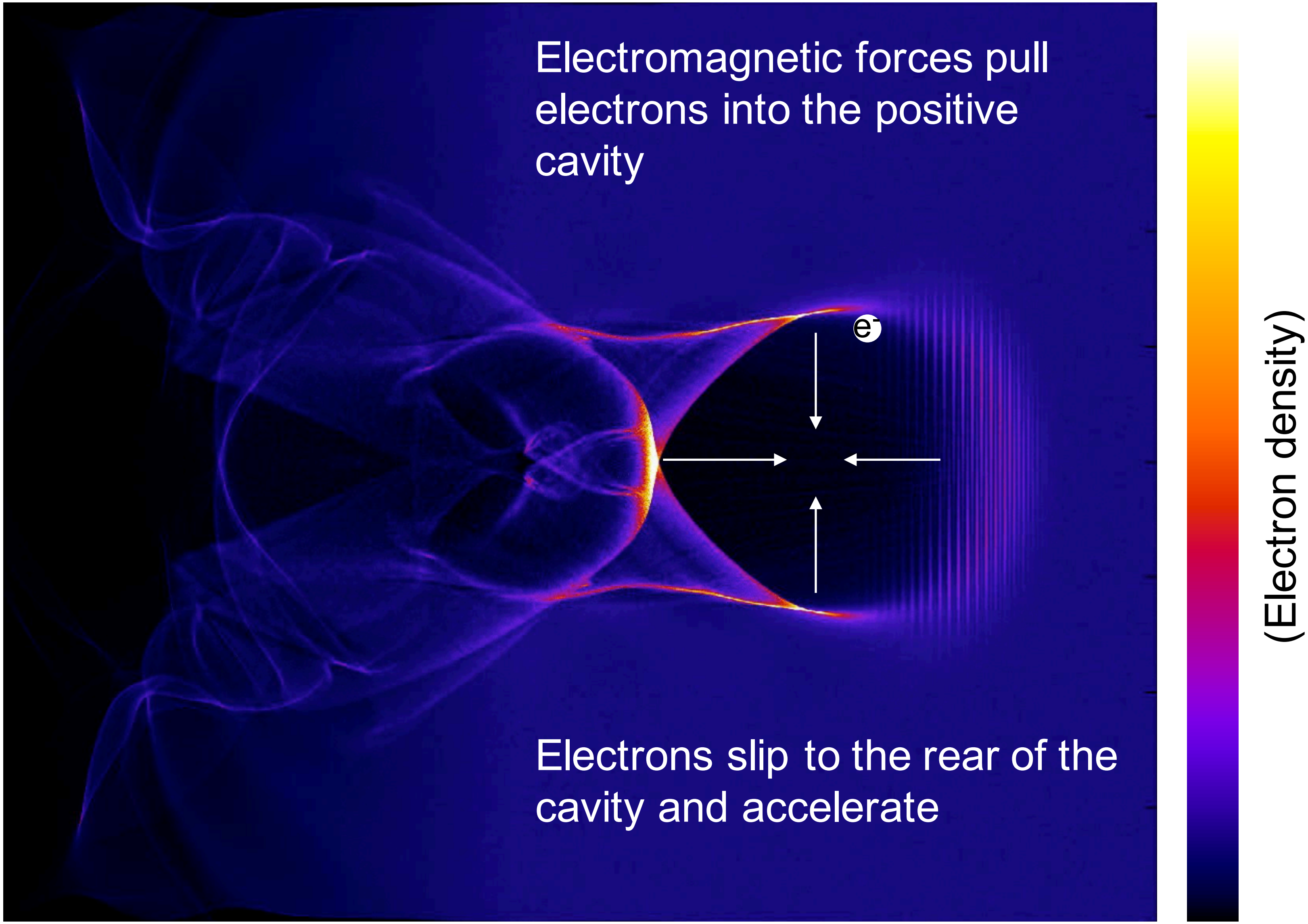
Self-injection instead of wave-breaking



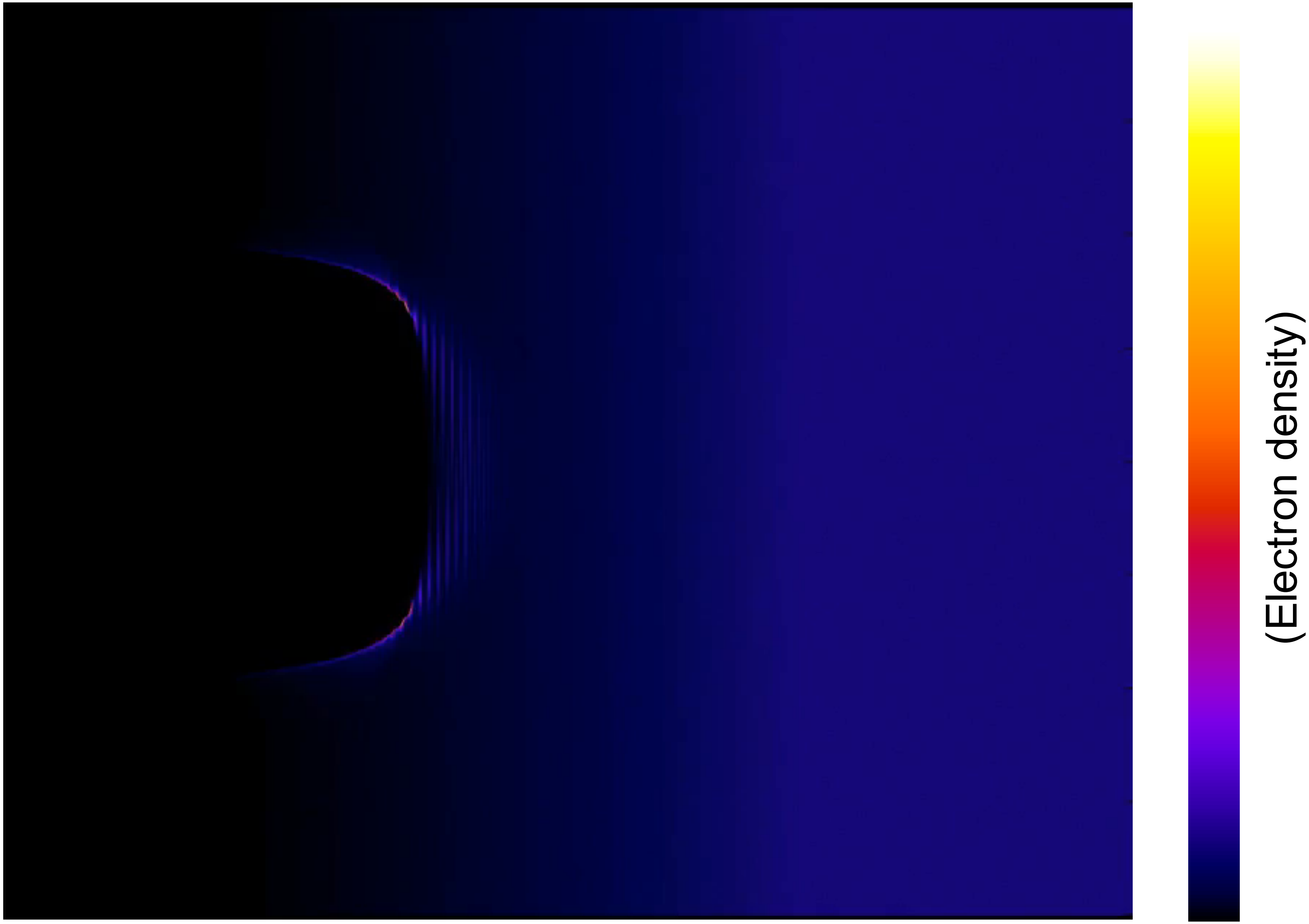
Self-injection instead of wave-breaking



Self-injection instead of wave-breaking



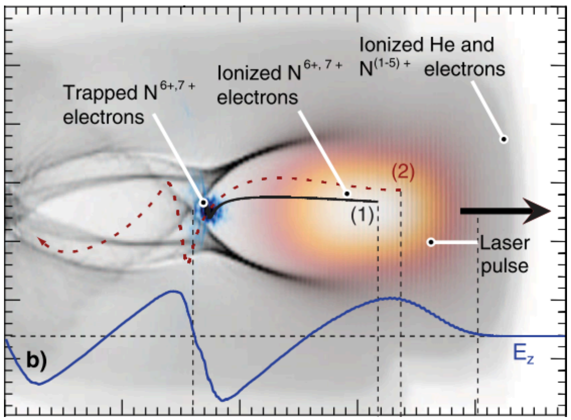
Self-injection instead of wave-breaking



Other injection options

Self-injection relies on laser pulse evolution (self-focussing and self-compression), so is intrinsically variable.

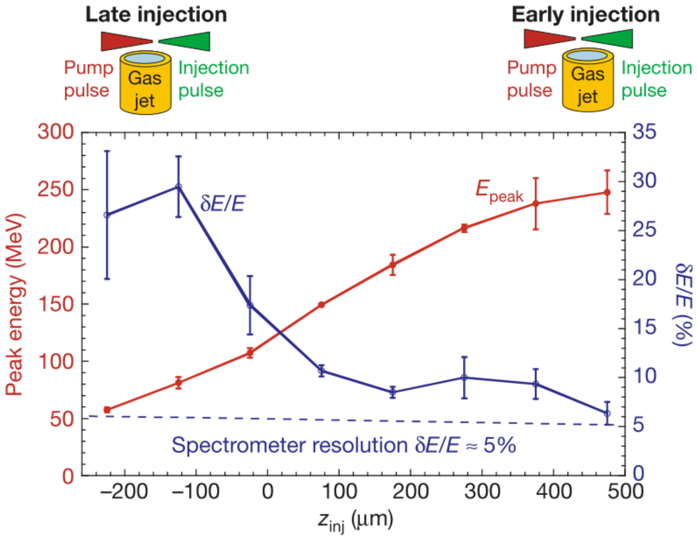
Ionisation



Inject electrons from dopant gases. Higher charge, easier to inject, larger energy spread

A. Pak *et al*, PRL, 2010

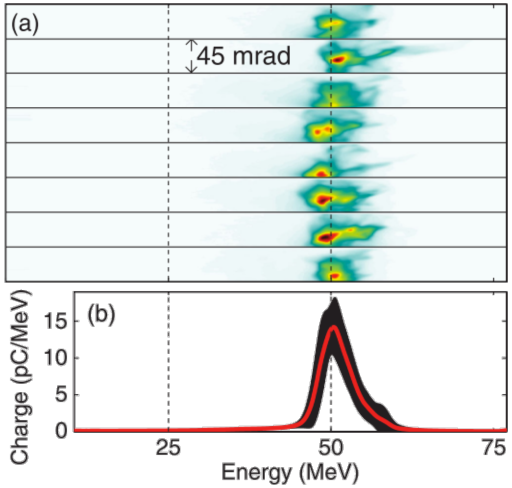
Colliding pulse



Secondary pulse stimulates injection. Tunable, difficult to overlap focal spots

J. Faure *et al*, Nature, 2006

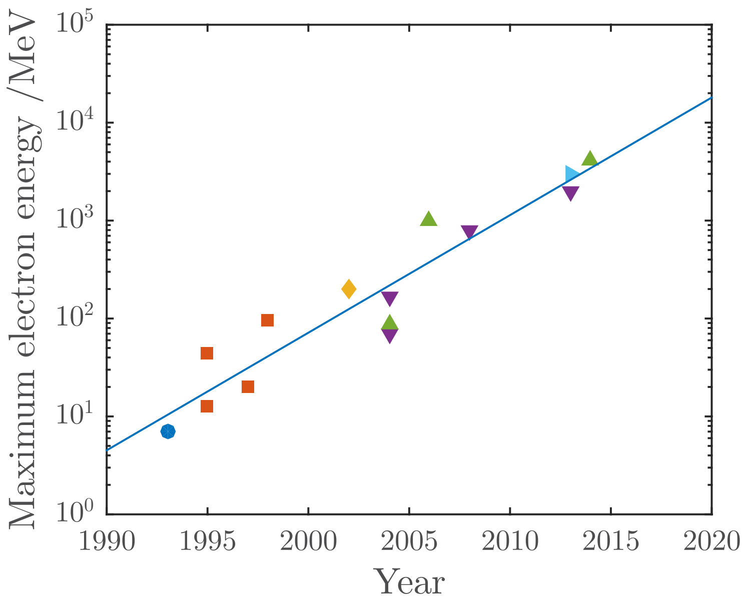
Shock

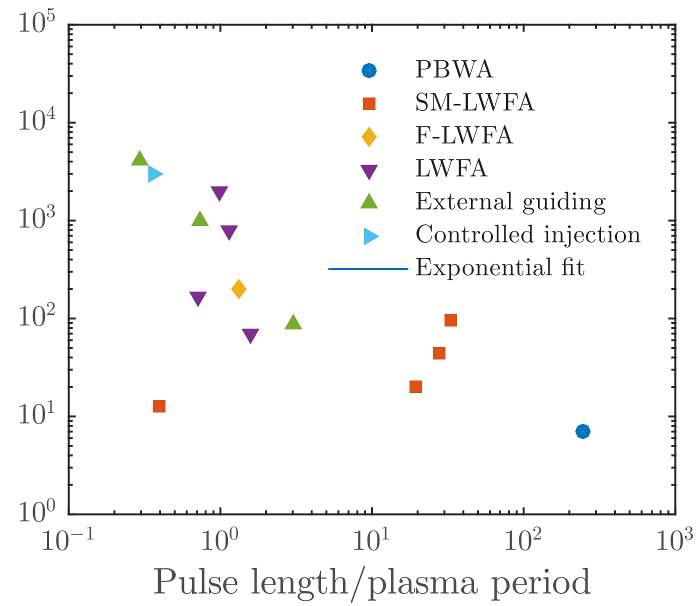


Create shock in plasma, localises injection. Good stability, narrower energy spread

A. Buck *et al*, PRL, 2013

Historical progress

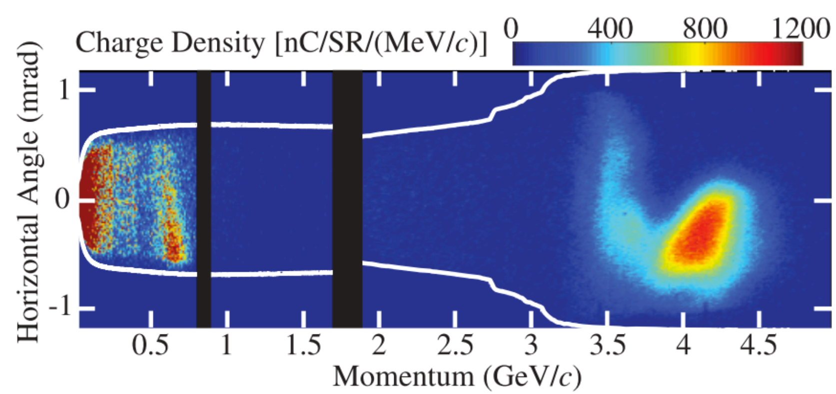




Increase in electron energies since 1990s has been rapid

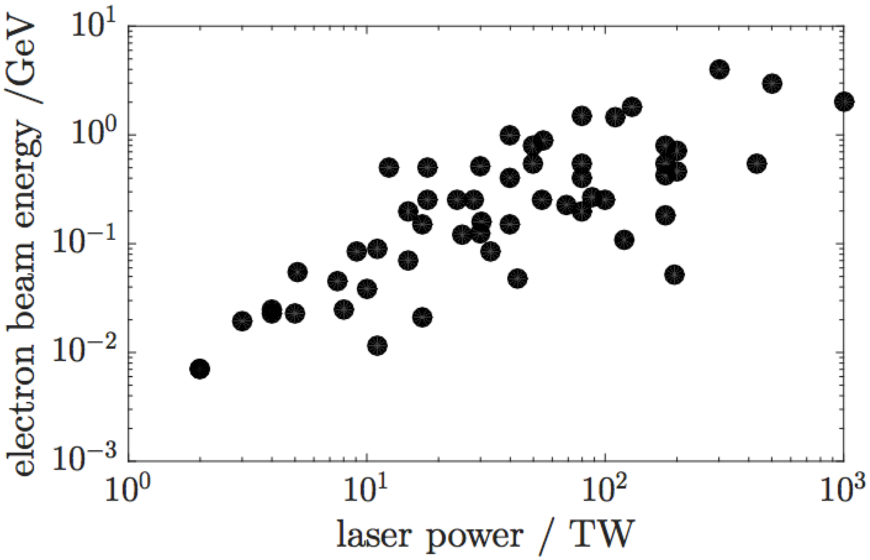
Driven by shortening laser pulses and higher laser powers

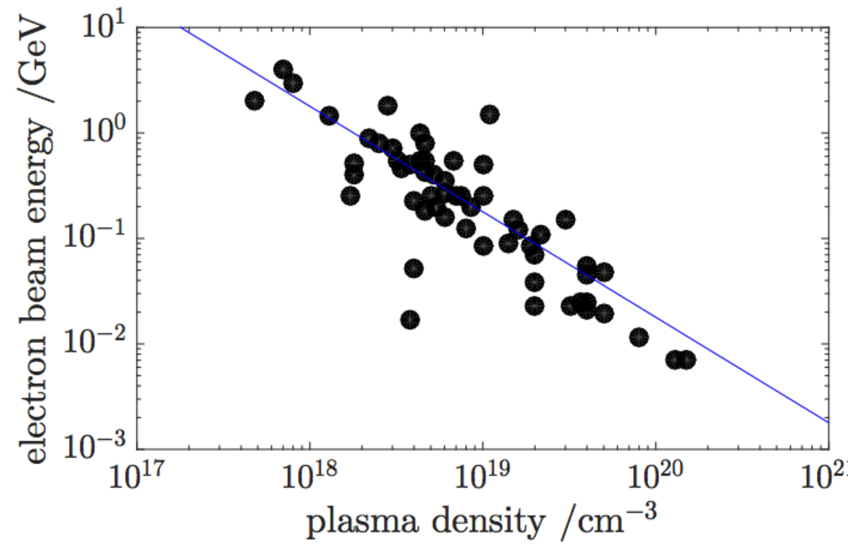
Current energy record 4.2 GeV



W. Leemans *et al*, PRL, 2014

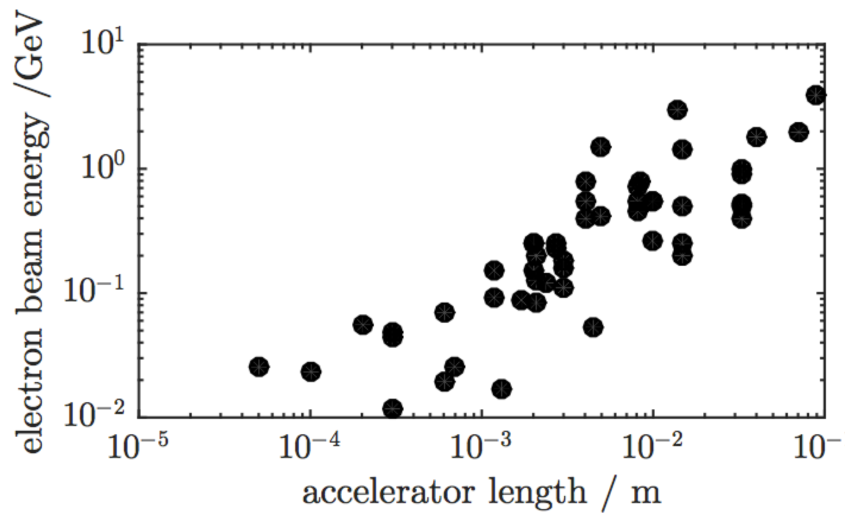
Historical progress





Electron energies are observed to increase experimentally with

- Higher laser power
- Lower plasma density
- Longer plasma lengths



S.P.D. Mangles, Proceedings of the CERN Accelerator School, 2014

Example: Astra-Gemini laser

Laser area

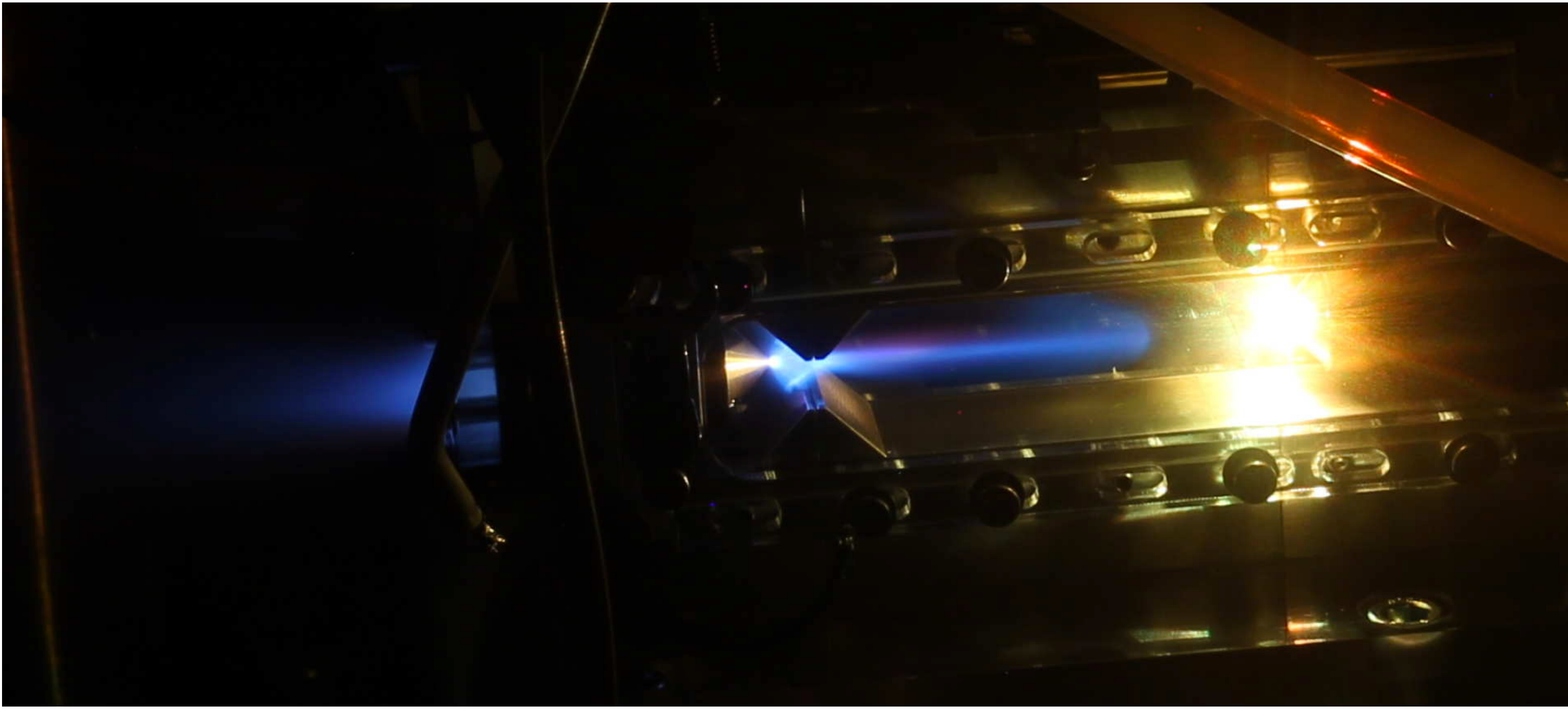
Amplification medium	Ti:Saph
Pulse wavelength	800 nm
Pulse energy	15 J
Pulse duration	40 fs
Pulse power	300 TW
Repetition rate	0.05 Hz

Target area

Run by UK Central Laser Facility

Access in 5-6 week experimental slots

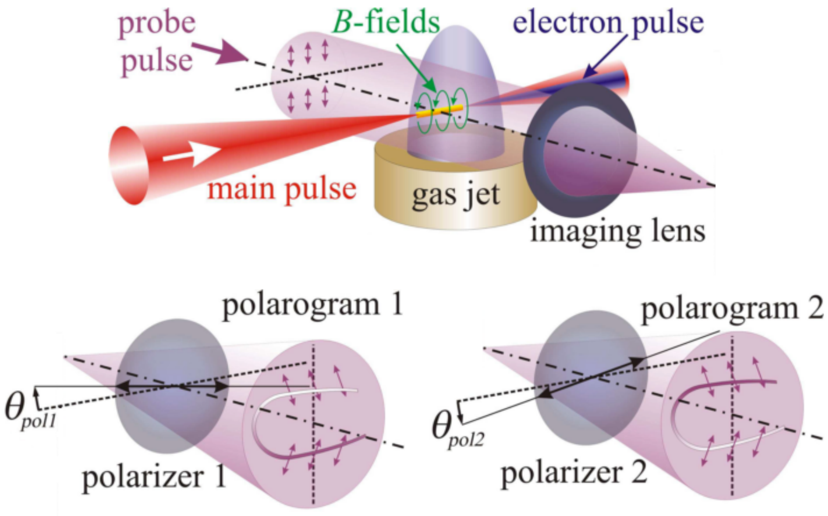
Plasma target: Helium gas cell



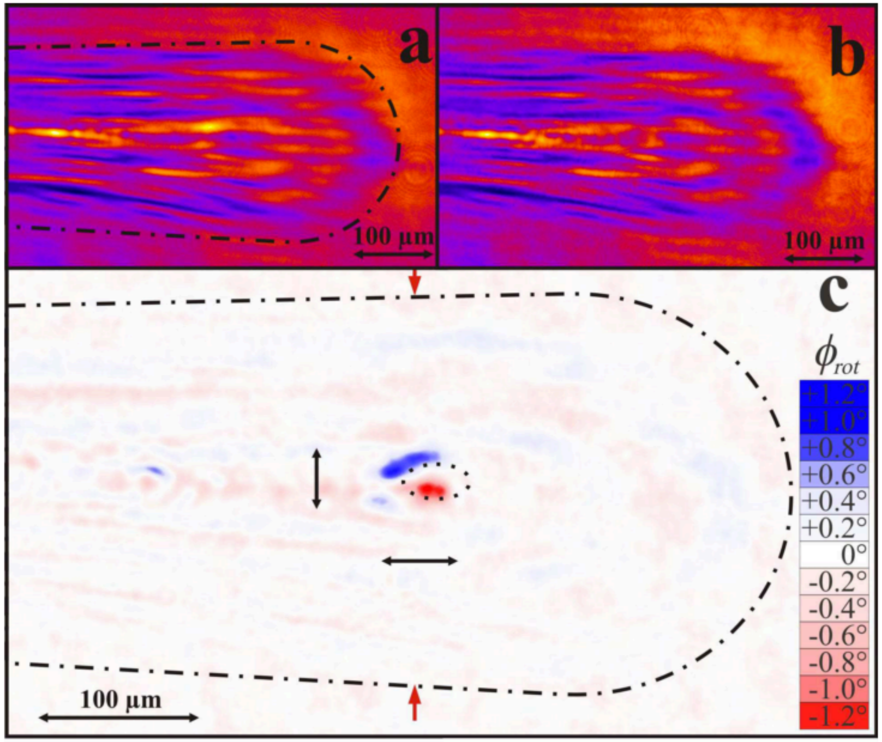
Blue glow is the plasma recombination light

Bright flash is due to a tiny reflection of laser light

Probing the wake - polarography



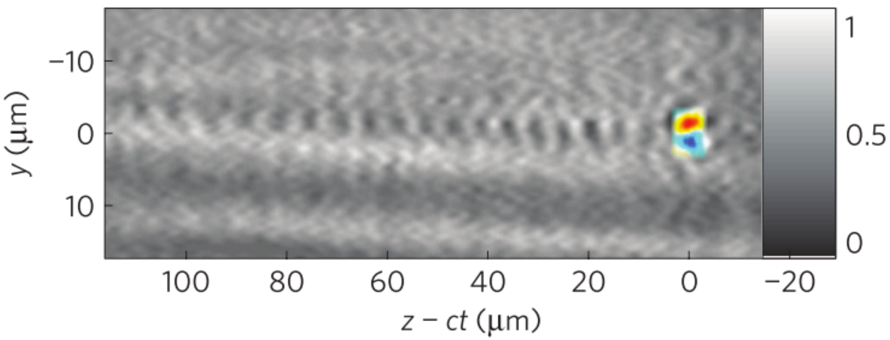
M.C. Kaluza *et al*, PRL, 2010



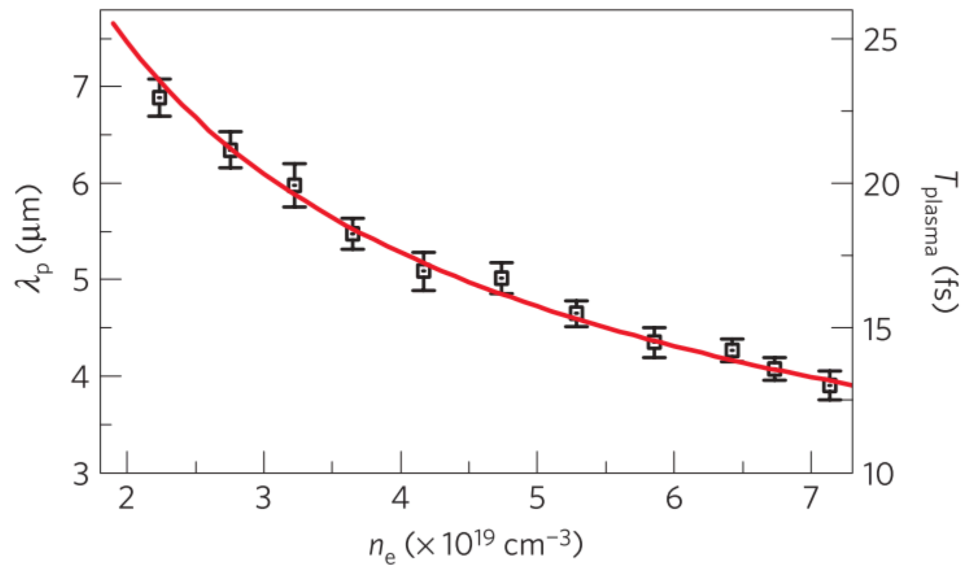
Use transversely-propagating short probe pulse.

Use Faraday rotation to infer magnetic field, and therefore presence of electron beam – high charge (pC - nC), short duration (fs)

Probing the wake – polarography + shadowgraphy



A. Buck *et al*, Nature Physics, 2011



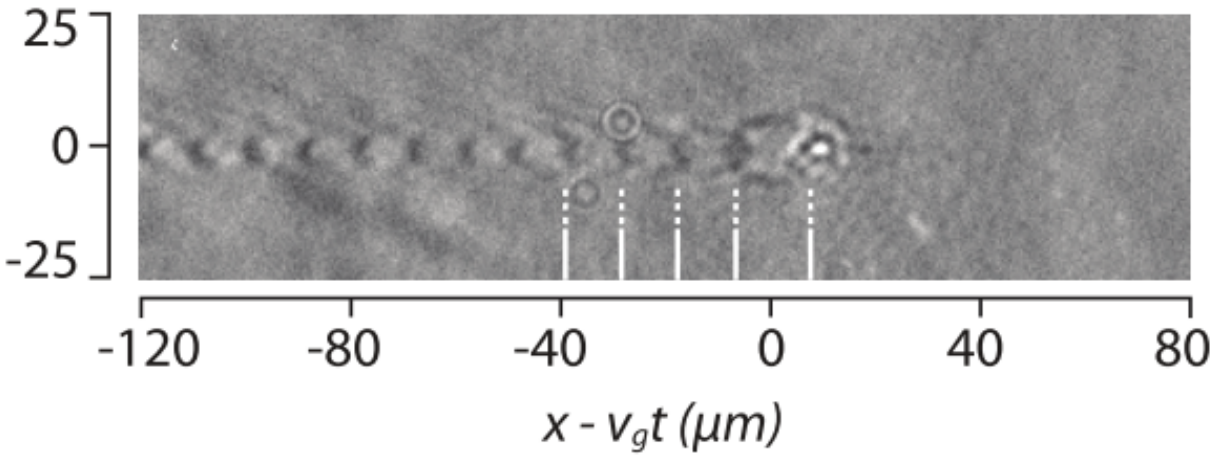
Diffraction of probe light generates caustics – shadowgrams

With short enough probe (< 7 fs) directly image the periodicity of wake

Compare plasma wavelength to theory

Imperial College London
JAI John Adams Institute for Accelerator Science

Probing the wake – shadowgraphy

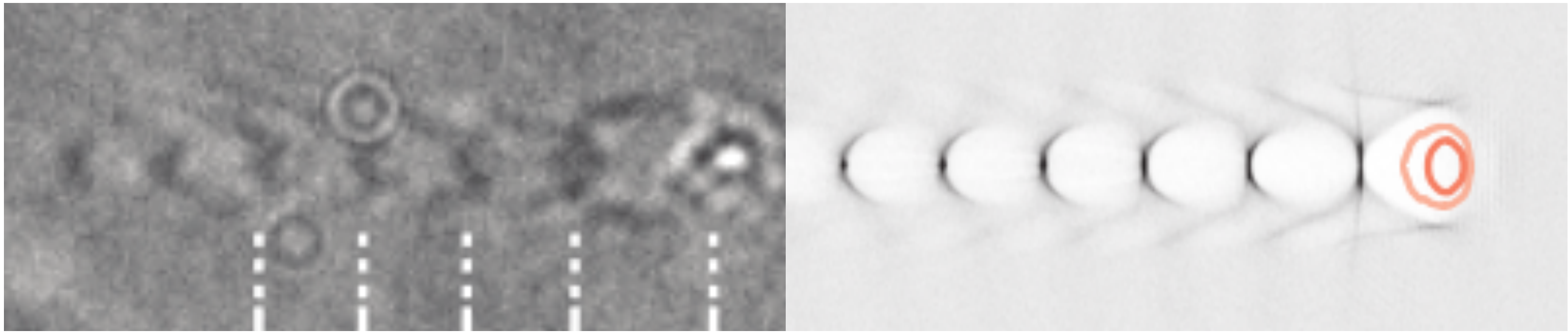


A. Savert *et al*, PRL, 2015

When probe is extremely short (< 5 fs), can directly observe longitudinal and transverse structure of the wake

Diagnose wake dynamics, investigate electron injection

Probing the wake – shadowgraphy

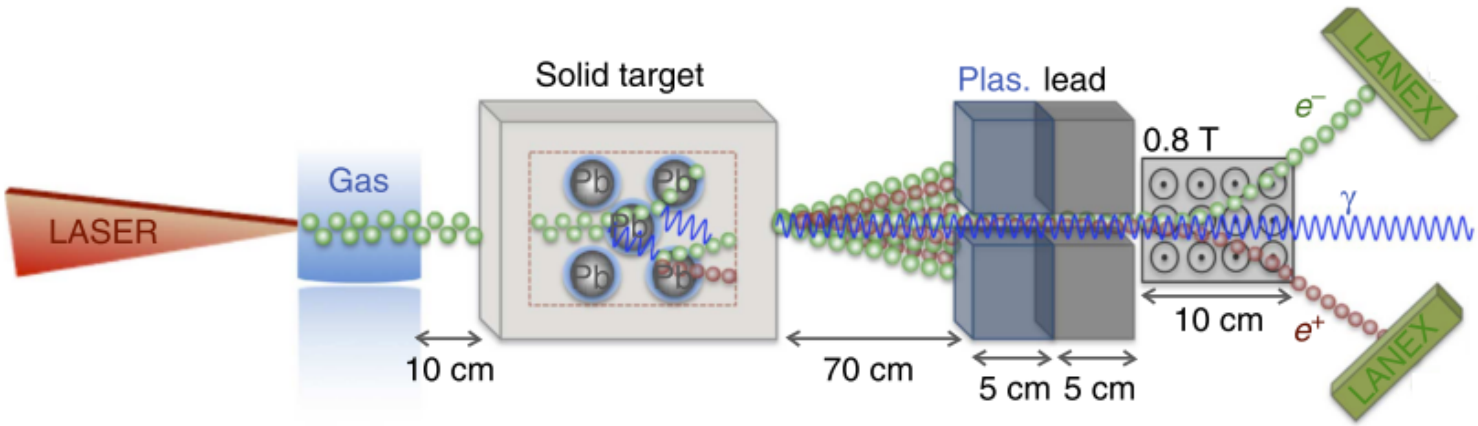


A. Savert *et al*, PRL, 2015

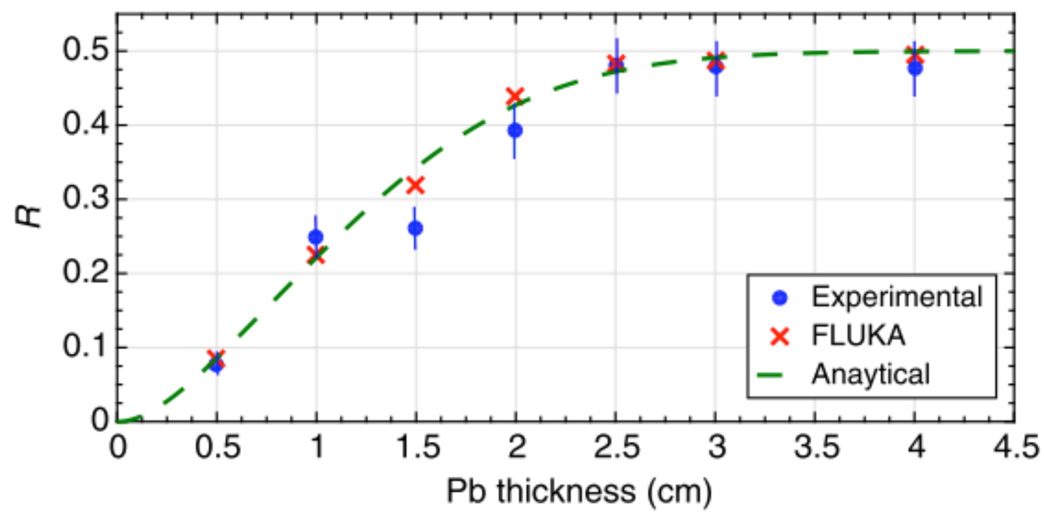
When probe is extremely short (< 5 fs), can directly observe longitudinal and transverse structure of the wake

Diagnose wake dynamics, investigate electron injection

Applications - Dense neutral electron-positron plasmas



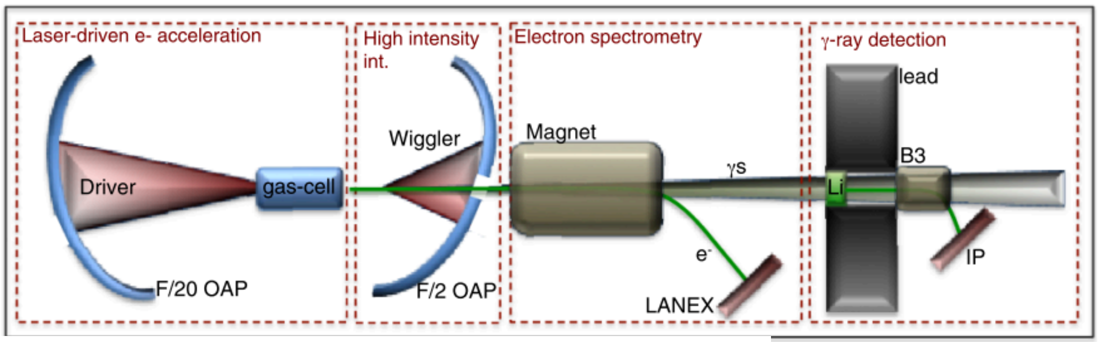
Take advantage of short, dense LWFA electron bunch to create positrons in lead target



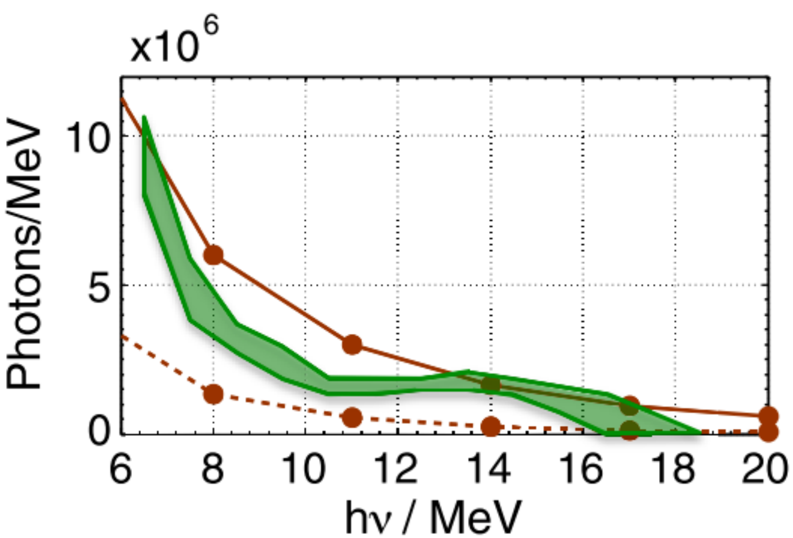
G. Sarri *et al*, Nature Communications, 2015

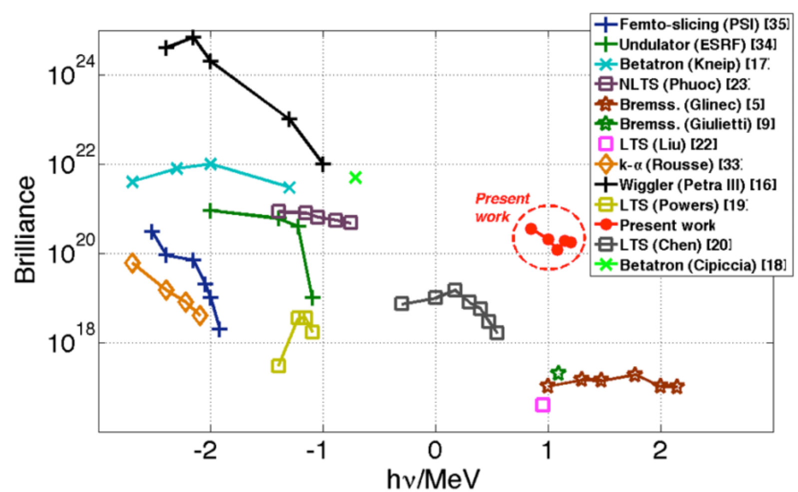
Applications - High brilliance γ-ray beams

Interact the LWFA electron bunch with a second laser pulse.
Take advantage of the intrinsic femtosecond synchronisation between bunch and laser



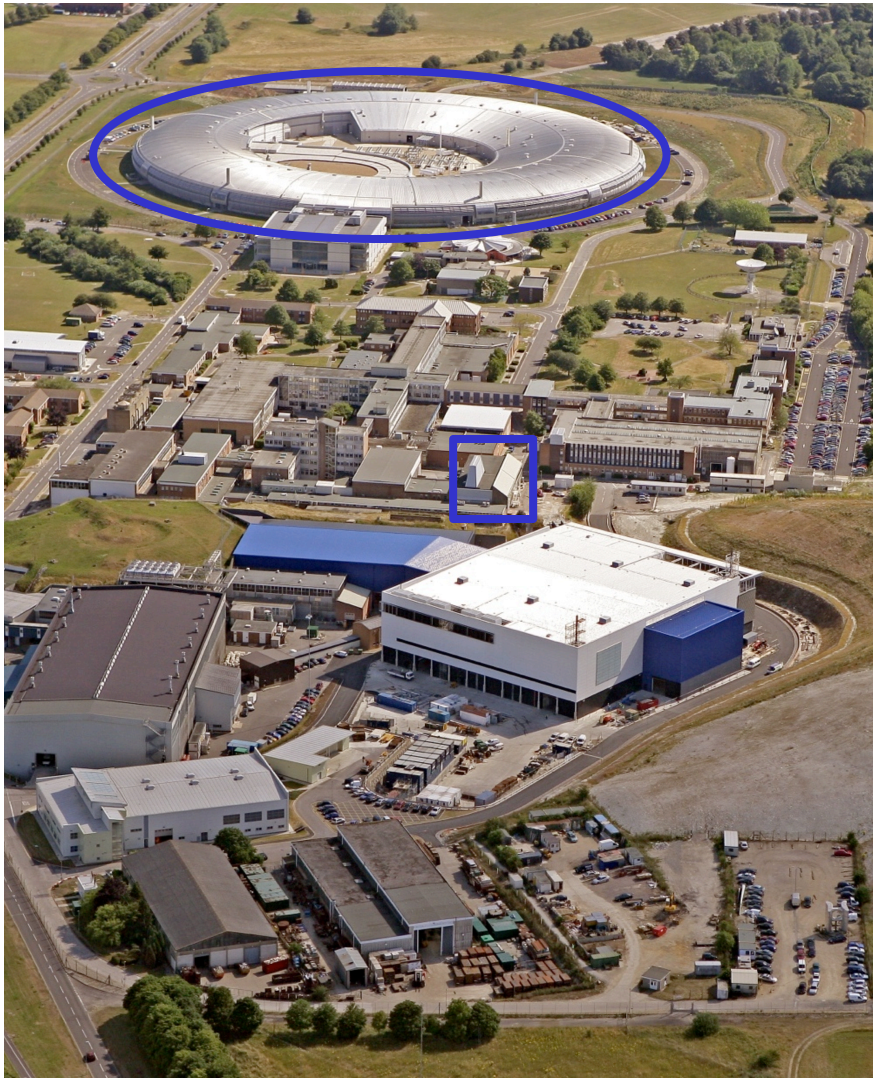
G. Sarri *et al*, PRL, 2014





Applications – Laser-driven x-ray sources

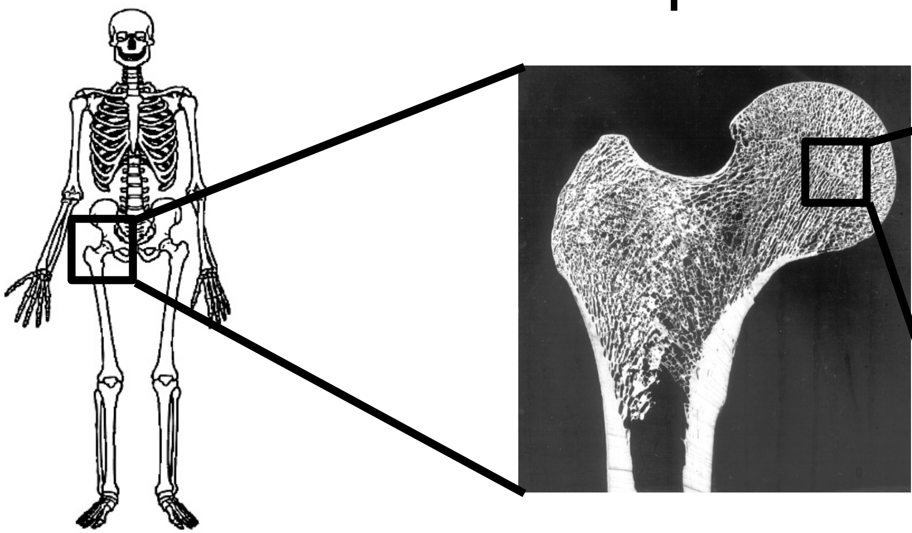
Rutherford Appleton Laboratory

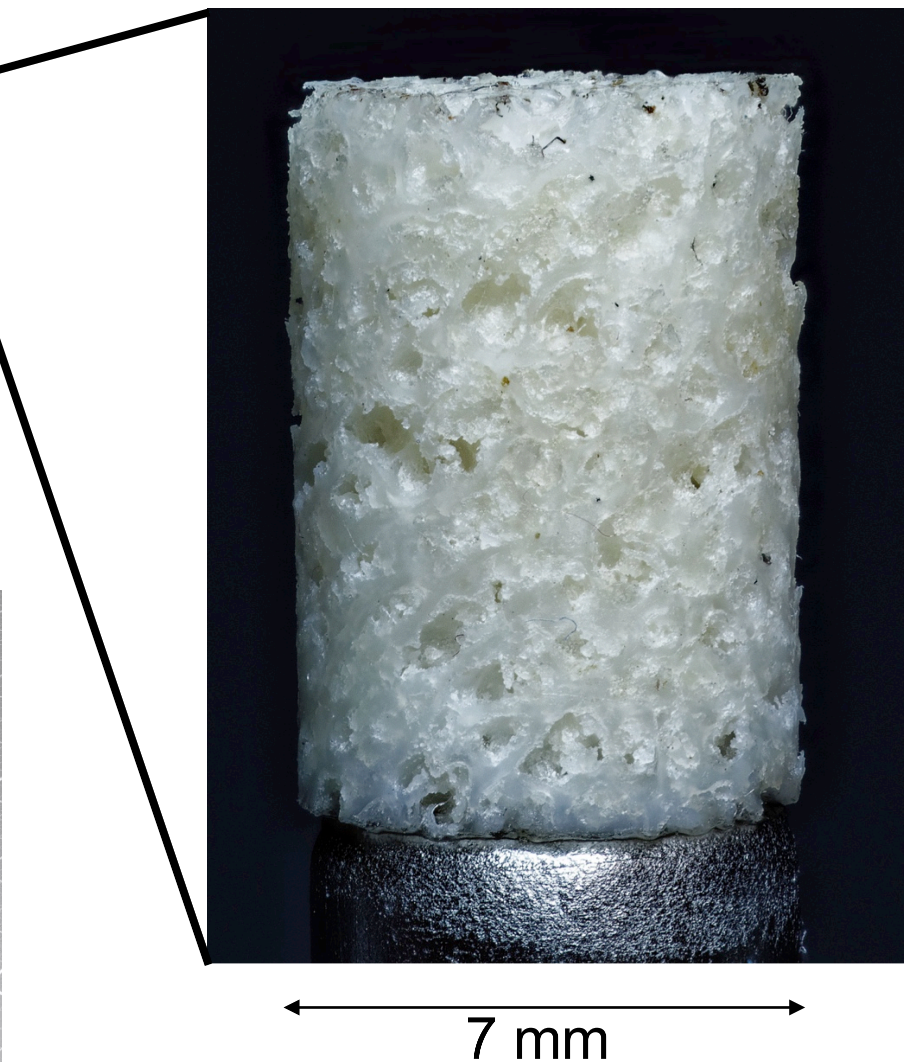


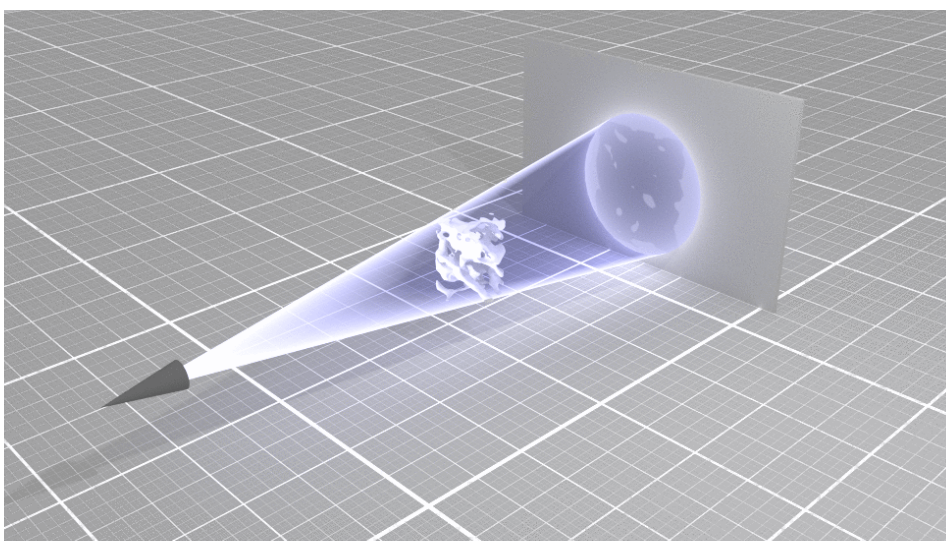
Diamond light source
£300 million
3 GeV
4 football pitches

Astra-Gemini laser
£5 million
2 GeV
1 squash court

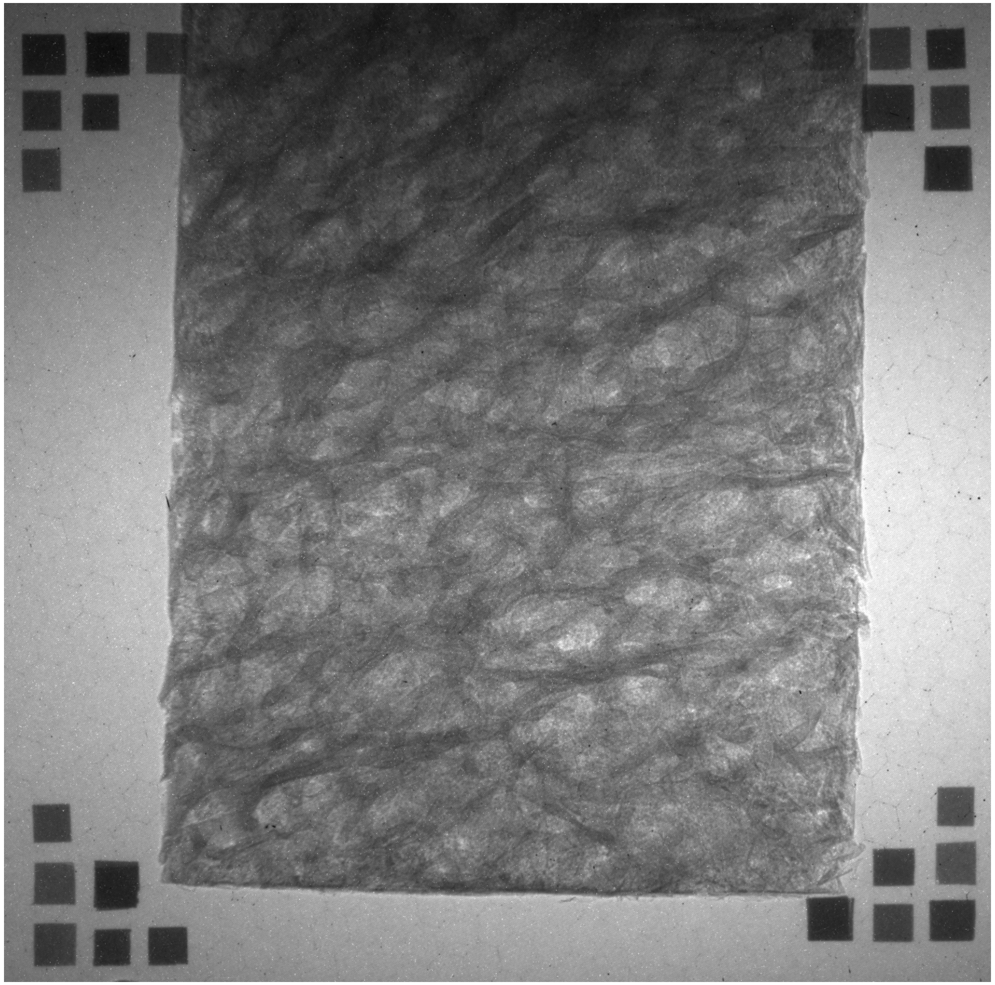
Micro-computed tomography of bone





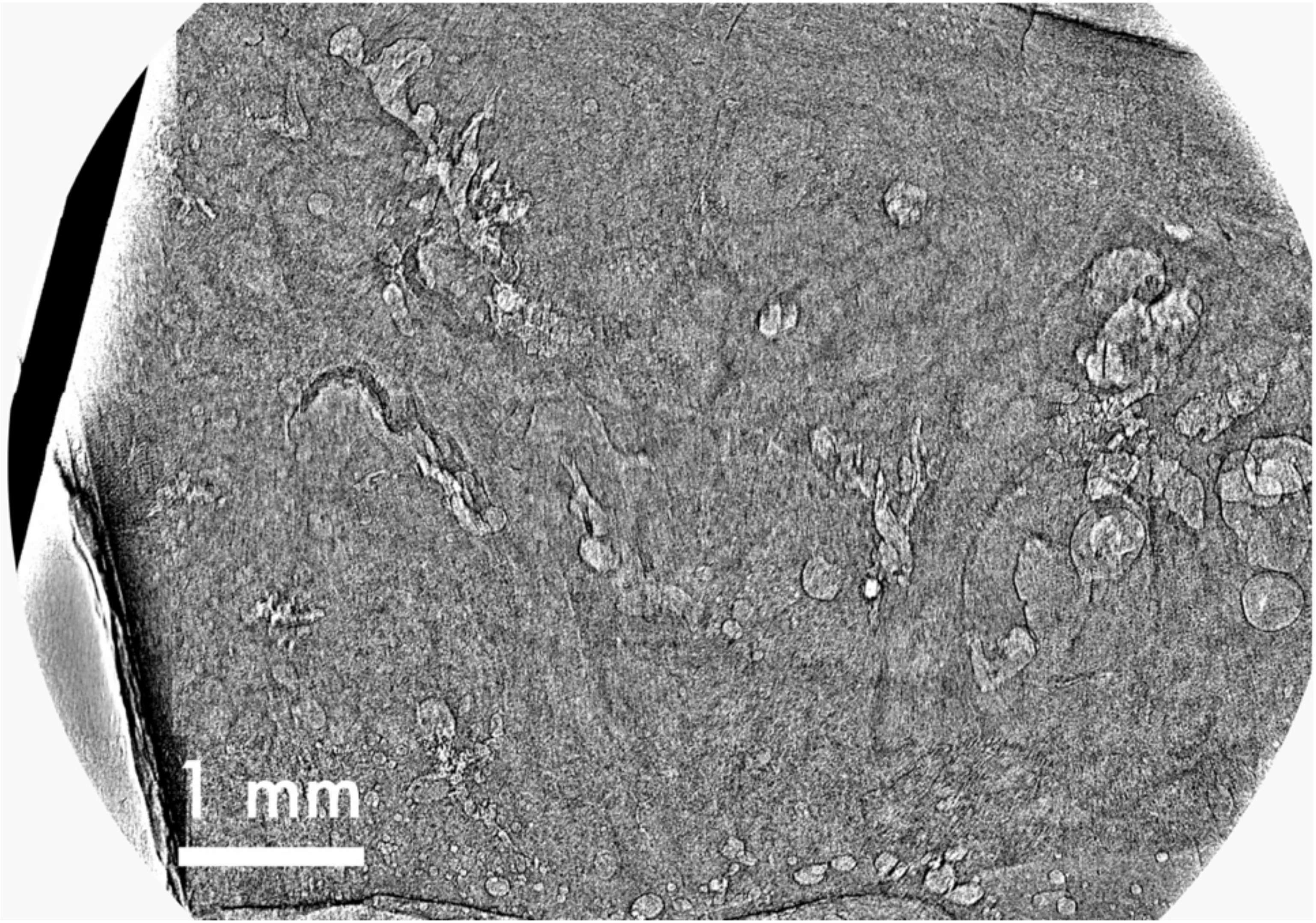


Micro-computed tomography of bone



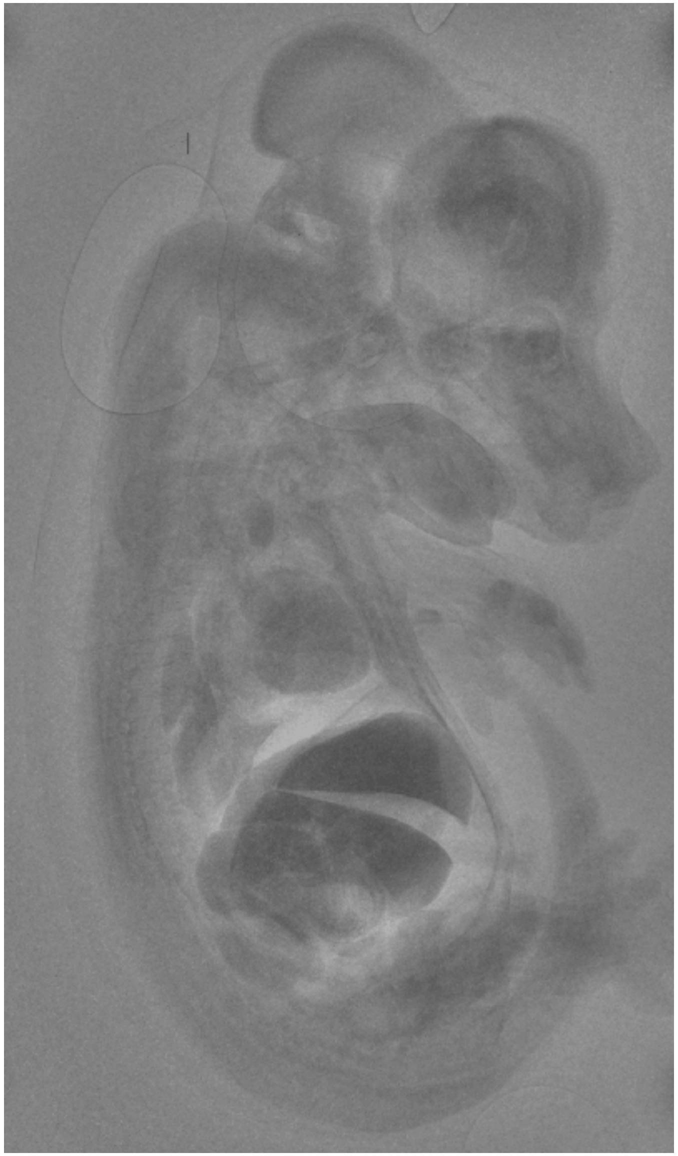
J.M. Cole *et al*, Scientific Reports 2015

Phase contrast imaging of human prostate

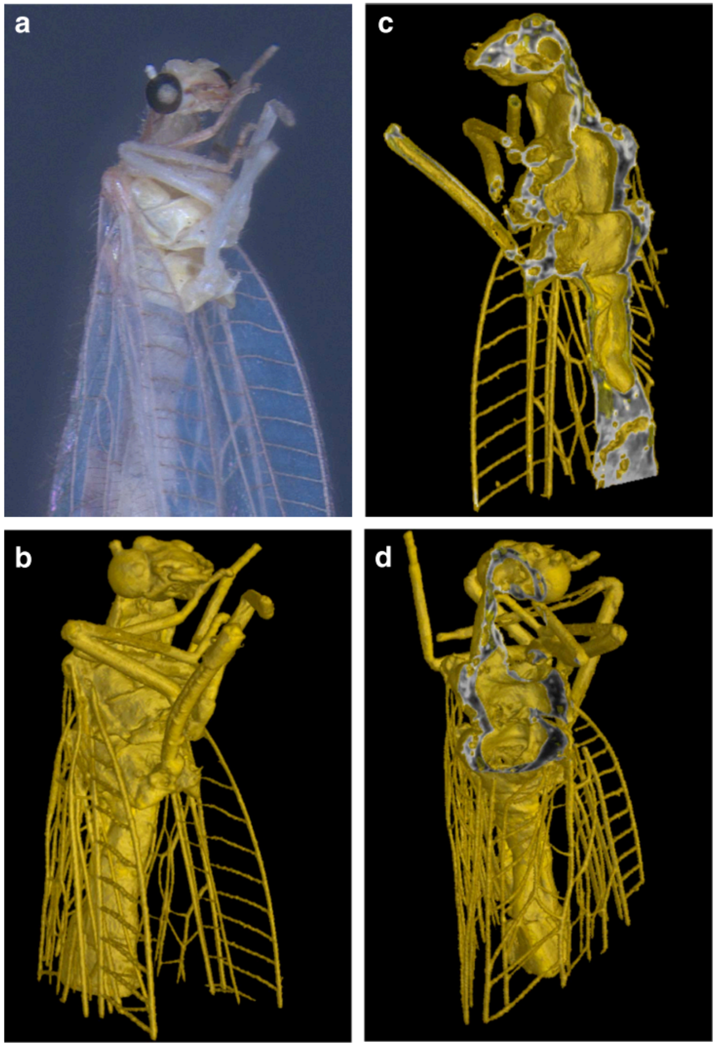


Holotomographic scans

Mouse embryo



Green lacewing

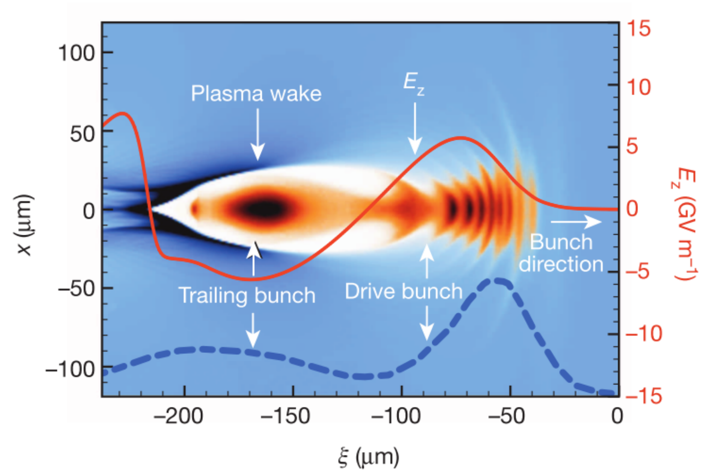


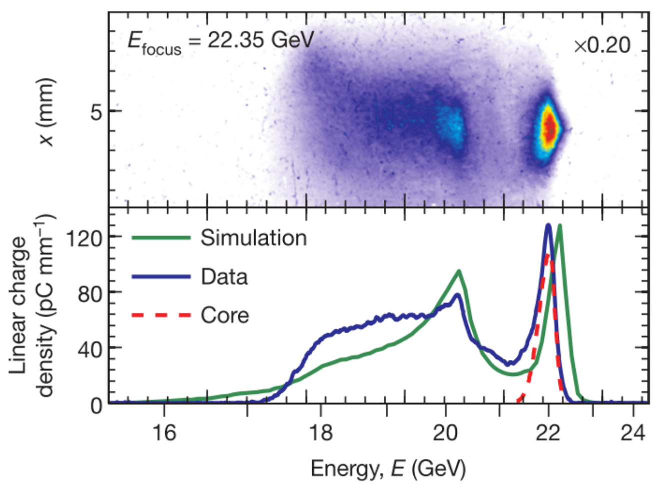
J. Wenz *et al*, Nature Communications, 2015

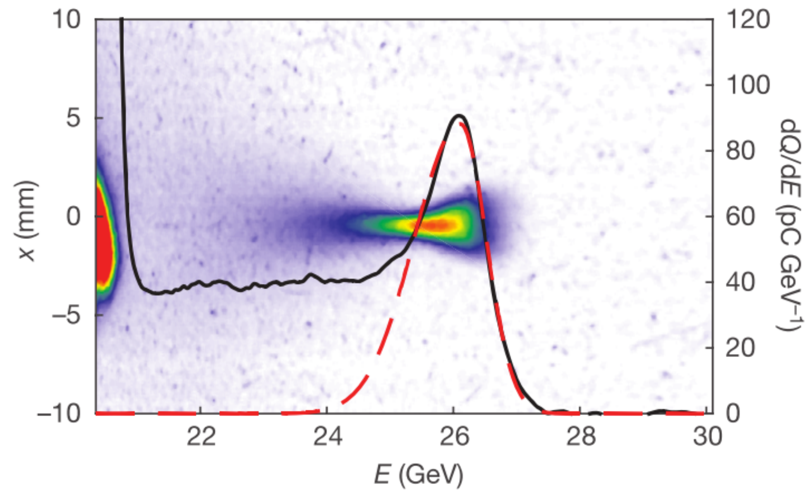
Beam-driven experiments (PWFA)

Instead of a laser pulse, use an intense particle bunch to drive a wake

P in PWFA is for plasma







Efficient acceleration of electrons

M. Litos *et al*, Nature, 2014

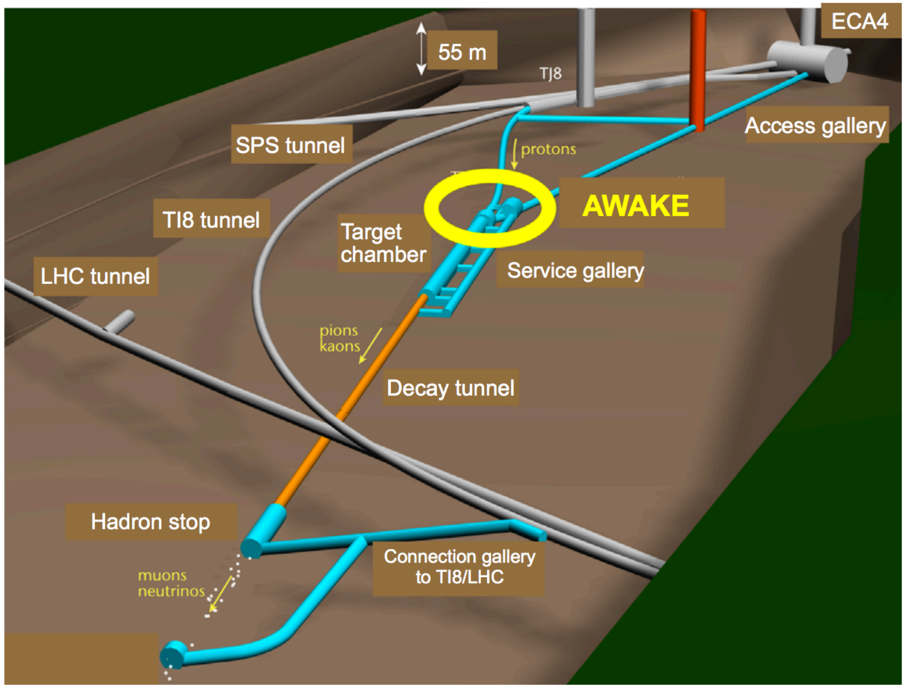
Acceleration of positrons

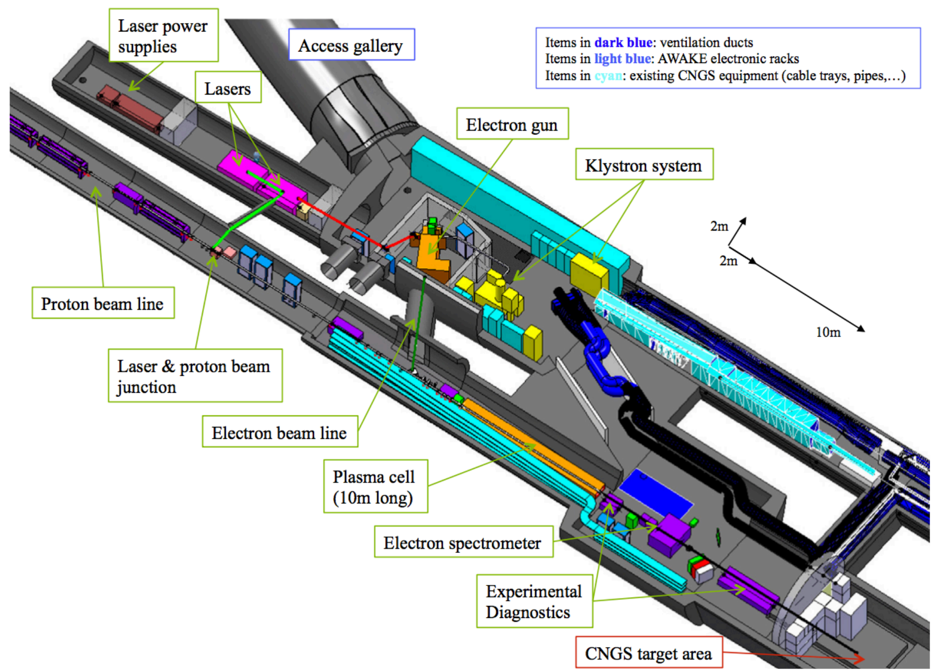
S. Corde *et al*, Nature, 2015

Imperial College London

John Adams Institute for Accelerator Science

The AWAKE experiment





Preferable to use heavier protons to accelerate electrons, for a given Lorentz factor they contain much more energy to drive a wake

AWAKE is a modification to the CNGS area which will use the SPS proton bunch to drive a wake in a 10m long plasma cell

The near future of LWFA

Pushing the energy frontier

ELI – Extreme Light Infrastructure

Centres in the Czech Republic, Romania, Hungary.

10 – 200(?) PW lasers at up to 10Hz, compared to 1PW now

Goal of 10s GeV

The near future of LWFA

Pushing towards applications

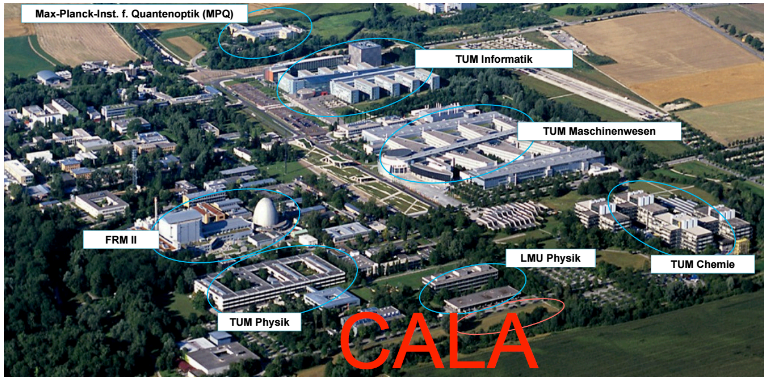
CALA - Centre for Advanced Laser Applications, Munich

3PW @ 10 Hz

SCAPA – Scottish Centre for the Application of Plasma-based Accelerators

0.35 – 1 PW

Designed for x-ray imaging and hadron therapy applications



The near future of LWFA

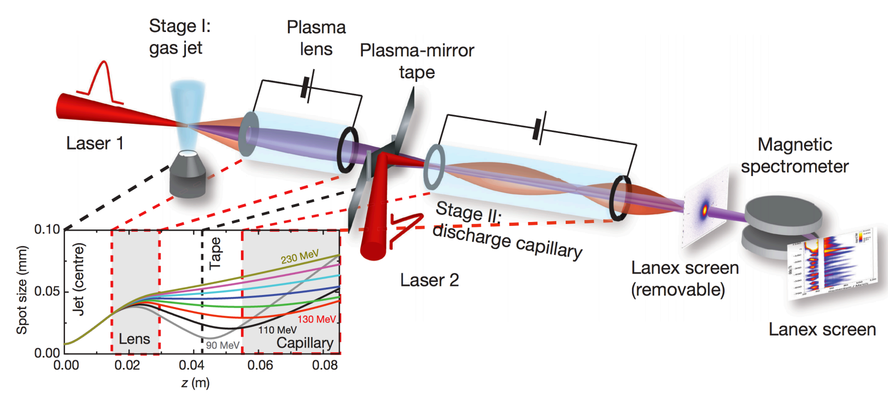
Pushing towards accelerators

EuPRAXIA – project to develop dedicated 5 GeV LWFA facility

EuPRAXIA

THE MAJOR OBJECTIVE OF THE EUPRAXIA DESIGN STUDY IS THE PREPARATION OF A CONCEPTUAL DESIGN REPORT FOR THE WORLDWIDE FIRST PLASMA-BASED ACCELERATOR AT 5 GEV WITH INDUSTRIAL BEAM QUALITY AND TWO USER AREAS.

Demonstration of LWFA staging, required to beat limitations on laser pulse energy



S. Steinke *et al*, Nature, 2016

Conclusions

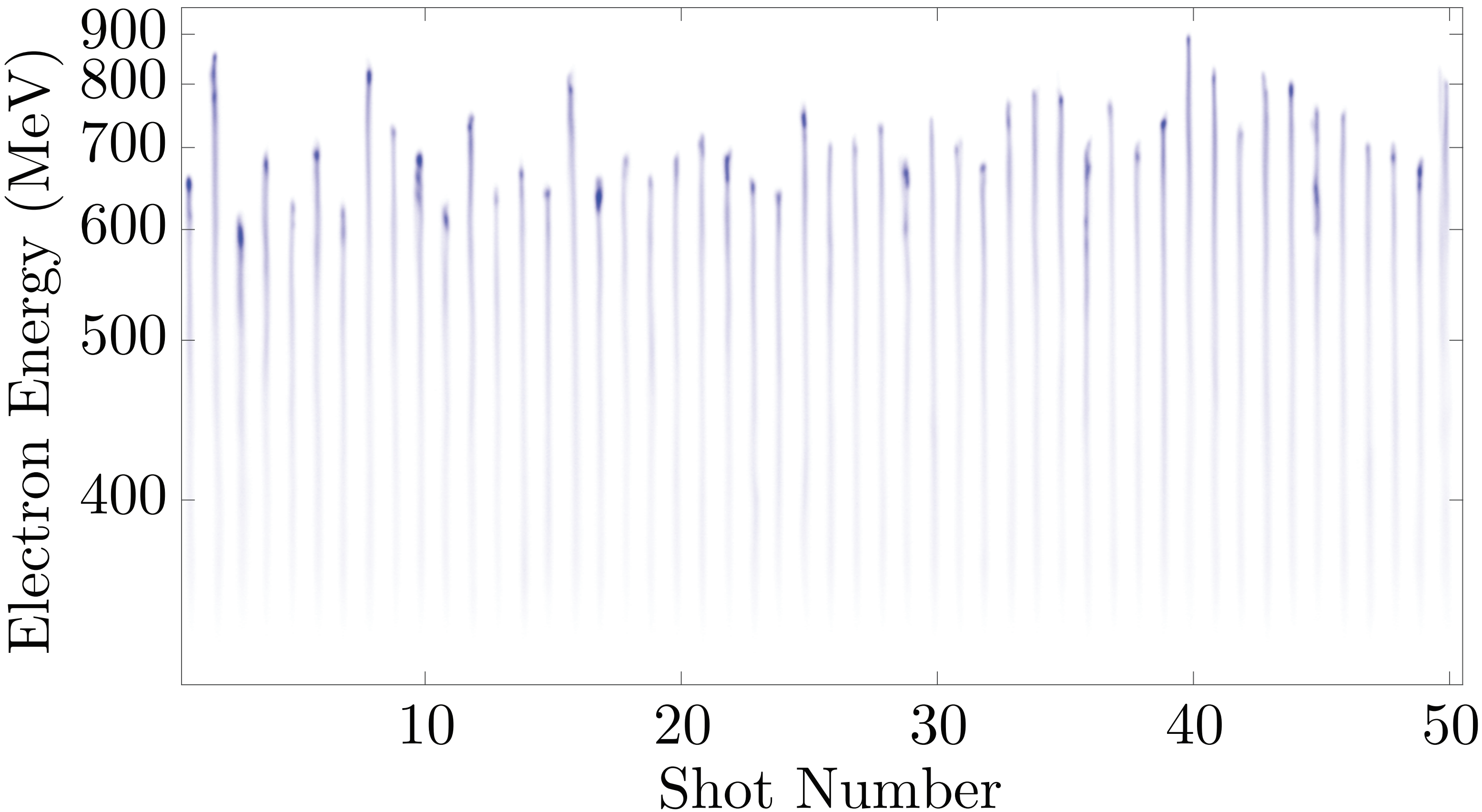
Laser wakefield accelerators are an exciting technology, capable of the production of energetic (GeV), short (fs), high-charge (nC) electron beams in a compact configuration

The understanding of the physics evolves as plasma and laser diagnostics improve

Groups are increasingly testing applications for LWFA particle and photon sources

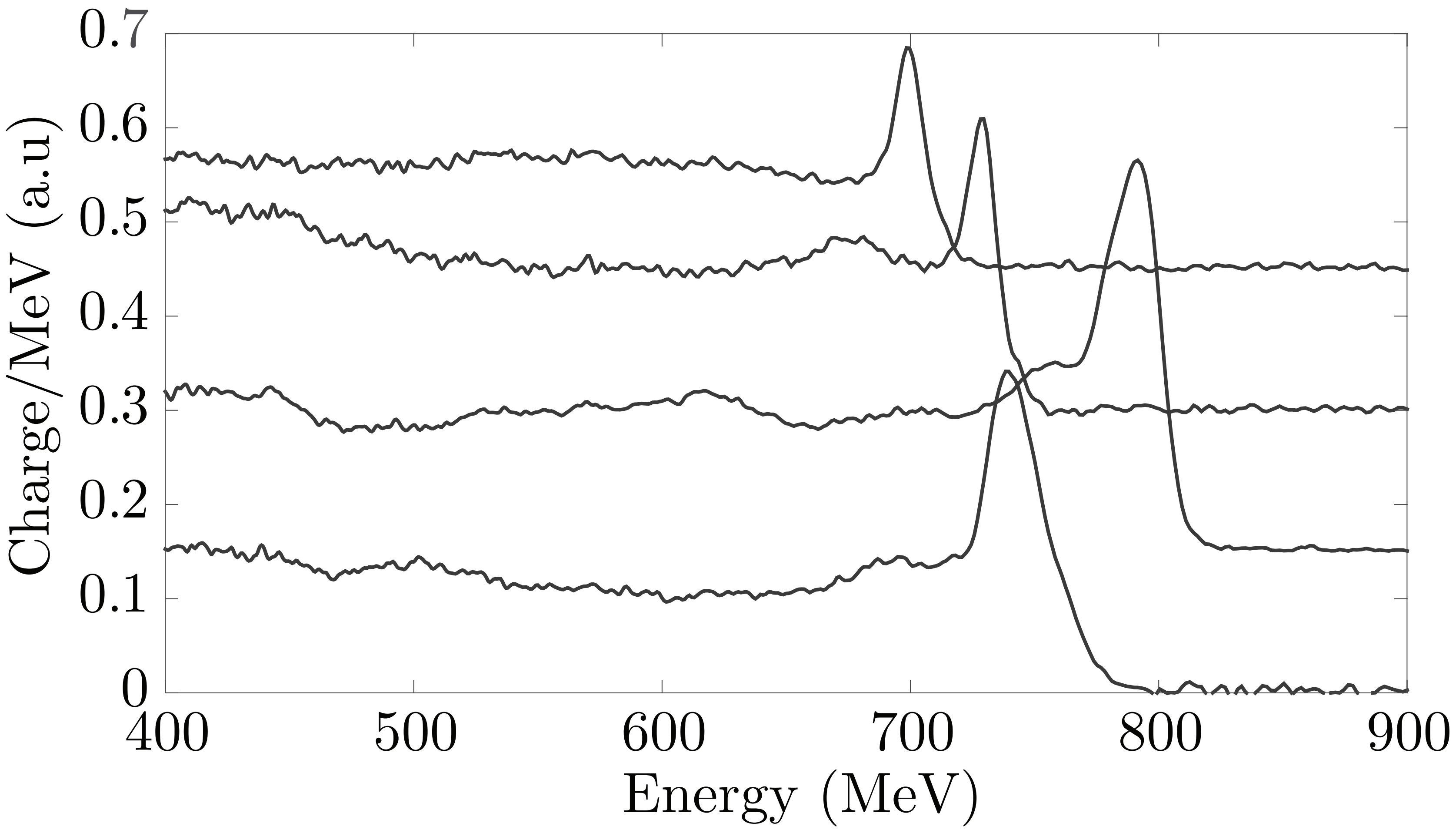
The research community is expanding as new laser facilities continue to come online

Electron beams



Laser energy stability ±3%
Beams above 400 MeV on 97% of shots (> 200 shots)

Electron beams



Electron spectra peaked, energy of peak 710 MeV ± 9%