Laser Wakefield Experiments

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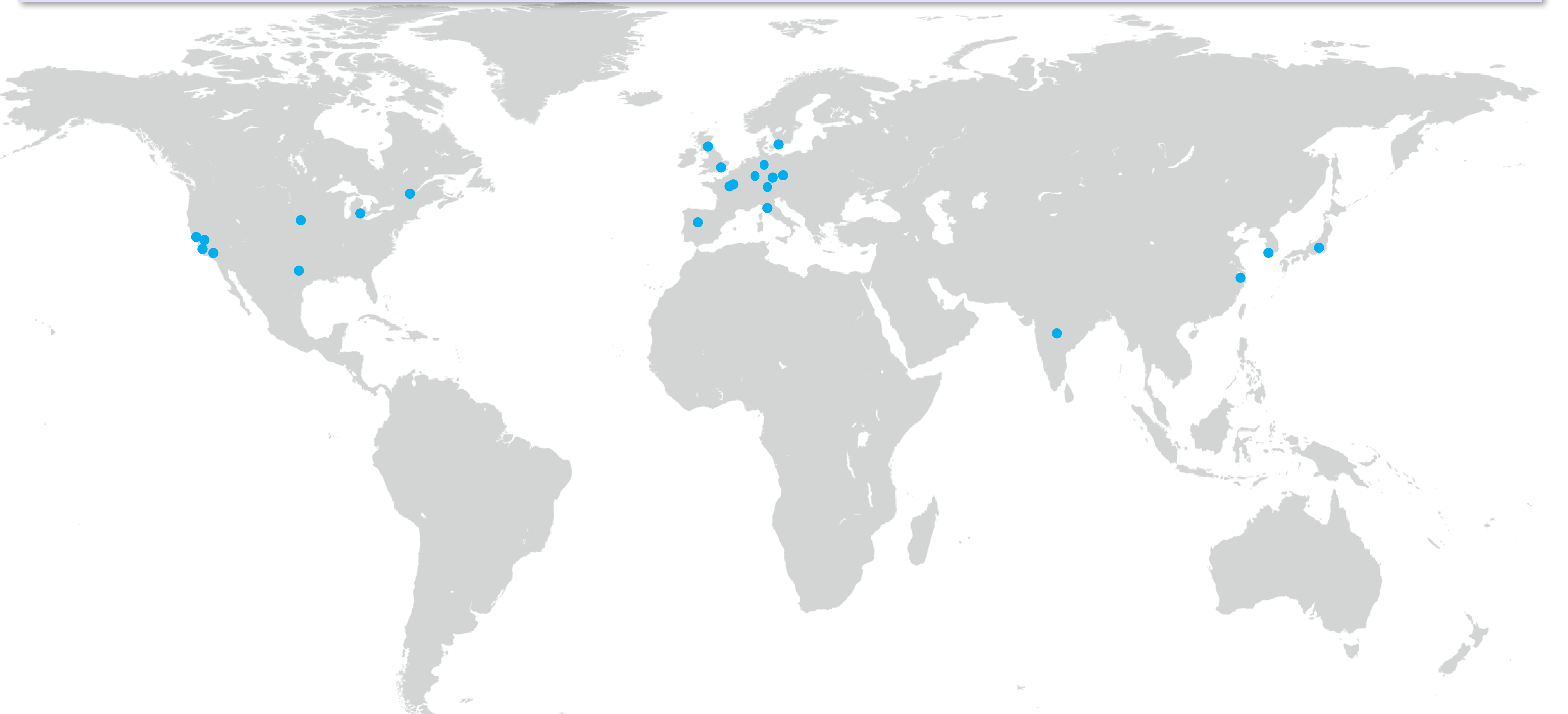
Imperial College London

Laser wakefield accelerators around the World



- There are many labs around the world doing laser driven wakefield experiments
- This lecture could never cover them all!

Laser Wakefield Accelerator Experiments can be split into a few broad categories

characterising beam properties

electron beam energy frontier

diagnosing physics of wakefields

stability frontier

applications of wakefield accelerators

Laser Wakefield Accelerator Experiments can be split into a few broad categories

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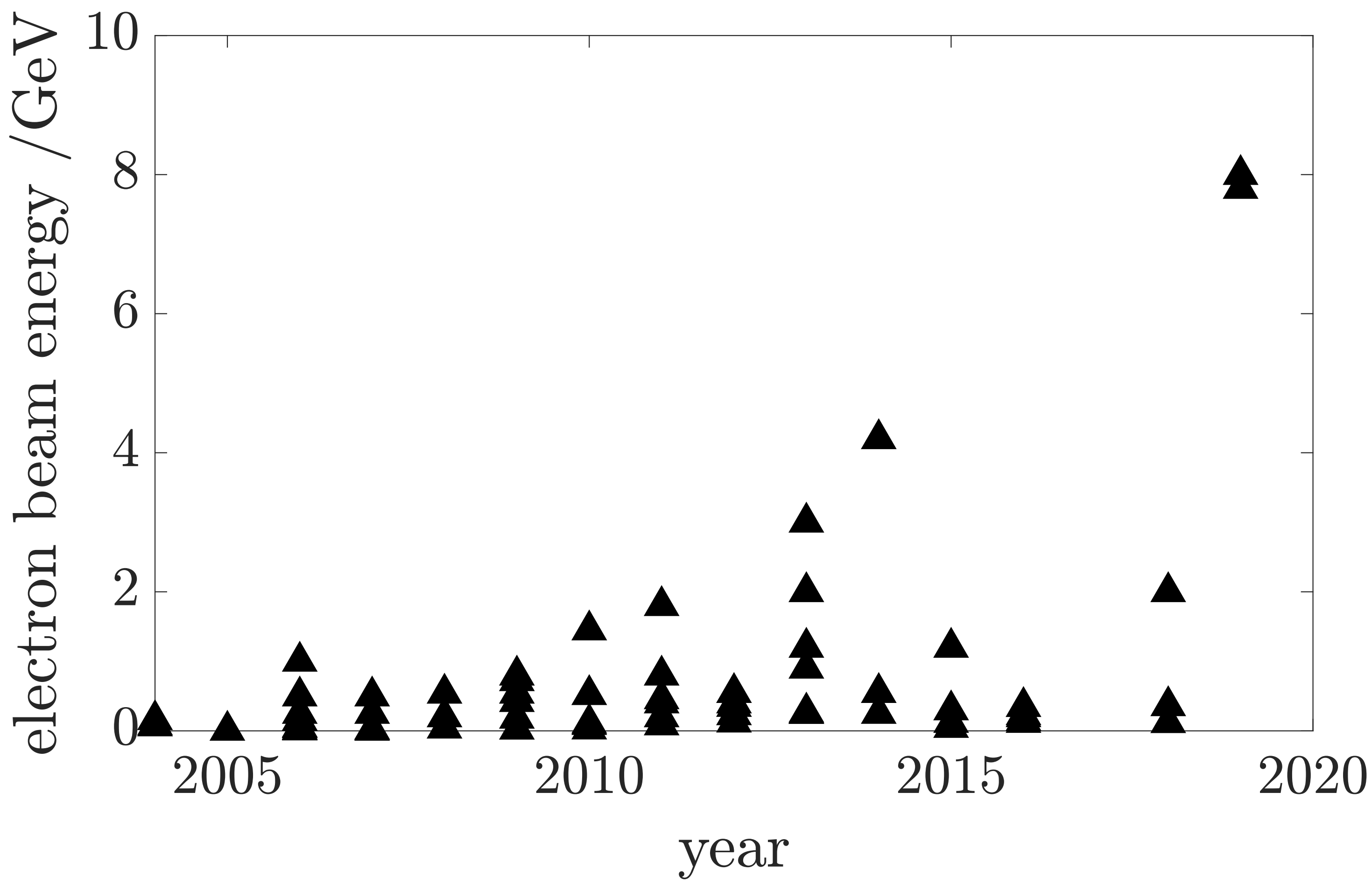
Fast progress in electron beam energy



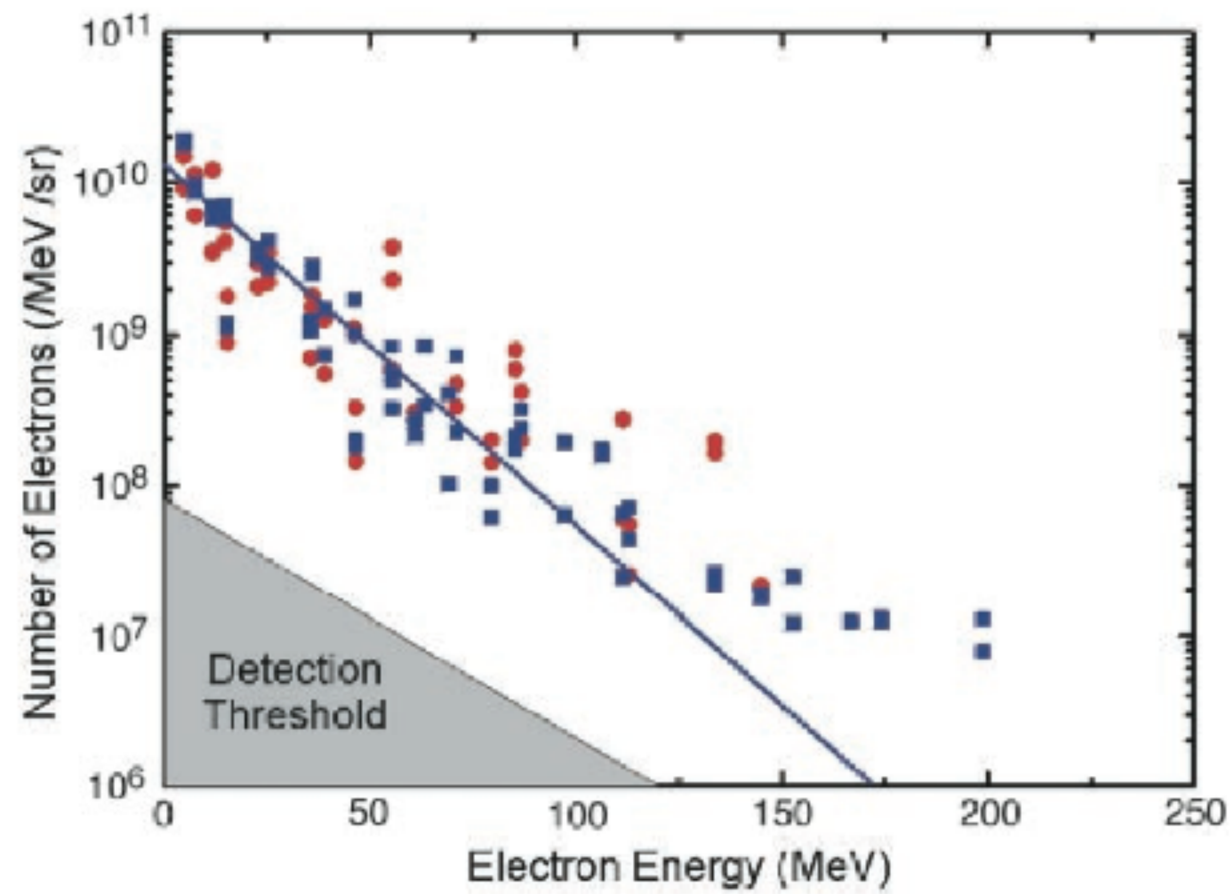
- Electron beam from laser wakefield accelerators has been going up steadily since 2004 results.
  - How has this been achieved?

Experiments at the energy frontier: 2002

Electron Acceleration by a Wake Field Forced by an Intense Ultrashort Laser Pulse

V. Malka,[1*] S. Fritzler,[1] E. Lefebvre,[2] M.-M. Aleonard,[3] F. Burgy,[1] J.-P. Chambaret,[1] J.-F. Chemin,[3] K. Krushelnick,[4] G. Malka,[3] S. P. D. Mangles,[4] Z. Najmudin,[4] M. Pittman,[1] J.-P. Rousseau,[1] J.-N. Scheurer,[3] B. Walton,[4] A. E. Dangor[4]

Plasmas are an attractive medium for the next generation of particle accelerators because they can support electric fields greater than several hundred gigavolts per meter. These accelerating fields are generated by relativistic plasma waves—space-charge oscillations—that can be excited when a high-intensity laser propagates through a plasma. Large currents of background electrons can then be trapped and subsequently accelerated by these relativistic waves. In the forced laser wake field regime, where the laser pulse length is of the order of the plasma wavelength, we show that a gain in maximum electron energy of up to 200 megaelectronvolts can be achieved, along with an improvement in the quality of the ultrashort electron beam.



V. Malka, Science, 298, 1596-1600 (2002)

- Extends to 200 MeV
- $n_e = 2.5 \times 10^{19}$ cm^{-3}, 3 mm gas jet
- P = 33 TW, “Salle Jaune” laser at LOA

Experiments at the energy frontier: 2006

GeV electron beams from a centimetre-scale accelerator

W. P. LEEMANS[1*†], B. NAGLER[1], A. J. GONSALVES[2], Cs. TÓTH[1], K. NAKAMURA[1,3], C. G. R. GEDDES[1], E. ESAREY[1*], C. B. SCHROEDER[1] AND S. M. HOOKER[2]

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[2]University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
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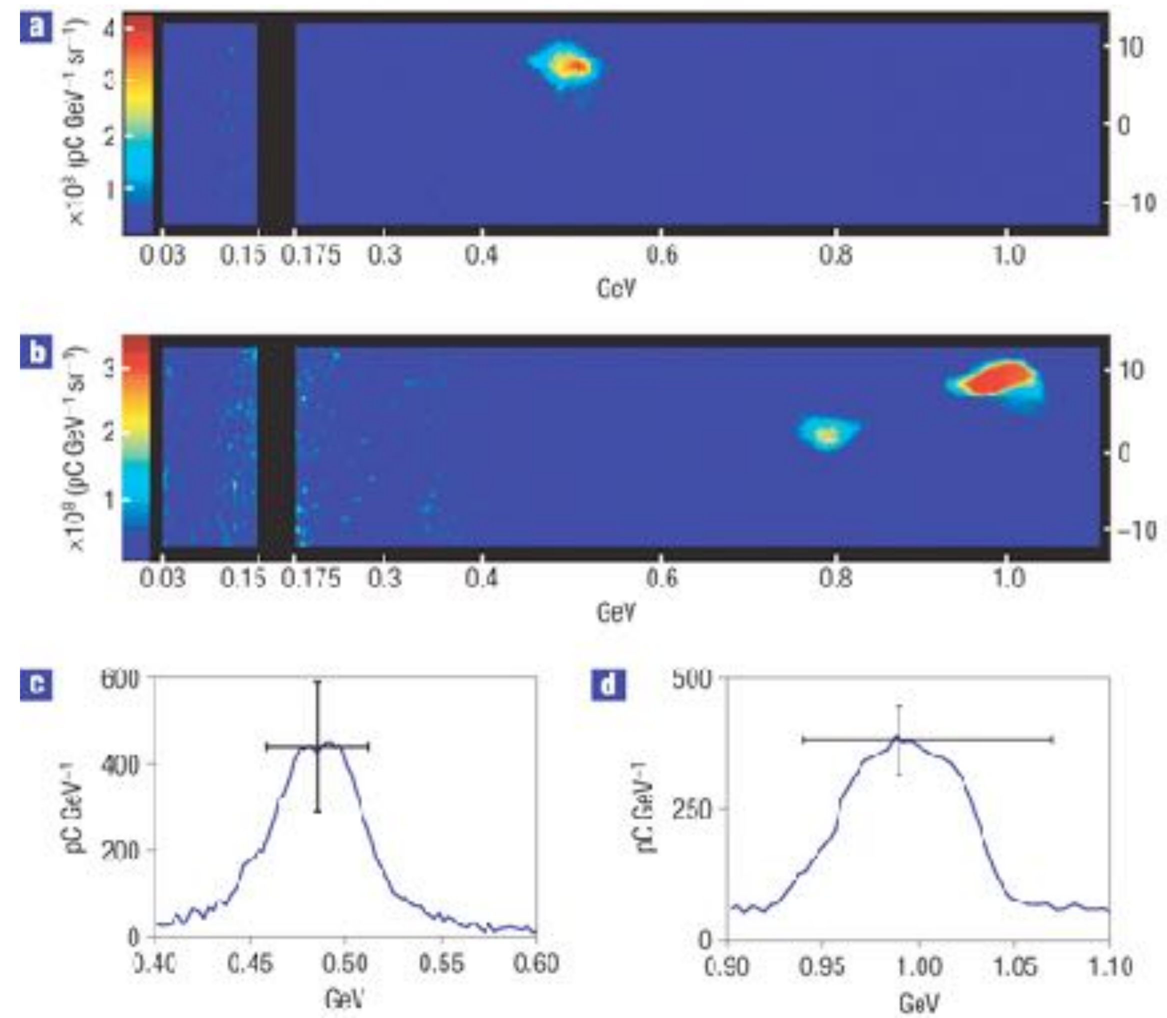
†e-mail: WPLeemans@lbl.gov

W.P. Leemans, Nature Physics, 2, 696-699 (2006)



- 1.0 GeV
- $n_e = 4.3 \times 10^{18}$ cm^{-3}, 33 mm capillary discharge waveguide
- P = 40 TW, TREX laser at LBNL

Experiments at the energy frontier: 2010

Self-Guided Laser Wakefield Acceleration beyond 1 GeV Using Ionization-Induced Injection

C. E. Clayton,[1,*] J. E. Ralph,[2] F. Albert,[2] R. A. Fonseca,[3] S. H. Glenzer,[2] C. Joshi,[1] W. Lu,[1] K. A. Marsh,[1] S. F. Martins,[3] W. B. Mori,[1] A. Pak,[1] F. S. Tsung,[1] B. B. Pollock,[2,4] J. S. Ross,[2,4] L. O. Silva,[3] and D. H. Froula[2]

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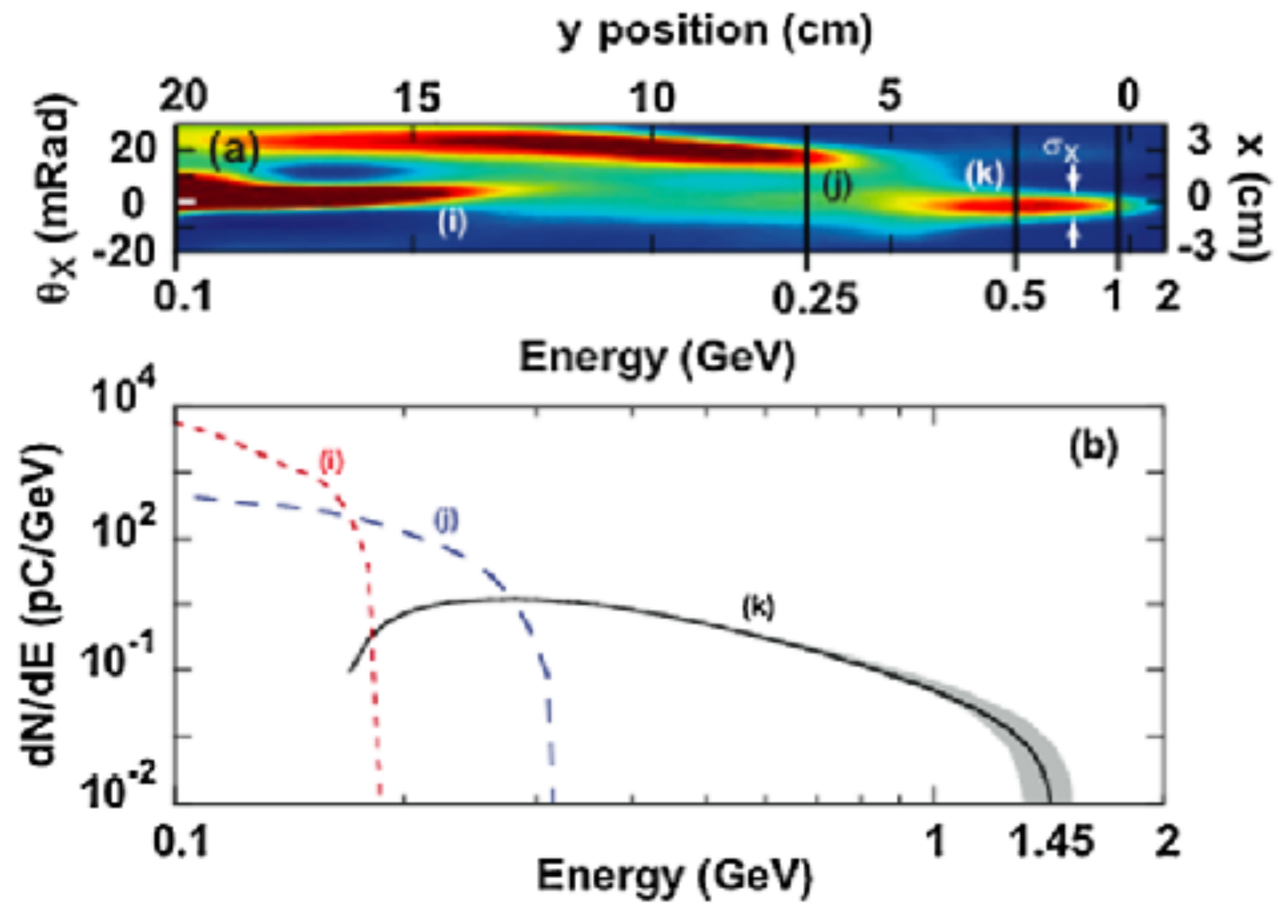
[2]*L-399, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, USA*
[3]*GoLP/IPFN-LA, Instituto Superior Técnico, Lisboa, Portugal*
[4]*MAE Department, University of California, San Diego, La Jolla, California 92093, USA*
(Received 23 April 2010; published 1 September 2010)

The concepts of matched-beam, self-guided laser propagation and ionization-induced injection have been combined to accelerate electrons up to 1.45 GeV energy in a laser wakefield accelerator. From the spatial and spectral content of the laser light exiting the plasma, we infer that the 60 fs, 110 TW laser pulse is guided and excites a wake over the entire 1.3 cm length of the gas cell at densities below $1.5 \times 10^{18}\ cm^{-3}$. High-energy electrons are observed only when small (3%) amounts of CO_2 gas are added to the He gas. Computer simulations confirm that it is the K-shell electrons of oxygen that are ionized and injected into the wake and accelerated to beyond 1 GeV energy.

C. Clayton, Phys. Rev. Lett, 105, 105003 (2010)



- Extends to 1.45 GeV
- n_e = 4.3 x 10^{18} cm^{-3}, 1.3 cm gas cell
- P = 220 TW Callisto Laser at LLNL

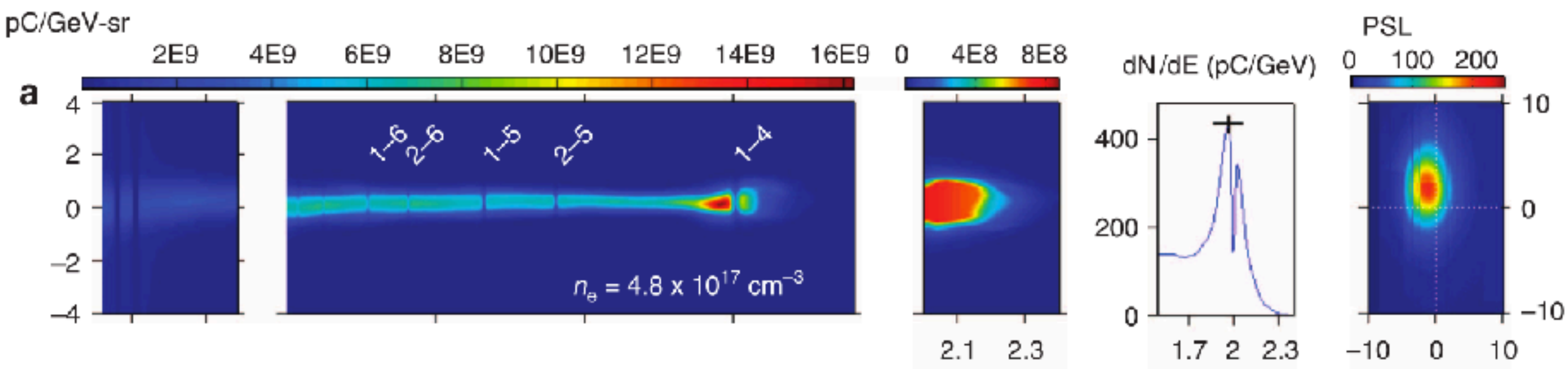
Experiments at the energy frontier: 2013

ARTICLE

Received 2 Dec 2012 | Accepted 8 May 2013 | Published 11 Jun 2013 DOI: 10.1038/ncomms2988 OPEN

Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

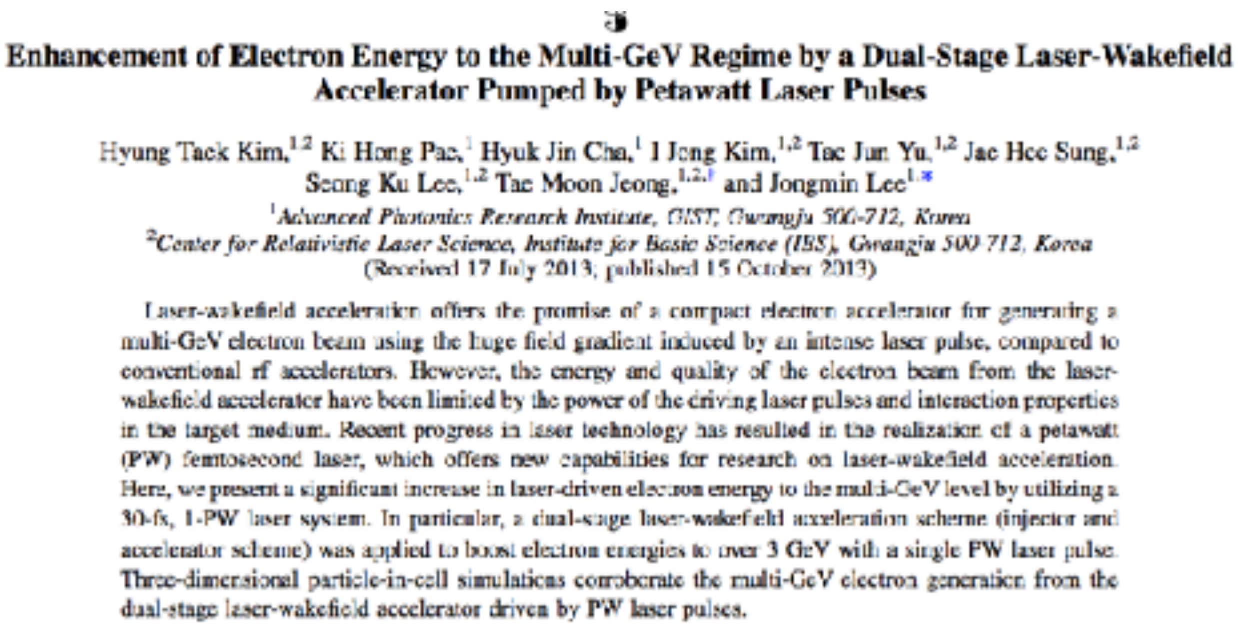
Xiaoming Wang[1], Rafal Zgadzaj[1], Neil Fazel[1], Zhengyan Li[1], S. A. Yi[1], Xi Zhang[1], Watson Henderson[1], Y.-Y. Chang[1], R. Korzekwa[1], H.-E. Tsai[1], C.-H. Pai[1], H. Quevedo[1], G. Dyer[1], E. Gaul[1], M. Martinez[1], A. C. Bernstein[1], T. Borger[1], M. Spinks[1], M. Donovan[1], V. Khudik[1], G. Shvets[1], T. Ditmire[1] & M. C. Downer[1]



X. Wang, Nature Communications, 4, 1988 (2013)

- 2 GeV
- $n_e = 4.8 \times 10^{17}$ cm^{-3}, 7 cm gas cell
- P = 1000 TW “Texas PetaWatt” at University of Texas

Experiments at the energy frontier: 2013



Enhancement of Electron Energy to the Multi-GeV Regime by a Dual-Stage Laser-Wakefield Accelerator Pumped by Petawatt Laser Pulses

Hyung Taek Kim,[1,2] Ki Hong Pae,[1] Hyuk Jin Cha,[1] I Jong Kim,[1,2] Tae Jun Yu,[1,2] Jae Hee Sung,[1,2] Seong Ku Lee,[1,2] Tae Moon Jeong,[1,2,†] and Jongmin Lee[1,*]
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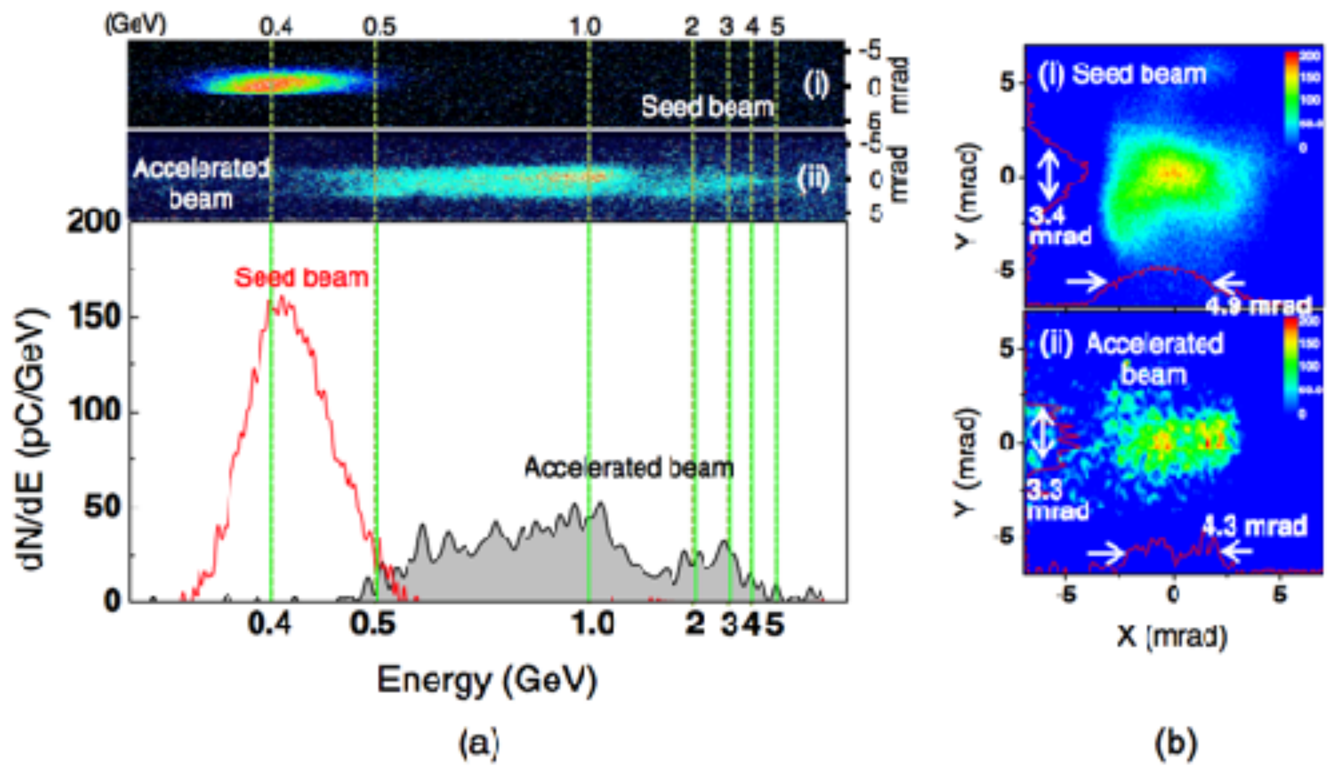
[2]Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 500-712, Korea
(Received 17 July 2013; published 15 October 2013)

Laser-wakefield acceleration offers the promise of a compact electron accelerator for generating a multi-GeV electron beam using the huge field gradient induced by an intense laser pulse, compared to conventional rf accelerators. However, the energy and quality of the electron beam from the laser-wakefield accelerator have been limited by the power of the driving laser pulses and interaction properties in the target medium. Recent progress in laser technology has resulted in the realization of a petawatt (PW) femtosecond laser, which offers new capabilities for research on laser-wakefield acceleration. Here, we present a significant increase in laser-driven electron energy to the multi-GeV level by utilizing a 30-fs, 1-PW laser system. In particular, a dual-stage laser-wakefield acceleration scheme (injector and accelerator scheme) was applied to boost electron energies to over 3 GeV with a single PW laser pulse. Three-dimensional particle-in-cell simulations corroborate the multi-GeV electron generation from the dual-stage laser-wakefield accelerator driven by PW laser pulses.



H.T. Kim, Phys. Rev. Lett.. 111, 165002 (2013)

- 3 GeV
- $n_e = 8 \times 10^{17}$ cm^{-3}, 4 + 10 mm dual gas jet
- P = 1 PW laser at APRI

Experiments at the energy frontier: 2014

Accepted Paper

Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime

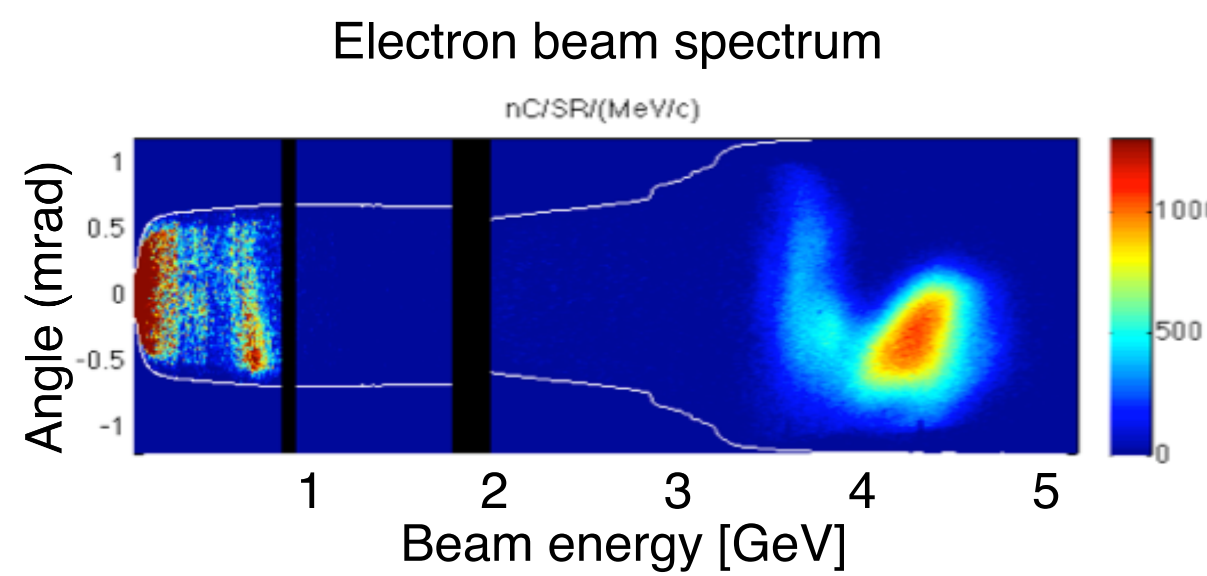
Phys. Rev. Lett.

W. P. Leemans, A. J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, Cs. Tóth, J. Daniels, D. E. Mittelberger, S. S. Bulanov, J.-L. Vay, C. G. R. Geddes, and E. Esarey

Accepted 21 October 2014

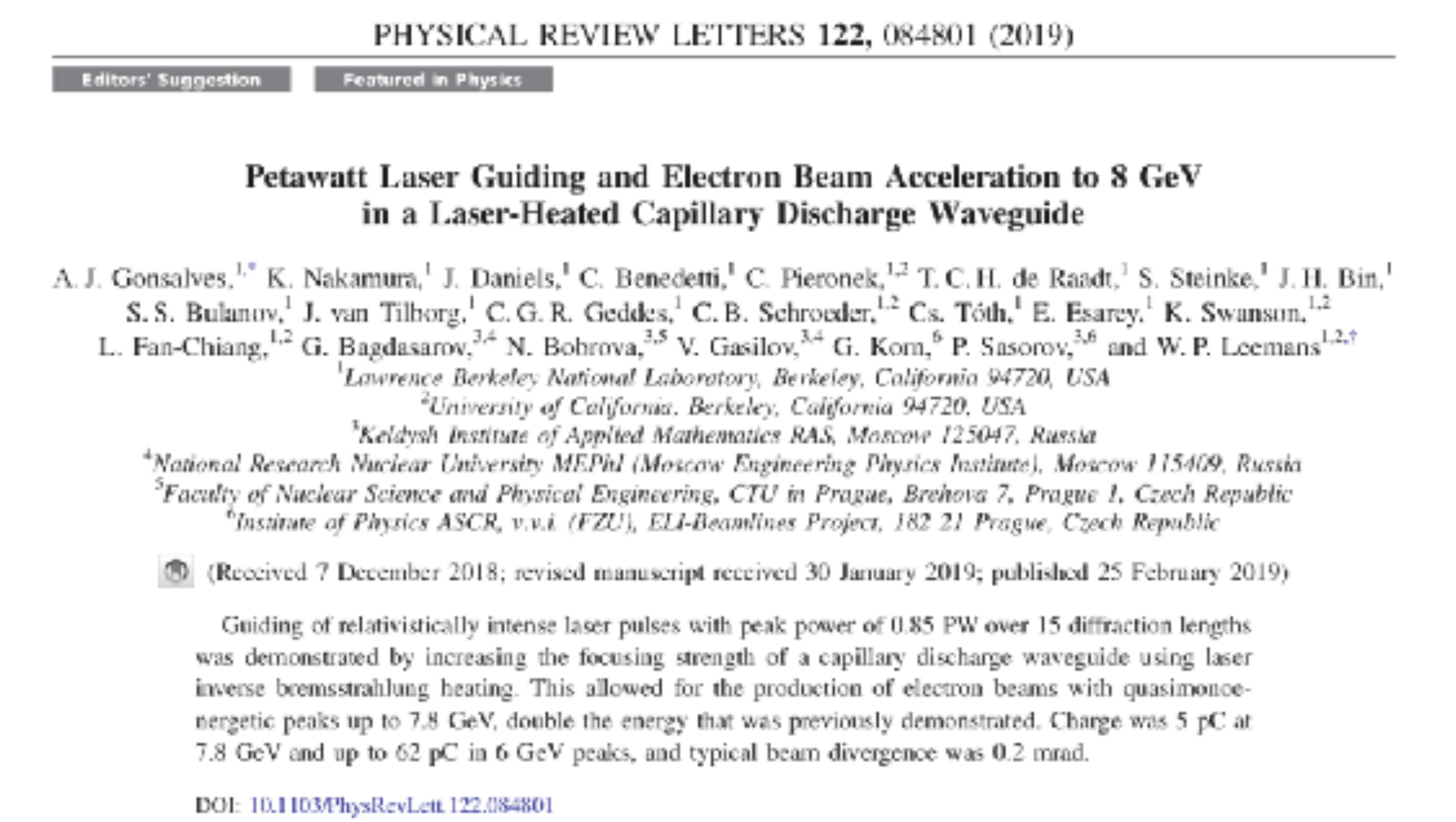
ABSTRACT

Multi-GeV electron beams with energy up to 4.2~GeV, 6~\% rms energy spread, 6\,\pico\coulomb charge, and 0.3\,\milli\radian rms divergence have been produced from a 9\,\centi\meter-long capillary discharge waveguide with a plasma density of \approx 7 \times 10^17\,\rm{cm}^-3, powered by laser pulses with peak power up to 0.3~PW. Preformed plasma waveguides allow the use of lower laser power compared to unguided plasma structures to achieve the same electron beam energy. Detailed comparison between experiment and simulation indicates the sensitivity in this regime of the guiding and acceleration in the plasma structure to input intensity, density, and near-field laser mode profile.



- 4 GeV
- $n_e = 7 \times 10^{17}$ cm^{-3}, 9 cm capillary discharge waveguide
- P = 300 TW "Bella" at LBNL

Experiments at the energy frontier: 2019



PHYSICAL REVIEW LETTERS 122, 084801 (2019)

Editors' Suggestion | Featured in Physics

Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide

A. J. Gonsalves,[1,*] K. Nakamura,[1] J. Daniels,[1] C. Benedetti,[1] C. Pieronek,[1,2] T. C. H. de Raadt,[1] S. Steinke,[1] J. H. Bin,[1] S. S. Bulanov,[1] J. van Tilborg,[1] C. G. R. Geddes,[1] C. B. Schroeder,[1,2] Cs. Tóth,[1] E. Esarey,[1] K. Swanson,[1,2] L. Fan-Chiang,[1,2] G. Bagdasarov,[3,4] N. Bobrova,[3,5] V. Gasilov,[3,4] G. Korn,[6] P. Sasorov,[3,6] and W. P. Leemans[1,2,†]

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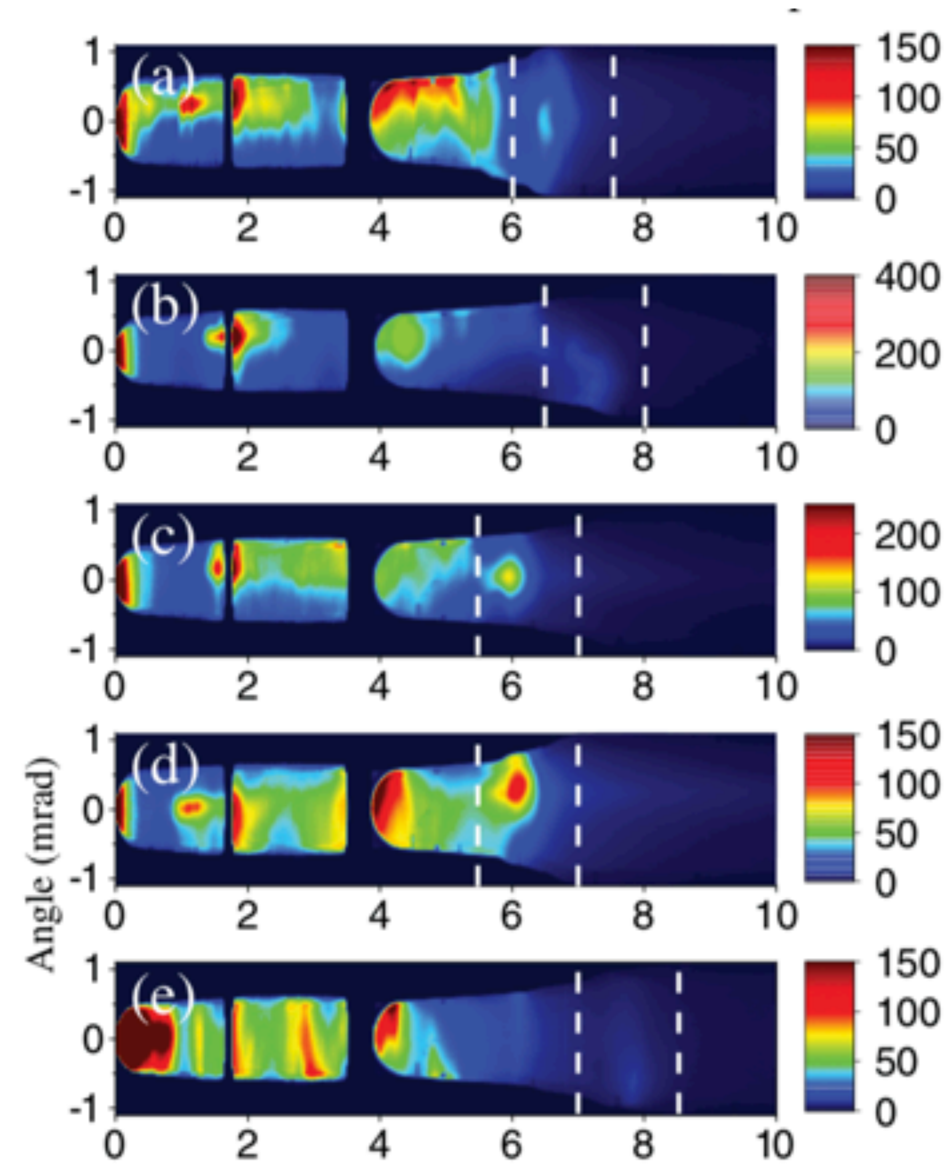
[5]*Faculty of Nuclear Science and Physical Engineering, CTU in Prague, Brehova 7, Prague 1, Czech Republic*
[6]*Institute of Physics ASCR, v.v.i. (FZU), ELI-Beamlines Project, 182 21 Prague, Czech Republic*

(Received 7 December 2018; revised manuscript received 30 January 2019; published 25 February 2019)

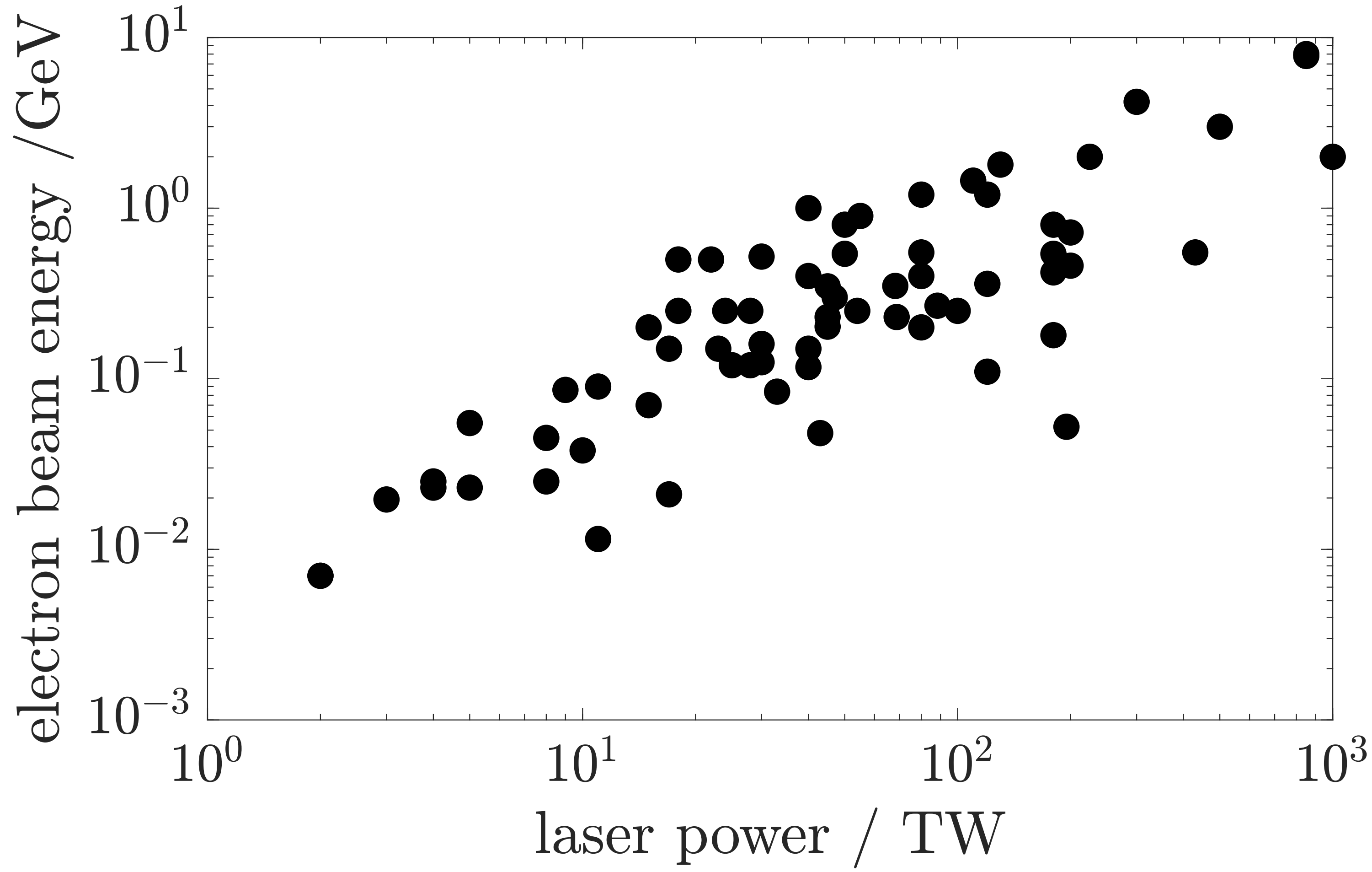
Guiding of relativistically intense laser pulses with peak power of 0.85 PW over 15 diffraction lengths was demonstrated by increasing the focusing strength of a capillary discharge waveguide using laser inverse bremsstrahlung heating. This allowed for the production of electron beams with quasimonoenergetic peaks up to 7.8 GeV, double the energy that was previously demonstrated. Charge was 5 pC at 7.8 GeV and up to 62 pC in 6 GeV peaks, and typical beam divergence was 0.2 mrad.

DOI: 10.1103/PhysRevLett.122.084801



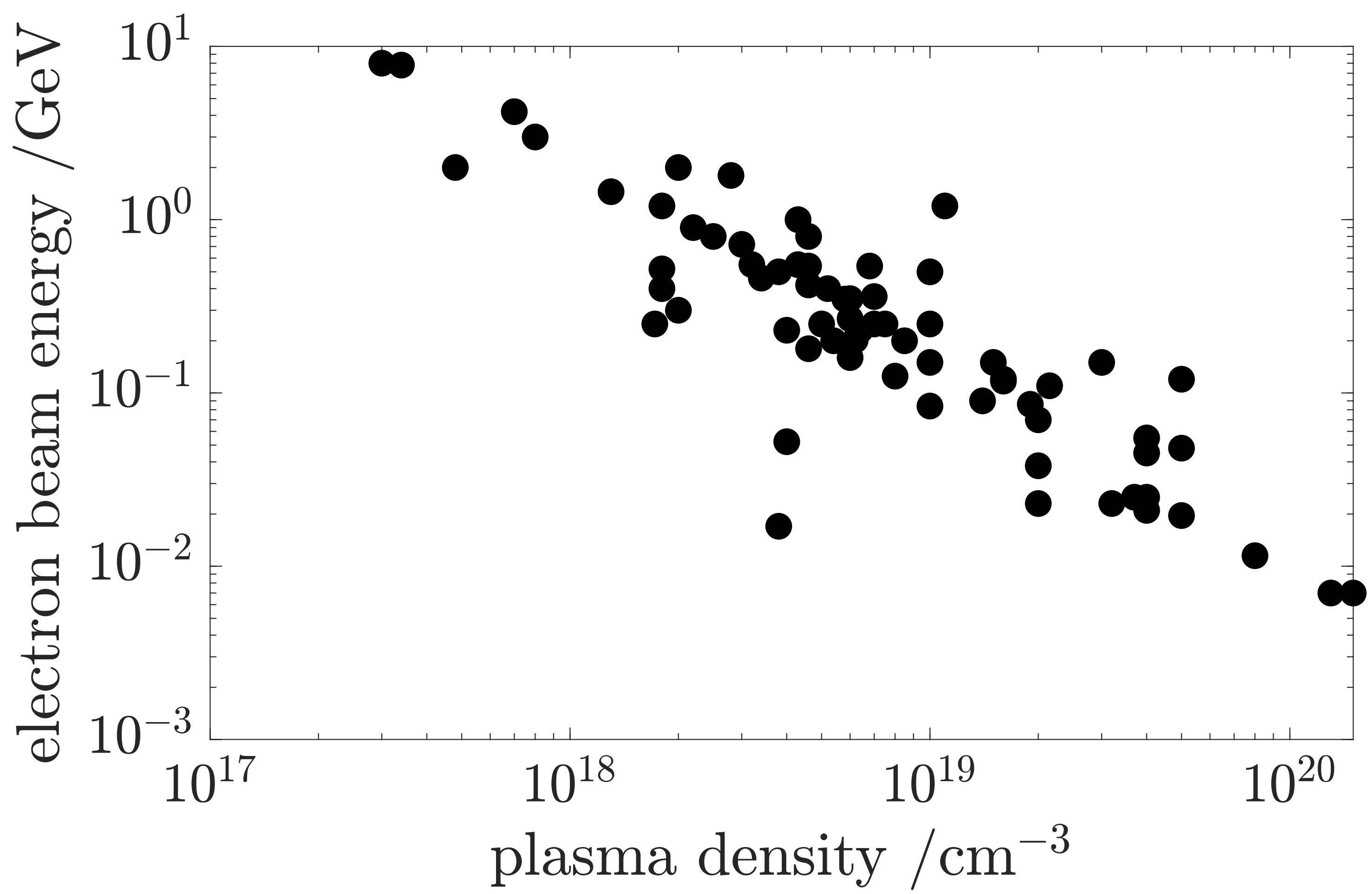
- 7.8 GeV
- $n_e = 7 \times 10^{17}$ cm^{-3}, 9 cm capillary discharge waveguide
- P = 850 TW "Bella" at LBNL

But science isn't about collecting World Records.... Can we extract some physics from the data trends?



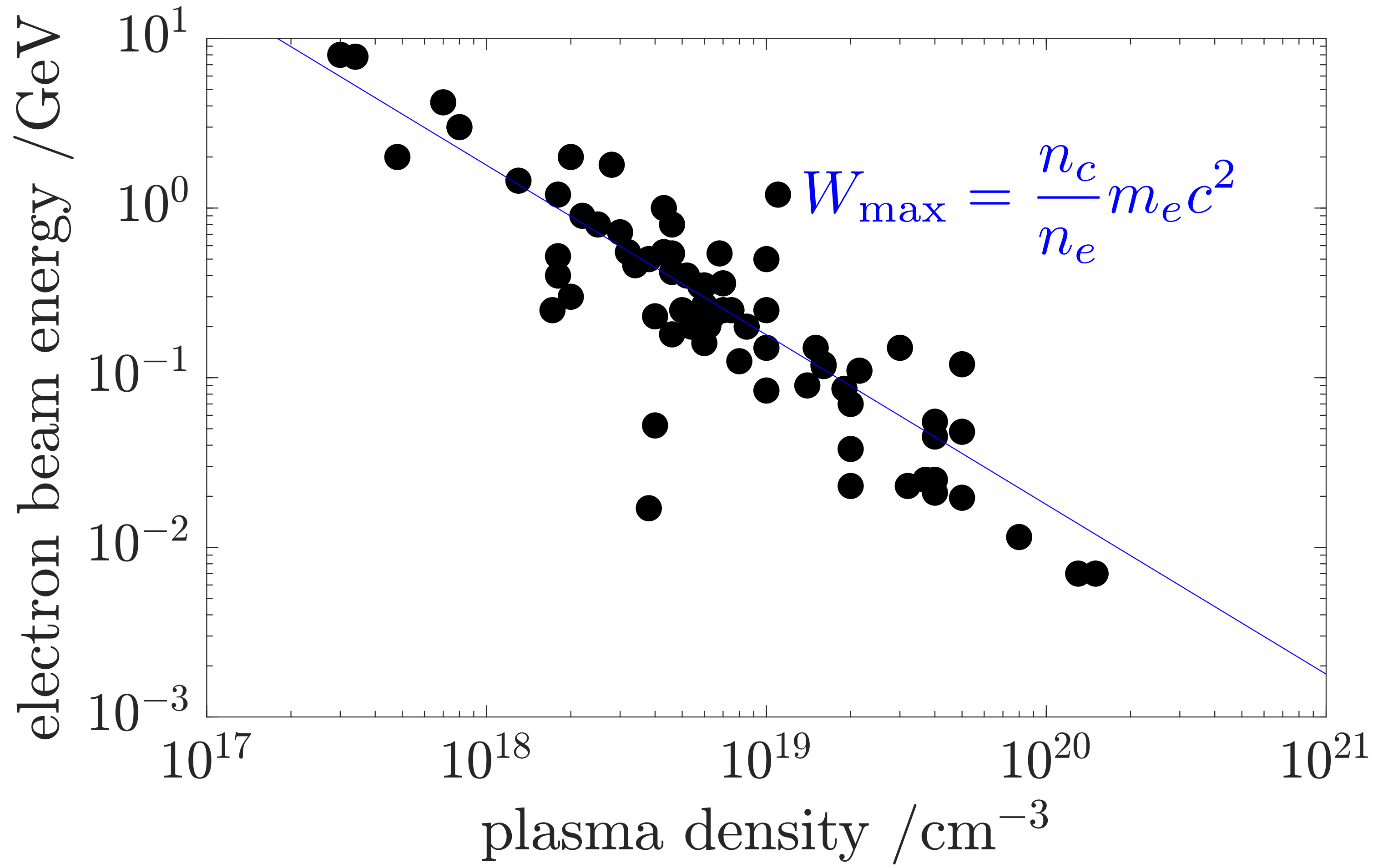
- Collection of data from a variety of experiments
  - (not just the record breakers, but probably the highest beam each experiment was capable of producing)
    - Trend is: higher laser power = higher electron energy
    - What is physics behind this?

Electron energy is limited by dephasing – move to lower densities



- Beam energy, W_{max}, is inversely proportional to plasma density as expected for dephasing

Electron energy is limited by dephasing – move to lower densities



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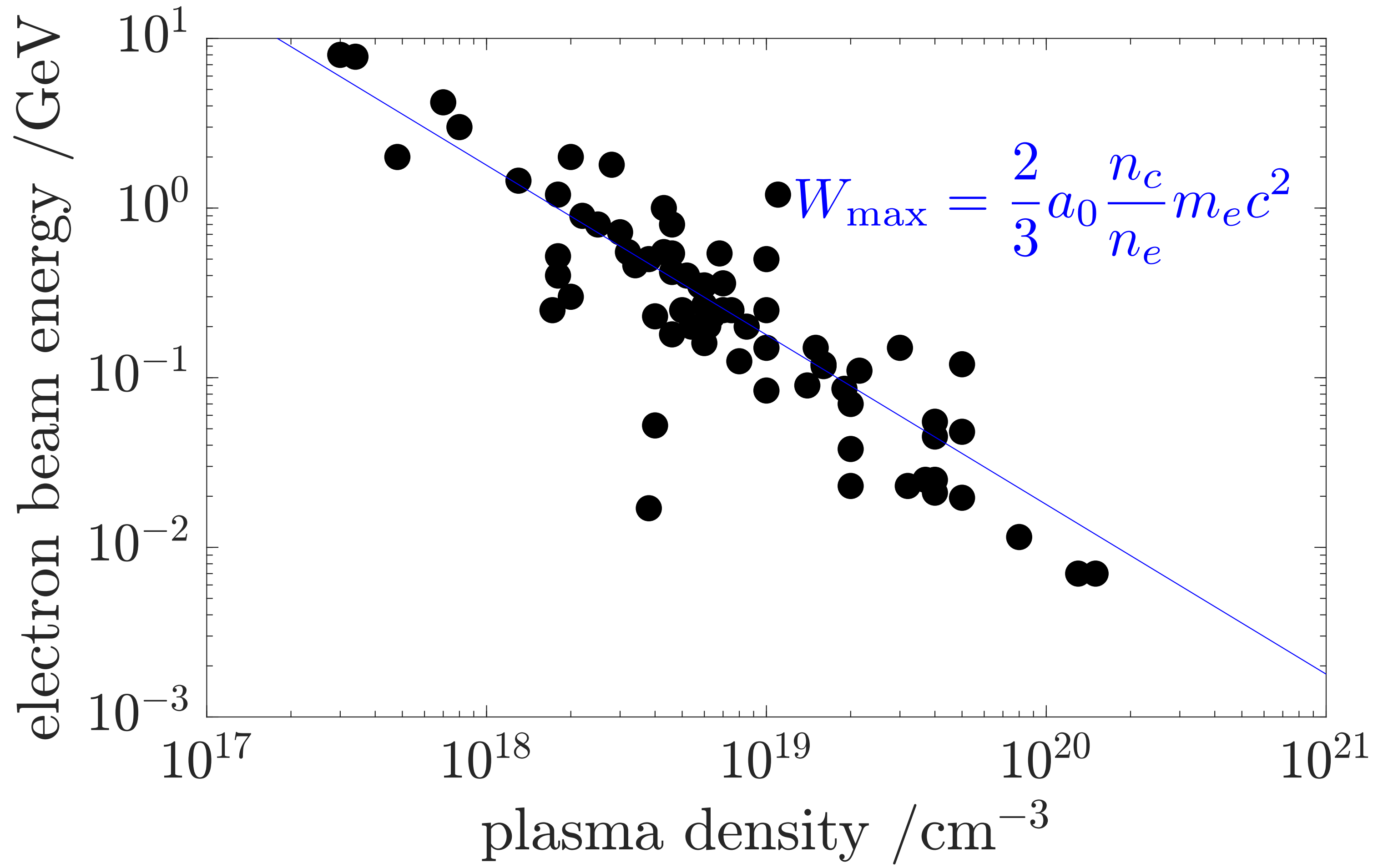
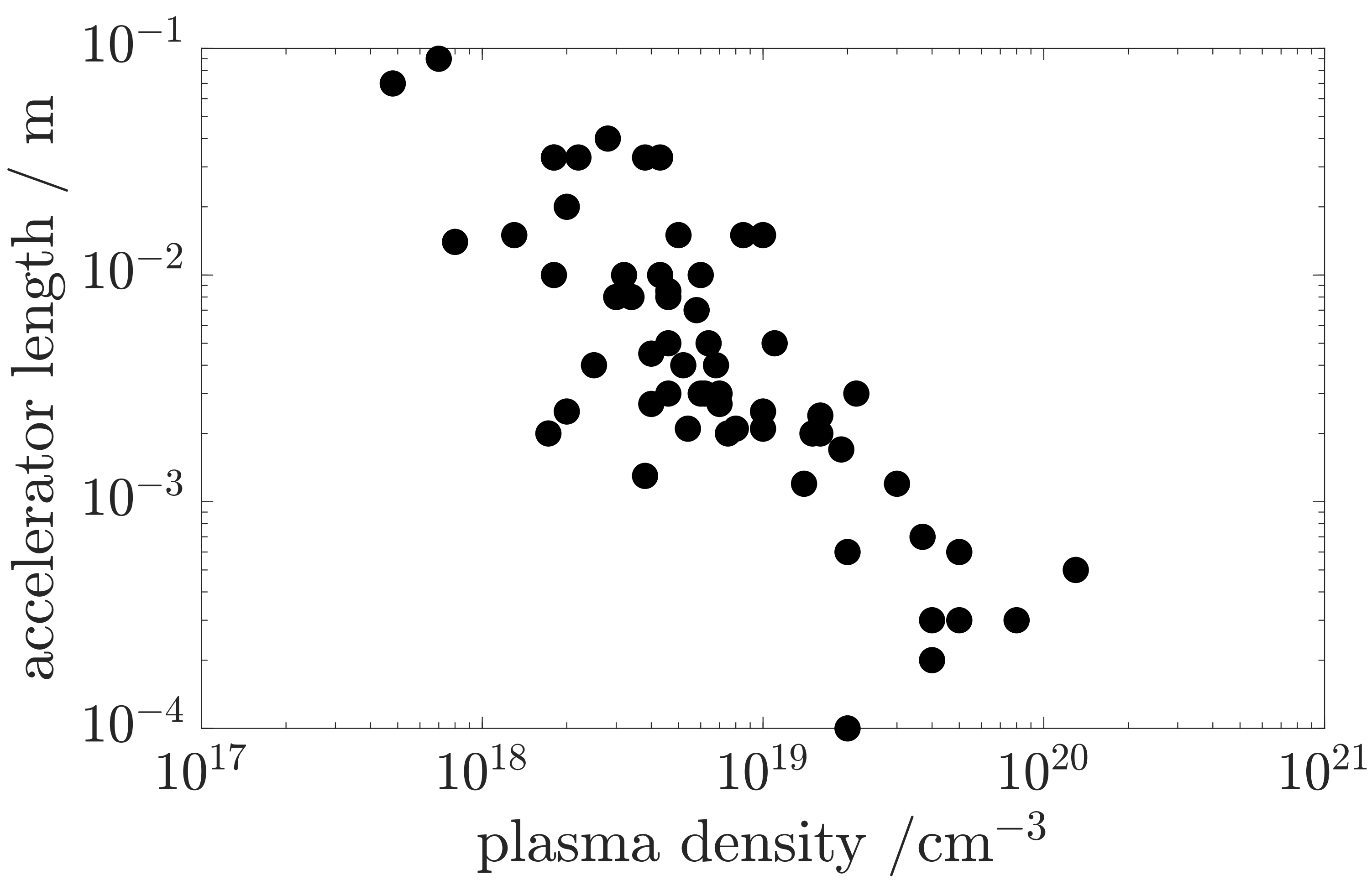
Electron energy is limited by dephasing – move to lower densities



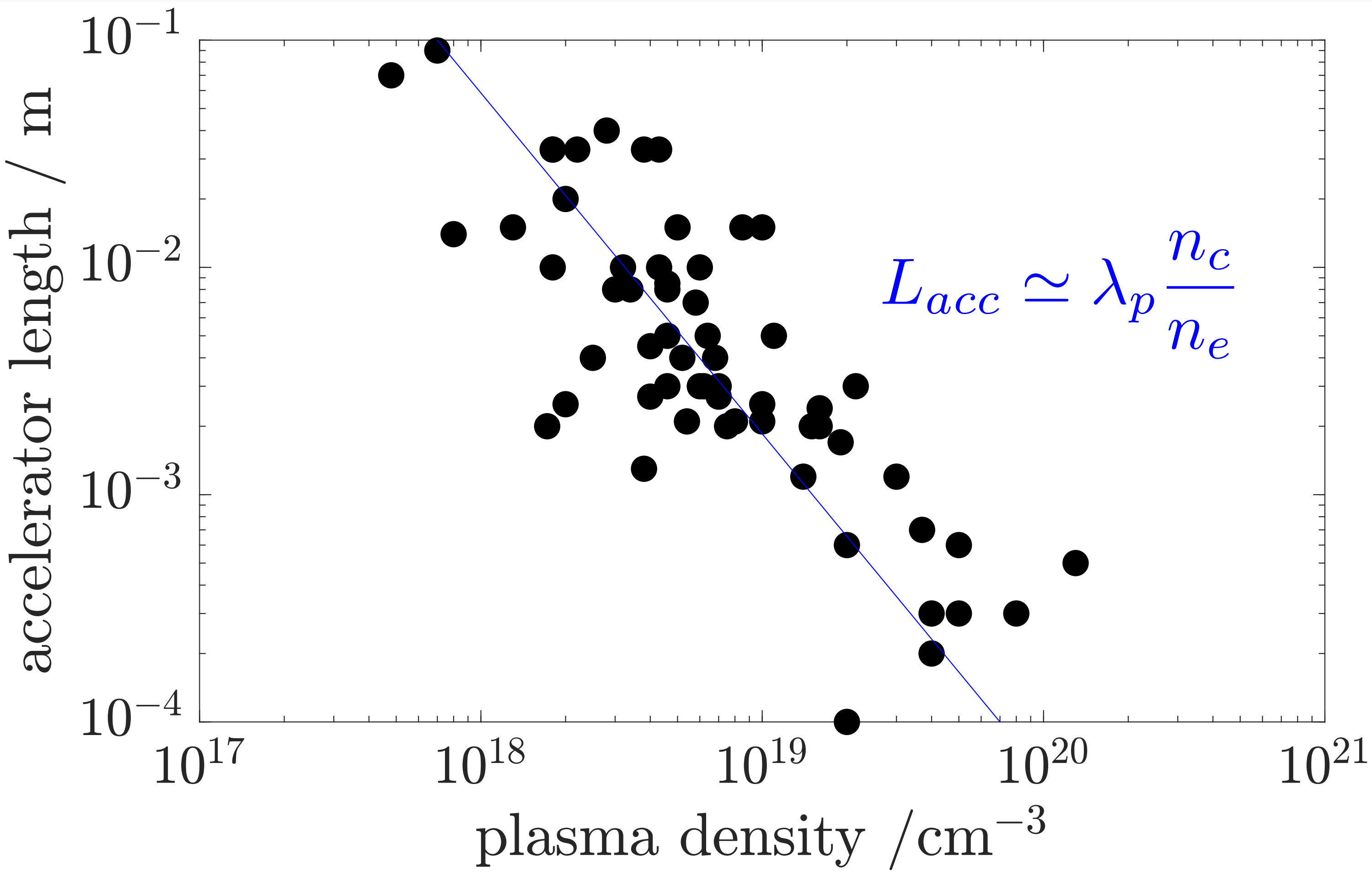
- In 3D non-linear wakes expect $W_{max} \propto a_0$ [Wei Lu, PRSTAB 2007]
- ***But*** these experiments were not at fixed value for vacuum a_0
  - Implies that plasma "prefers" (pulse evolution) $a_0 \approx 3$

Electron energy is limited by dephasing
– move to lower densities **and longer accelerators**



- Accelerator length increases for lower density experiments
  - consistent with dephasing limit

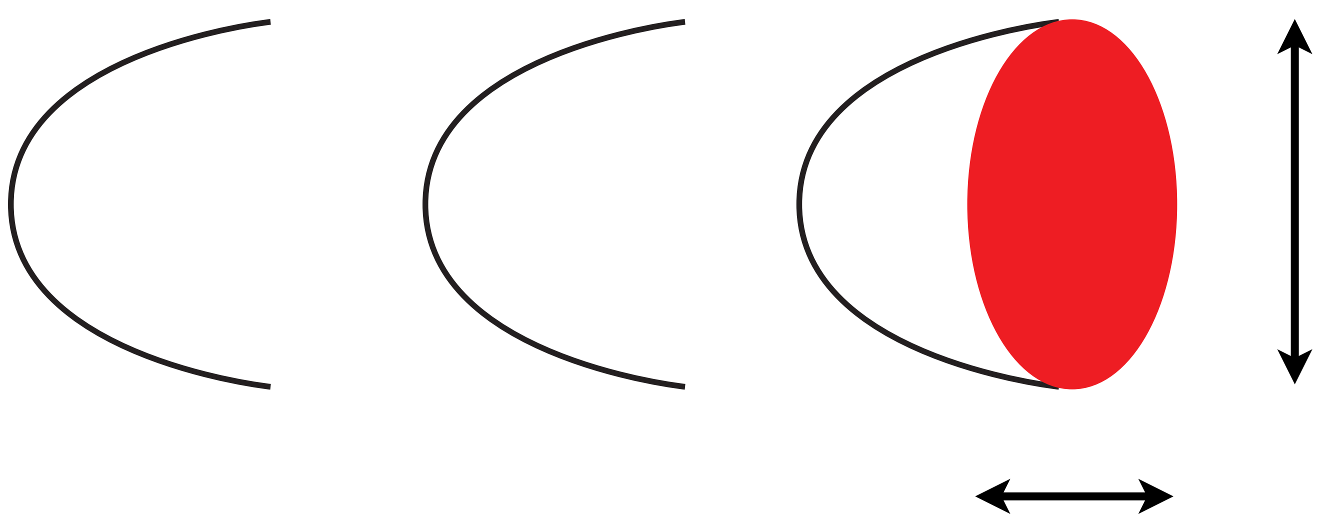
Electron energy is limited by dephasing
– move to lower densities **and longer accelerators**



- Accelerator length increases for lower density experiments
  - data lies close to dephasing length (even for simplest linear regime expression)

Electron energy is limited by dephasing – lower densities need more laser power

$$\text{Power} = \text{intensity} \times \text{area} \propto a_0^2 w_0^2$$



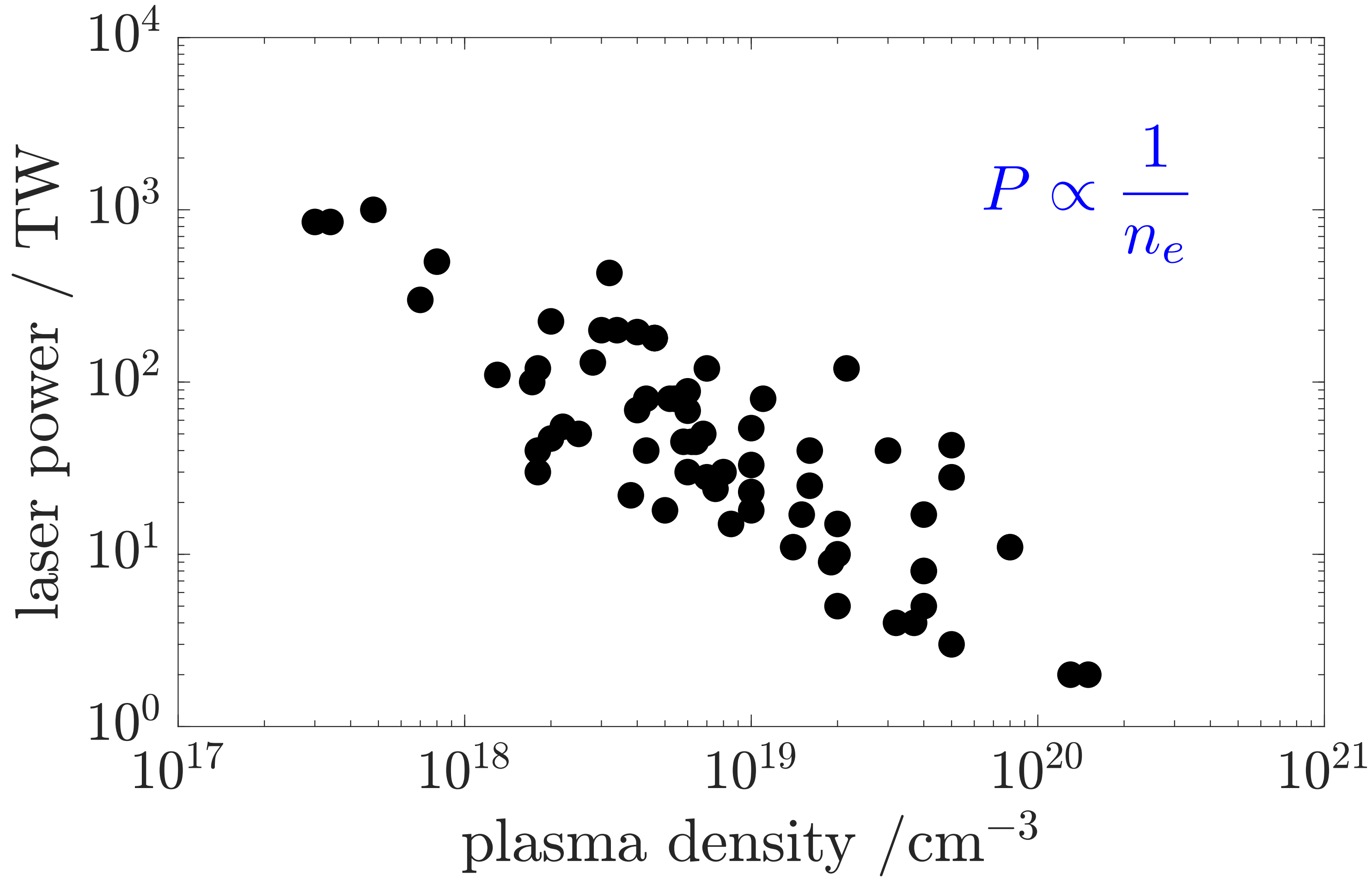
$$a_0 \simeq 3$$

$$2w_0 \simeq \lambda_p$$

$$P \propto \lambda_p^2 \propto \frac{n_c}{n_e}$$

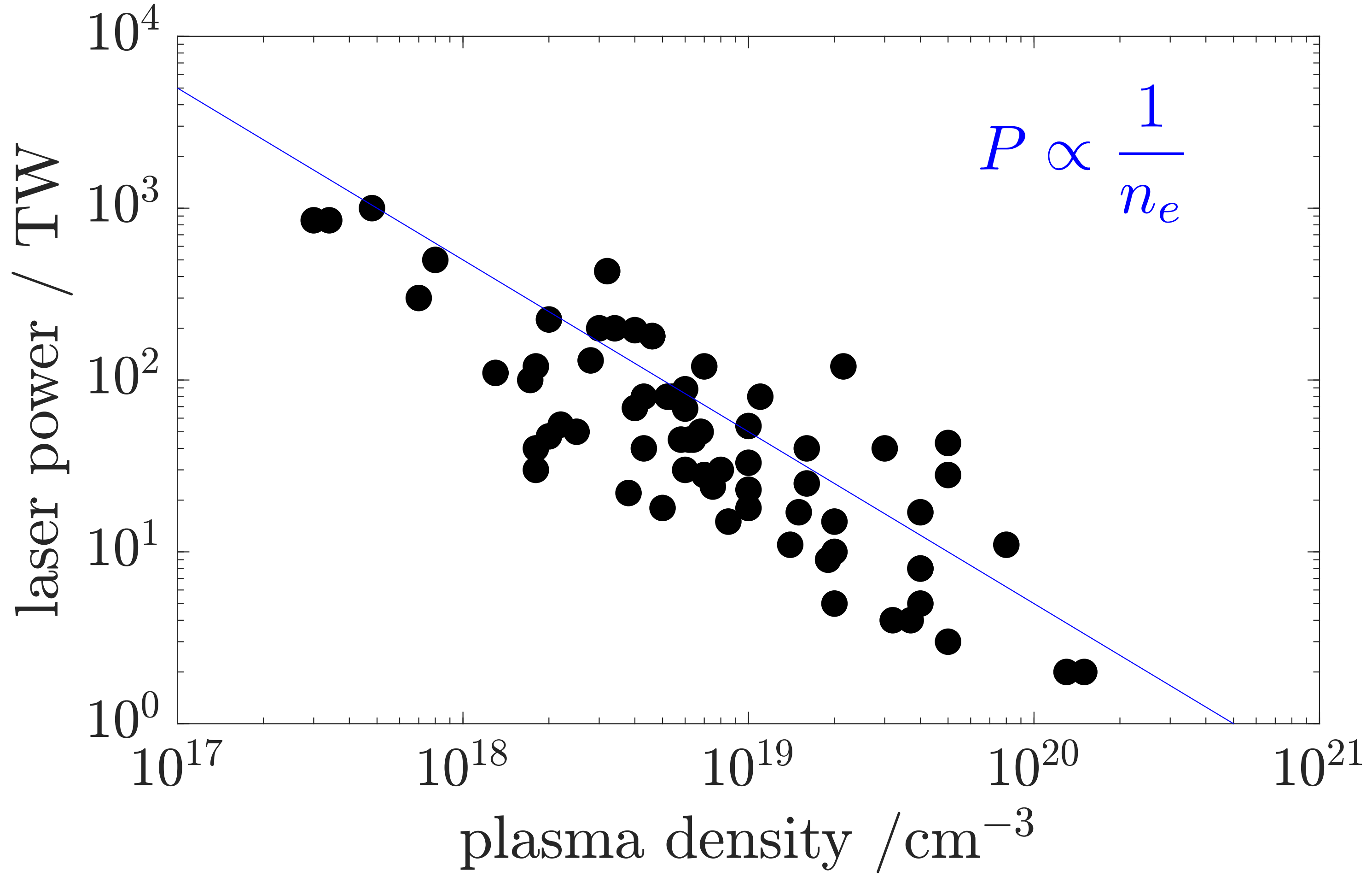
- Driving large amplitude plasma waves at lower density needs more laser power
  - So we expect an inverse relationship between the laser power used to drive the experiment and the density where highest energy beams are reported

Electron energy is limited by dephasing – lower densities need more laser power



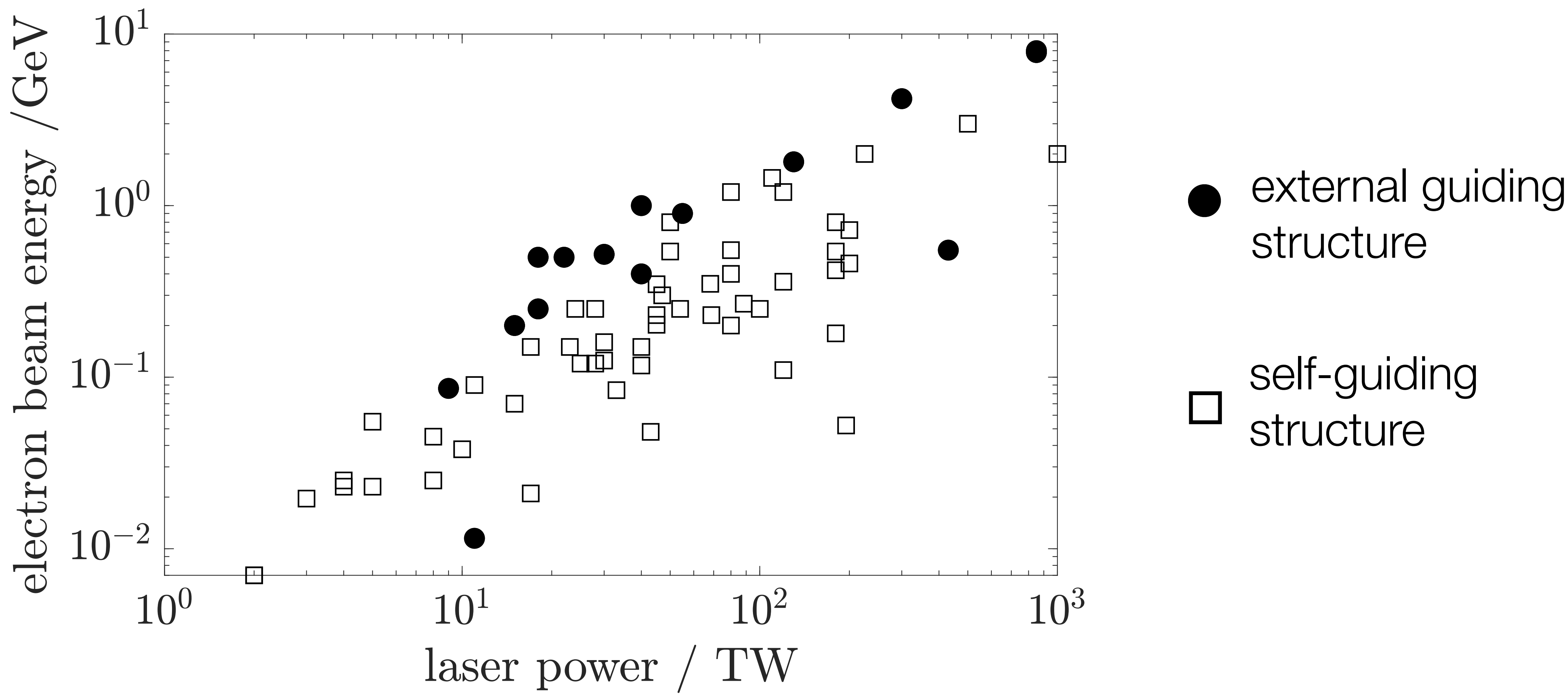
- We do indeed see this inverse scaling
  - can this data tell us anything else?

Electron energy is limited by dephasing – lower densities need more laser power



- We do indeed see this inverse scaling
  - can this data tell us anything else?

To guide or not to guide?



- Data shows that experiments in pre-formed plasma structures are "best" performers
  - i.e. for a given laser power the highest energy beams produced come from guided experiments
  - one (common) explanation is that guiding structure is less lossy

Is injection mechanism the same?

Laser-Driven Acceleration of Electrons in a Partially Ionized Plasma Channel

T. P. Rowlands-Rees,[1] C. Kamperidis,[2] S. Kneip,[2] A. J. Gonsalves,[1,*] S. P. D. Mangles,[2] J. G. Gallacher,[3] E. Brunetti,[3] T. Ibbotson,[1] C. D. Murphy,[4] P. S. Foster,[4] M. J. V. Streeter,[4] F. Budde,[5] P. A. Norreys,[4] D. A. Jaroszynski,[3] K. Krushelnick,[2] Z. Najmudin,[2] and S. M. Hooker[1]

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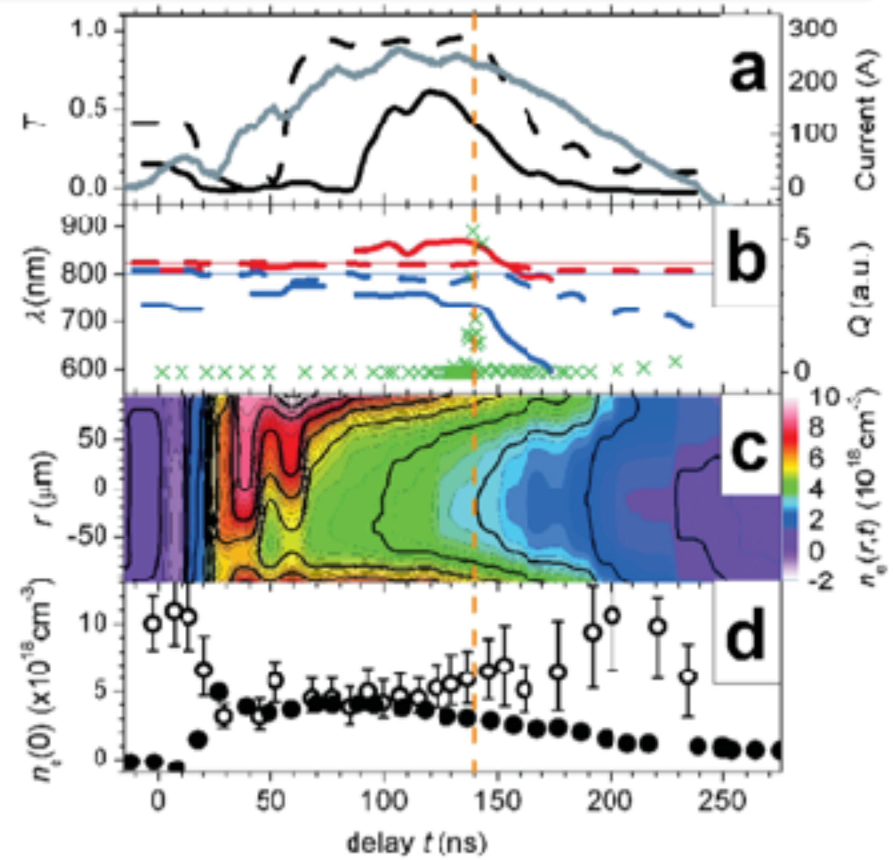
[4]*Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom*
[5]*Friedrich-Schiller-Universität, PF 07737 Jena, Germany*
(Received 19 November 2007; published 14 March 2008)

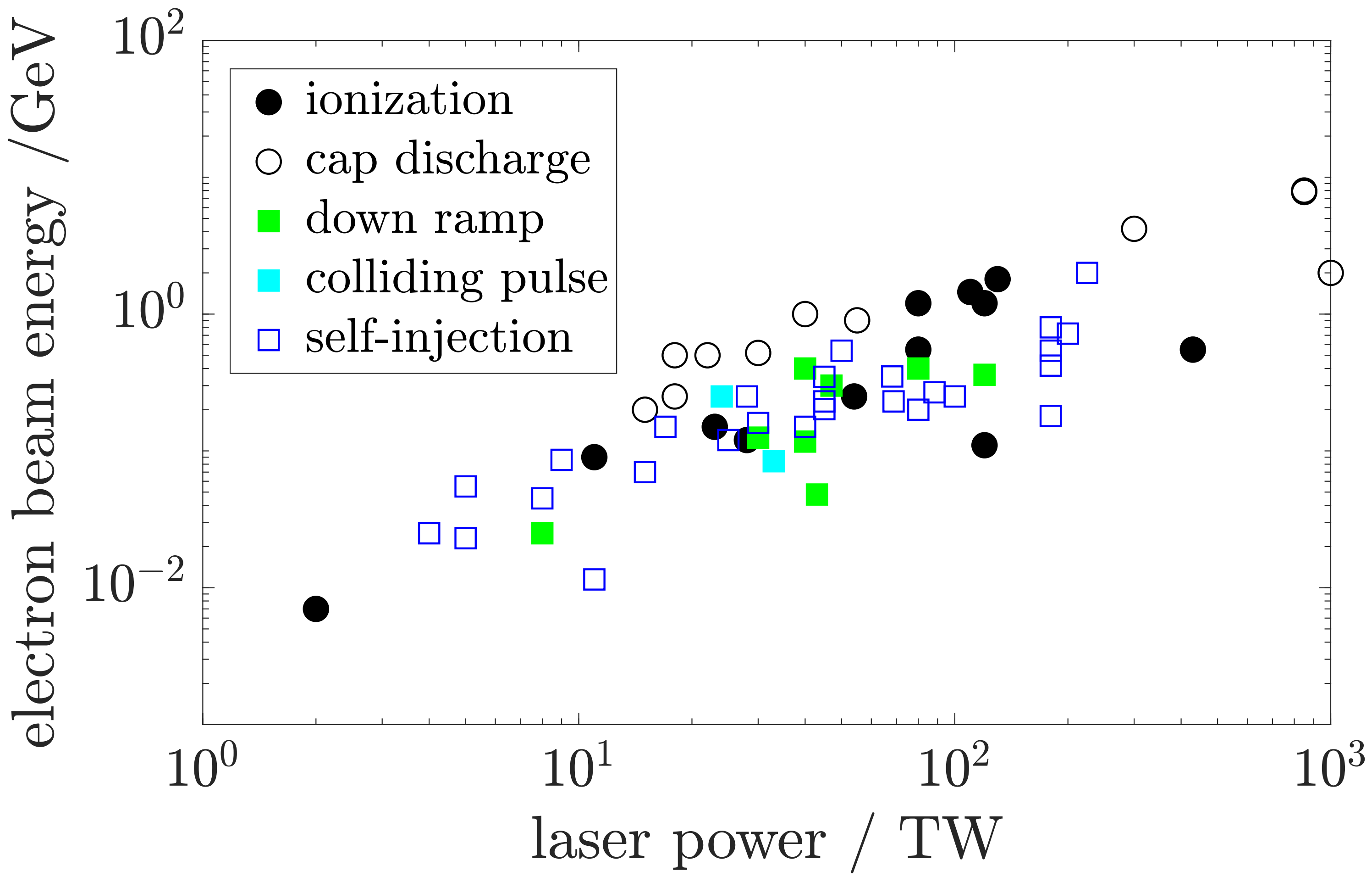
The generation of quasimonoenergetic electron beams, with energies up to 200 MeV, by a laser-plasma accelerator driven in a hydrogen-filled capillary discharge waveguide is investigated. Injection and acceleration of electrons is found to depend sensitively on the delay between the onset of the discharge current and the arrival of the laser pulse. A comparison of spectroscopic and interferometric measurements suggests that injection is assisted by laser ionization of atoms or ions within the channel.

T Rowlands-Rees, PRL, 100, 105005 (2008)



- But is that the final answer?
  - In 2008 an Oxford-led experiment at Astra in UK showed that ionisation injection can play a role inside capillary discharge waveguides
  - Could injection mechanism be the reason behind better performance?

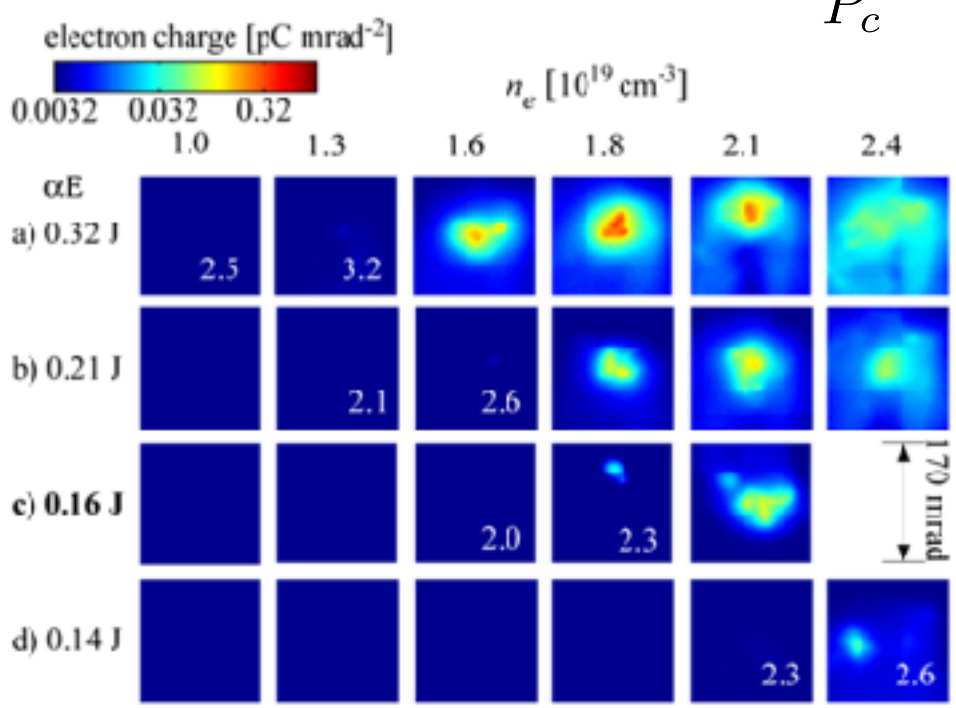
To inject or not to inject?

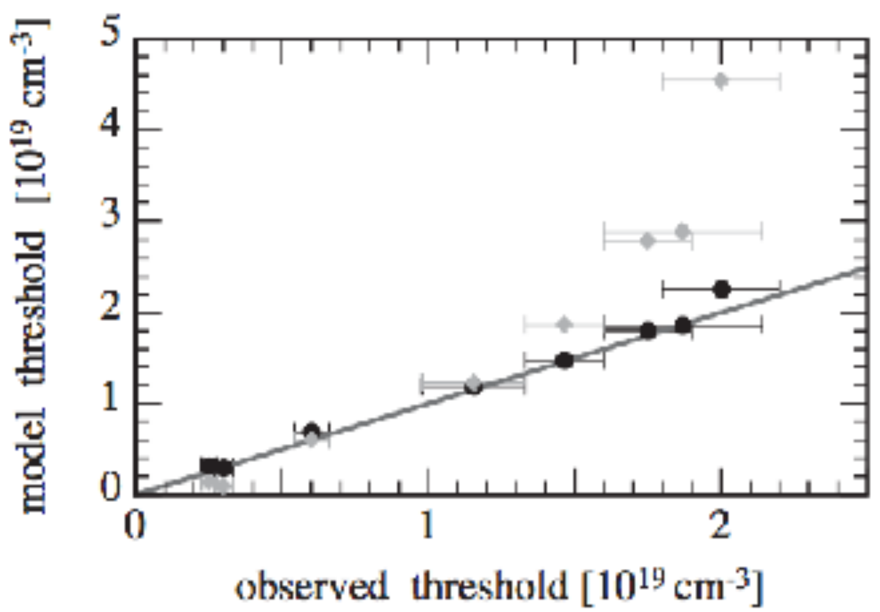


- some ionisation injection experiments also lie at upper edge of distribution
  - data too noisy for a definitive answer, but an interesting research question

Self-injection threshold model

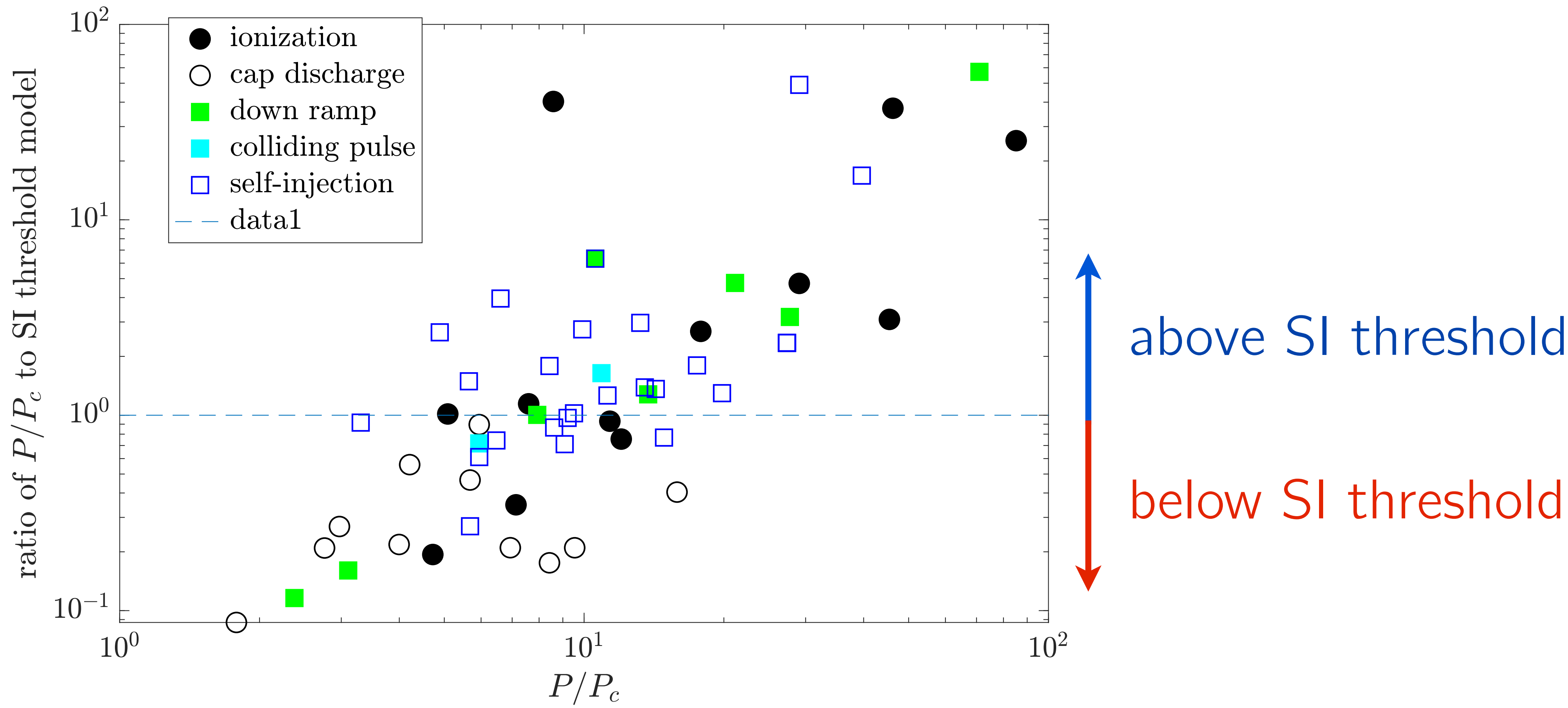
$$\frac{\alpha P}{P_c} > \frac{1}{16}\left[\ln\left(\frac{2n_c}{3n_e}\right) - 1\right]^3$$





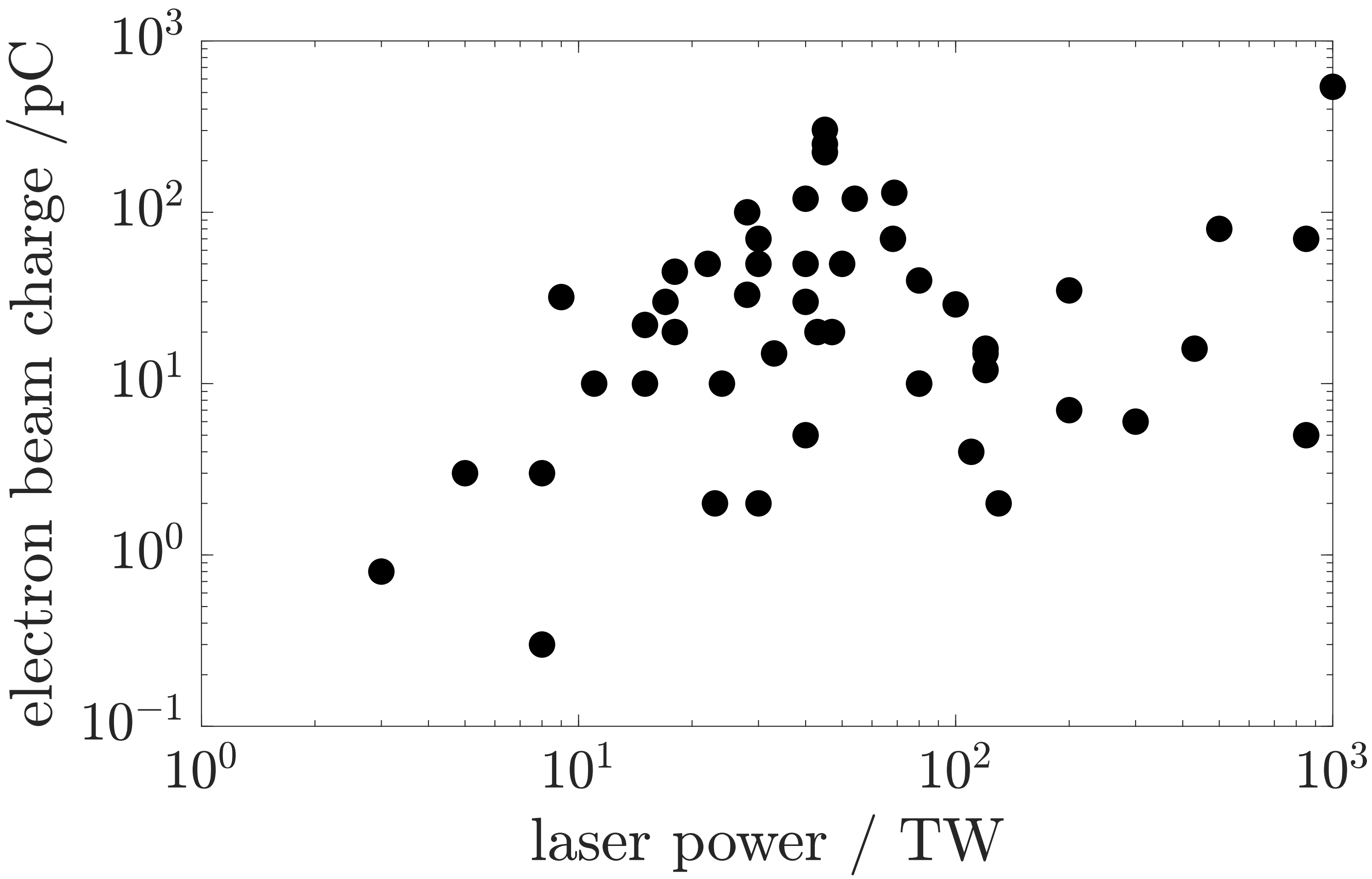
- Simple model for self-injection threshold [Mangles PRSTAB 2012]
  - takes into account pulse evolution (self-focusing and compression)
  - looks to see if bubble will reach size (amplitude) needed for SI
- – Experimental data where threshold is specifically reported agrees
- – what about this larger data set?

Self-injection threshold model



- many self-injection experiments (mostly) lie above this
- other injection method experiments often lie below this threshold

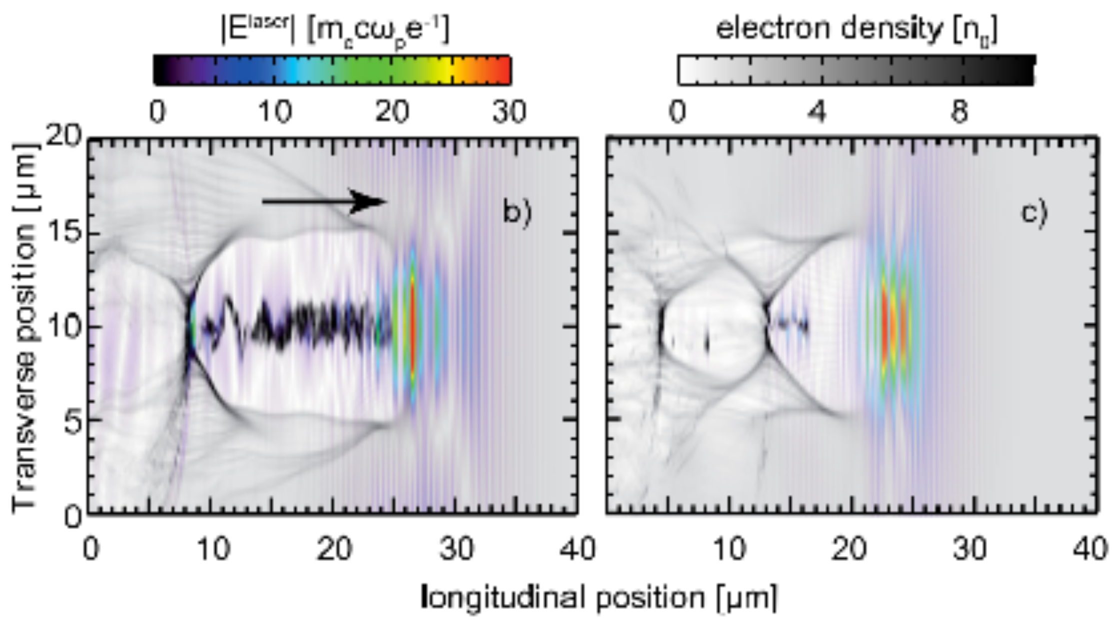
Electron beam charge

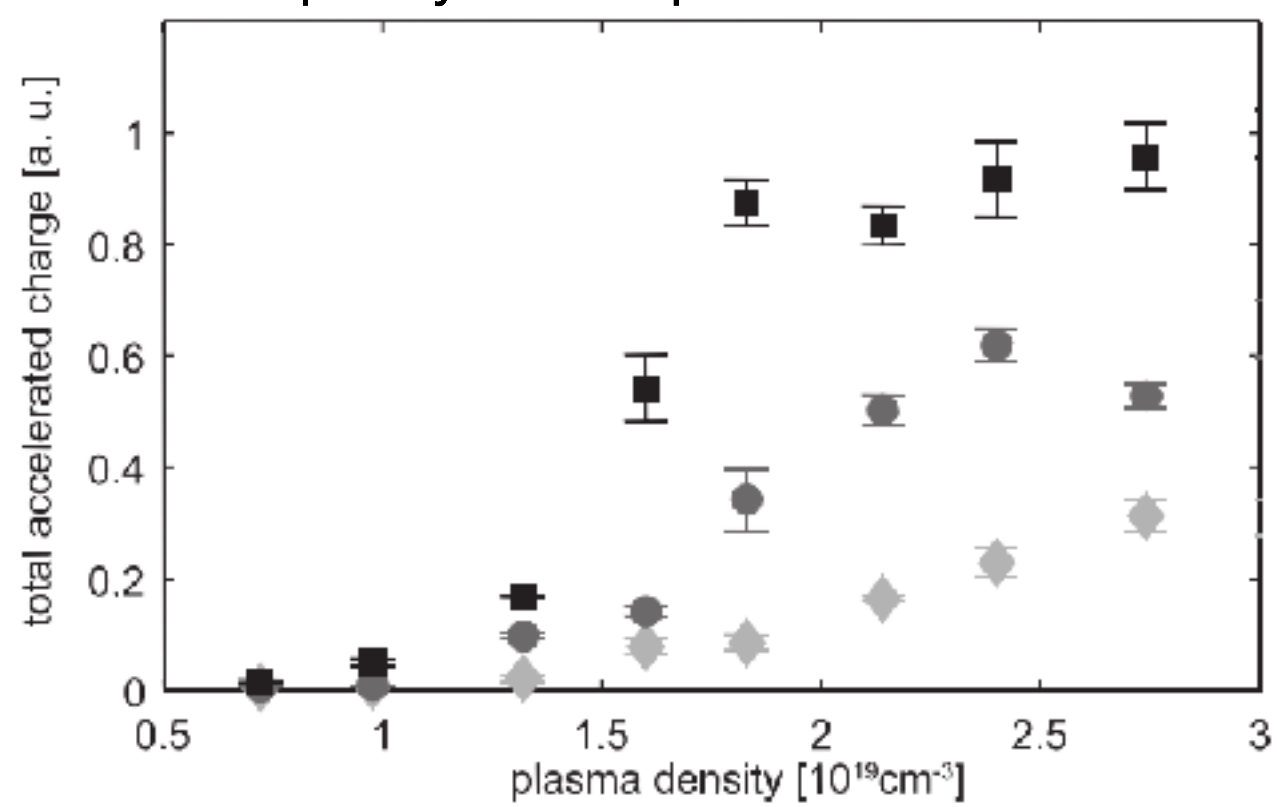


- Electron beam charge very variable between experiments
  - different measurement techniques?
  - different focal spot qualities?

But only energy within the focal spot is captured and drives the wakefield

same pulse energy, different quality focal spots:

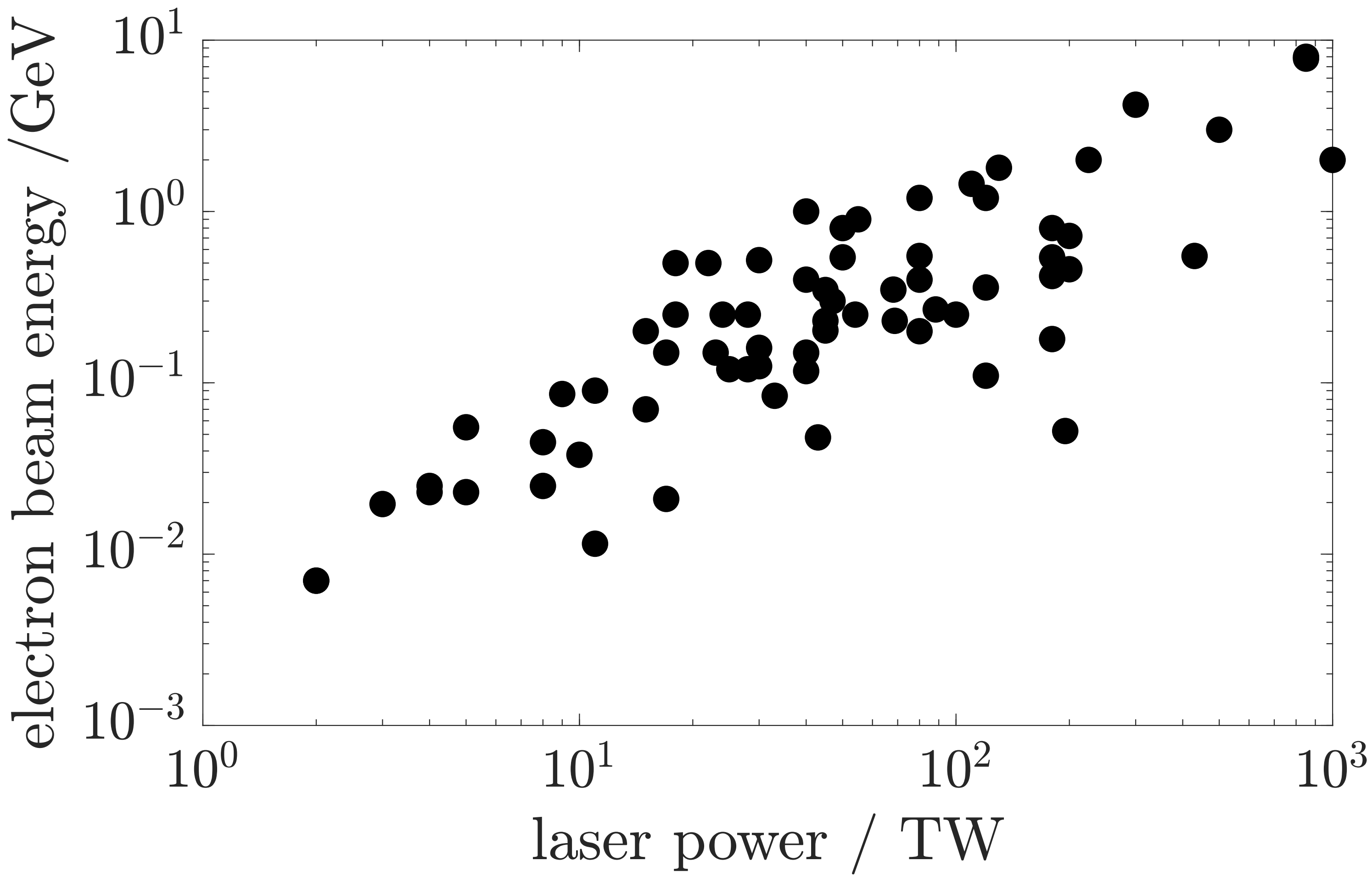




- Most (not all) groups only quote the ***total*** power for their laser system (i.e. total energy / pulse duration)
- But some of this is wasted and not coupled into the wake
  - e.g. Mangles PRSTAB 2012, Genoud POP 2013)
  - this is possibly why there is so much noise in the scaling plots

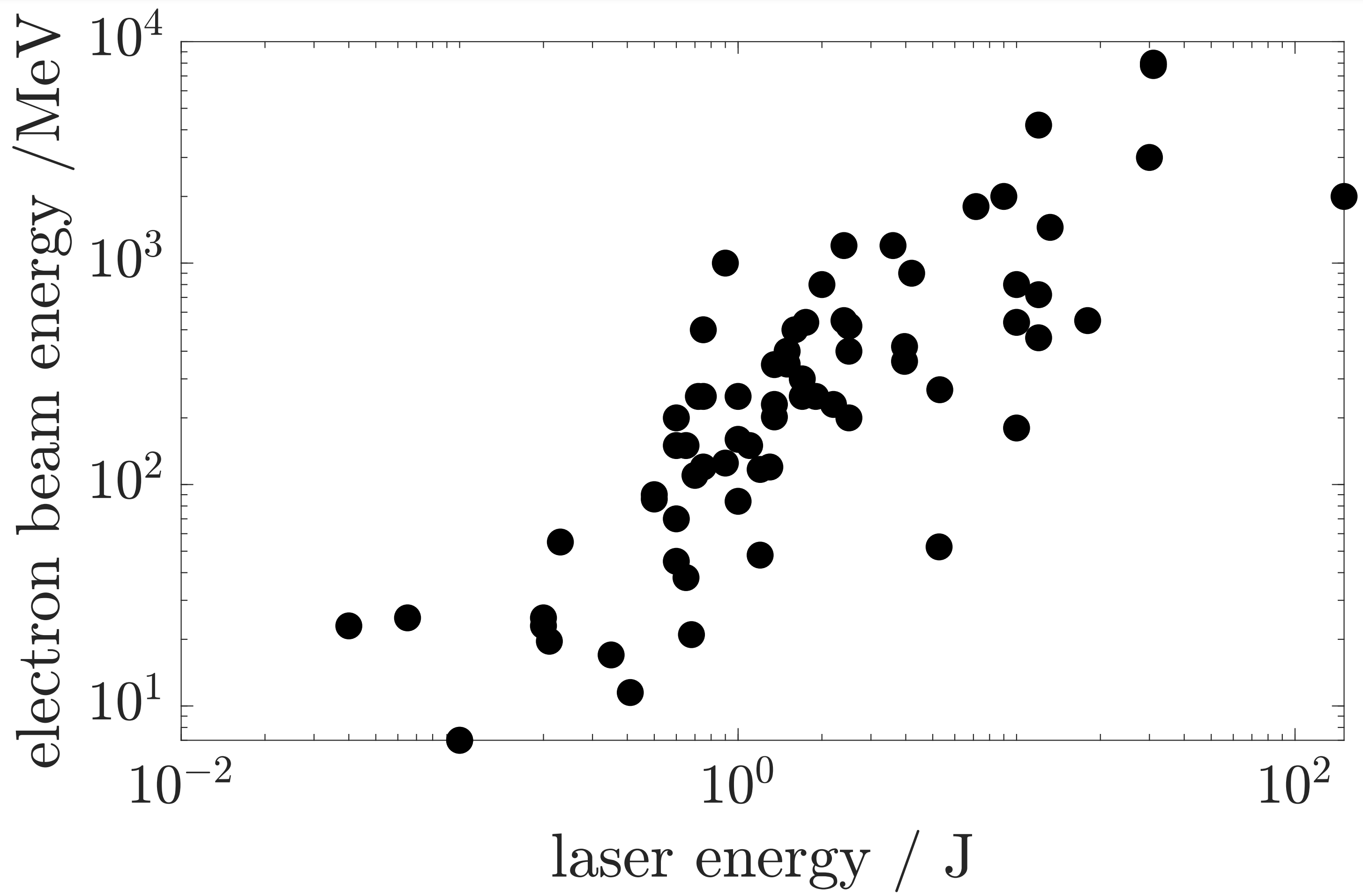
What are the next big directions going to be?

What are the next big directions going to be? – more power, more energy



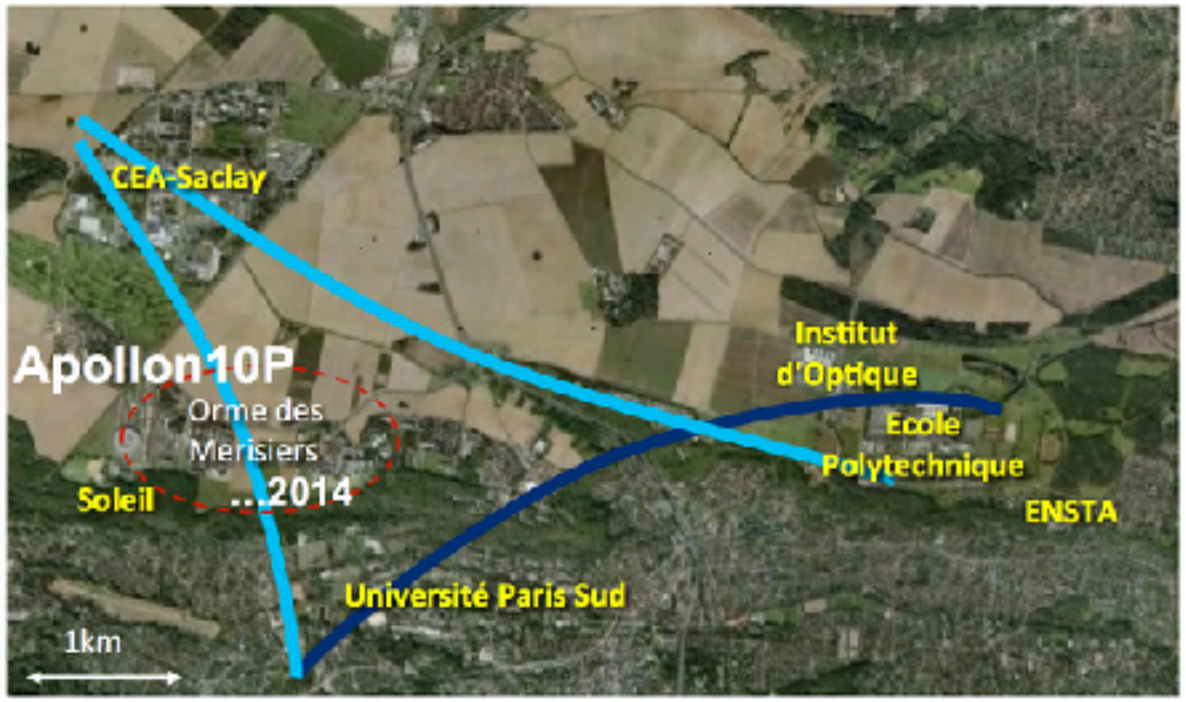
- Turn up the power, turn up the energy!

What are the next big directions going to be? – more power, more energy



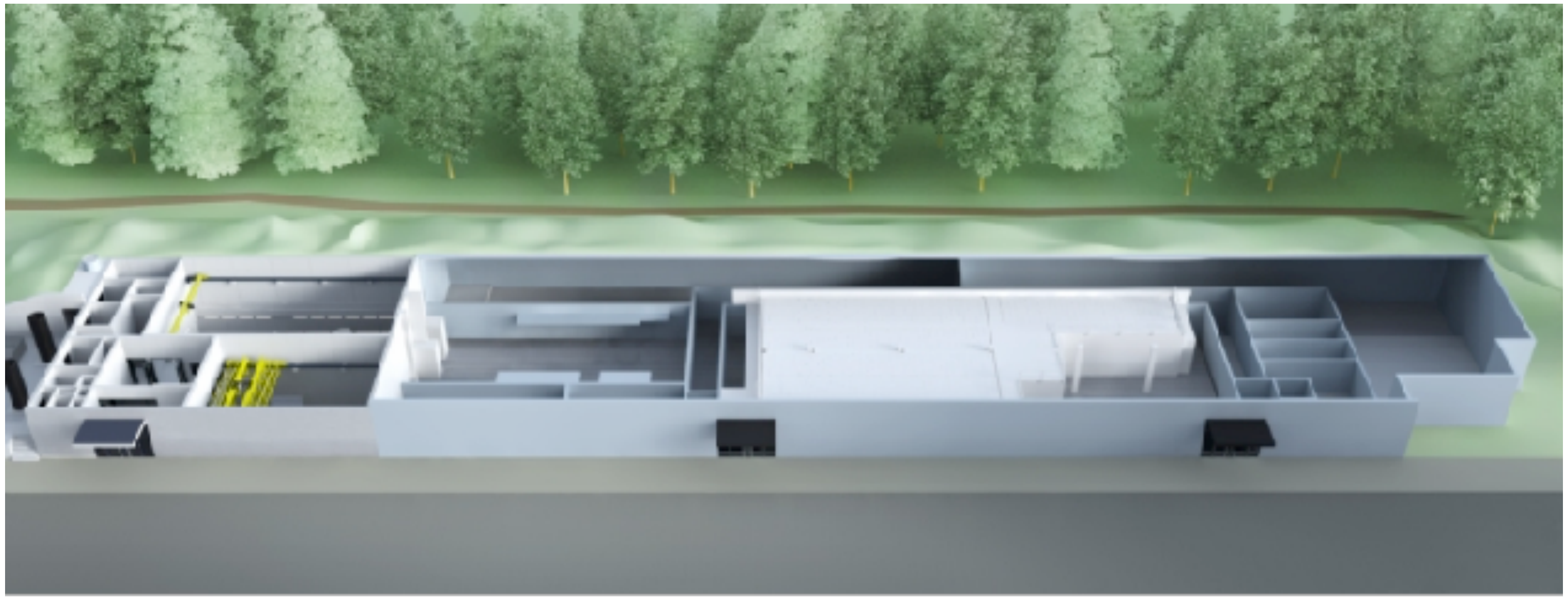
- **BUT** remember its not really the power that is important... pump depletion in blow-out regime is $L_{pd} \simeq \frac{n_e}{n_c} c\tau_L$
- compare this with simple expression for dephasing length $L_{dp} \simeq \frac{n_e}{n_c}\lambda_p$
- so, to get to dephasing energy we need pulse lengths $c\tau \simeq \lambda_p$
  - » to reach higher energy **we need high energy laser pulses**

What are the next big directions going to be? – more power, more energy



- Apollon laser in France
  - 150 J; 15 fs (10 PW)
  - 1 shot per minute
  - multiple beams
  - OPCPA front end with TiSapph amplifiers

What are the next big directions going to be?
– more power, more energy



- CALA laser facility at MPQ in Germany
  - ATLAS 3000
    - 50 - 75 J, 25 fs (2 - 3 PW)
    - 1 Hz
  - PFS & PFS Pro
  - 100 mJ, 5 fs (20 TW) or 1 J, 5 fs (200 TW)

What are the next big directions going to be?
– more power, more energy

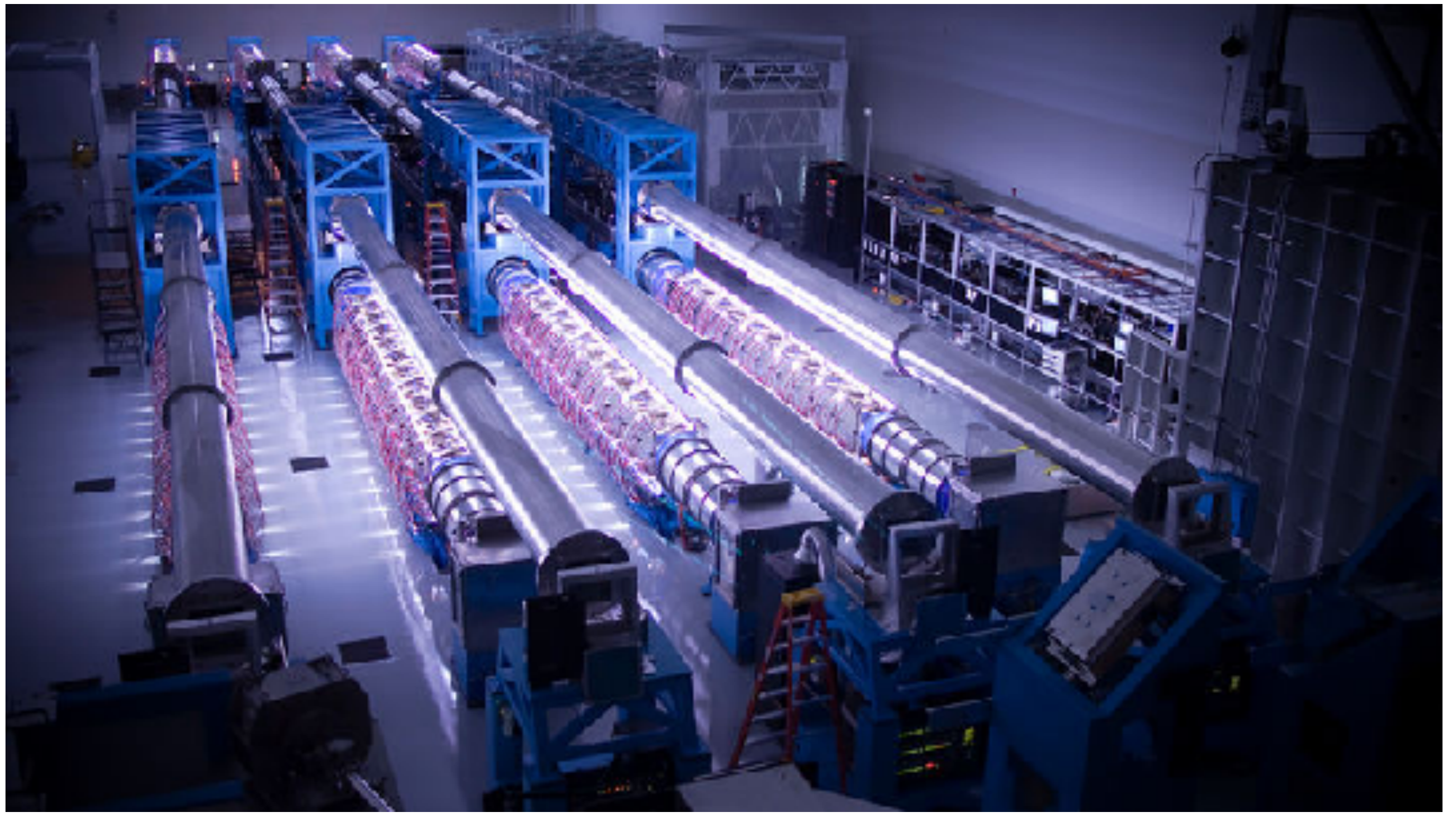
eli

- ELI Nuclear Physics (Romania)
  - 2 x 10 PW
  - 1.3 PW demonstrated

What are the next big directions going to be? – more power, more energy

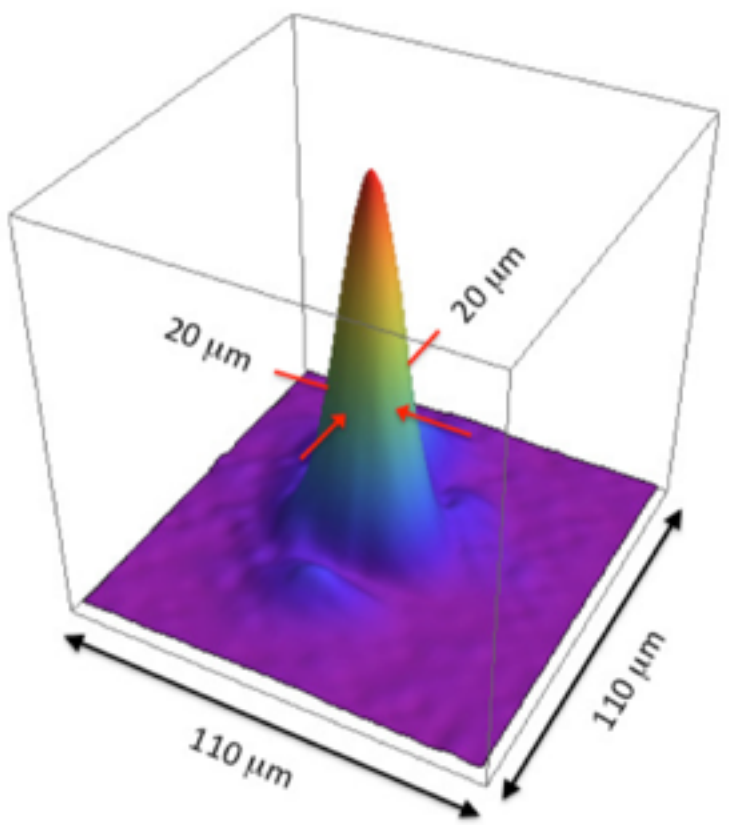
- ELI Beamlines (Czech Rep.)
  - 10 PW, 1.5 kJ in 150 fs

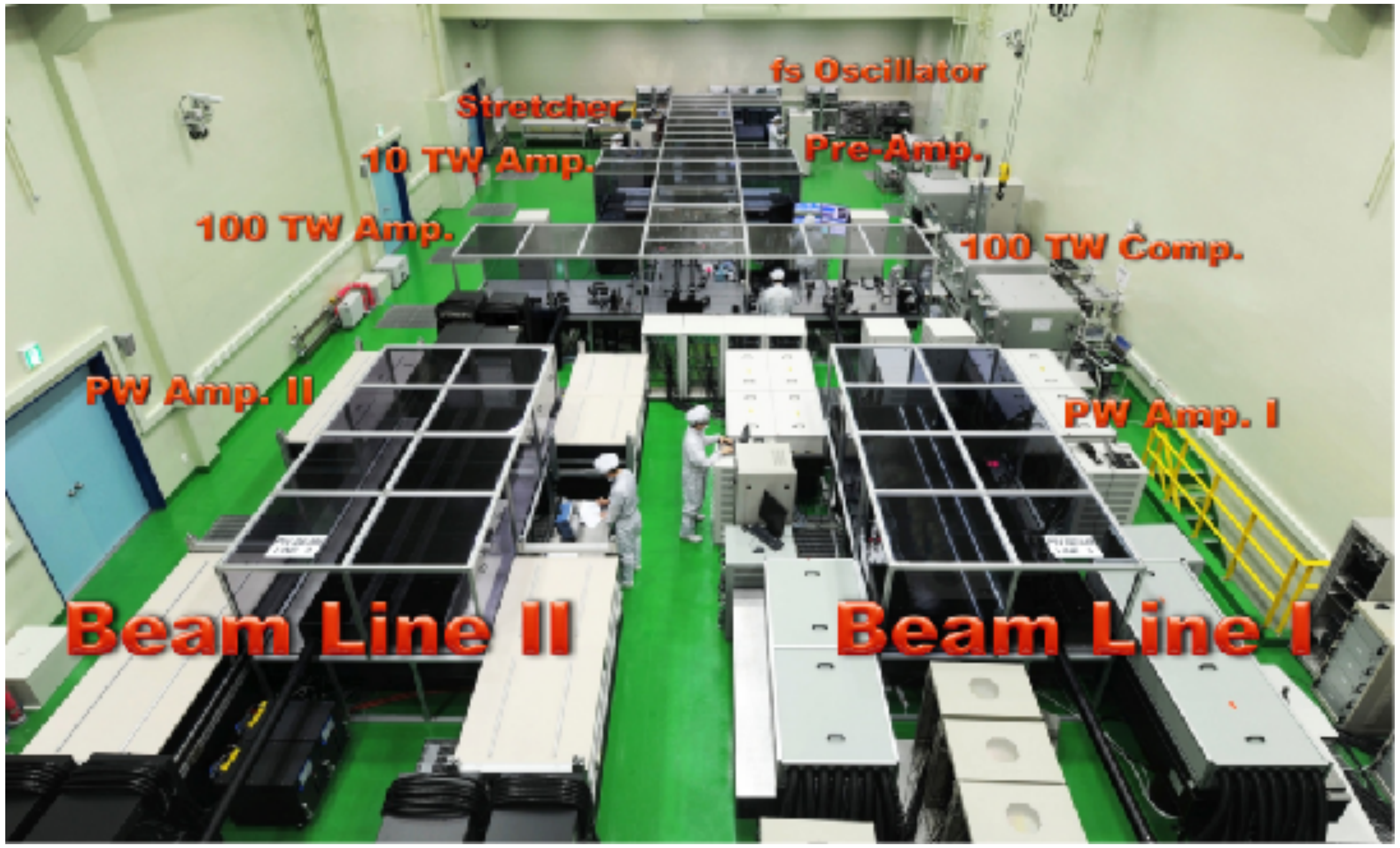
What are the next big directions going to be? – more power, more energy



- OPAL, Rochester USA
  - 75 PW (1.5 kJ, 20 fs)

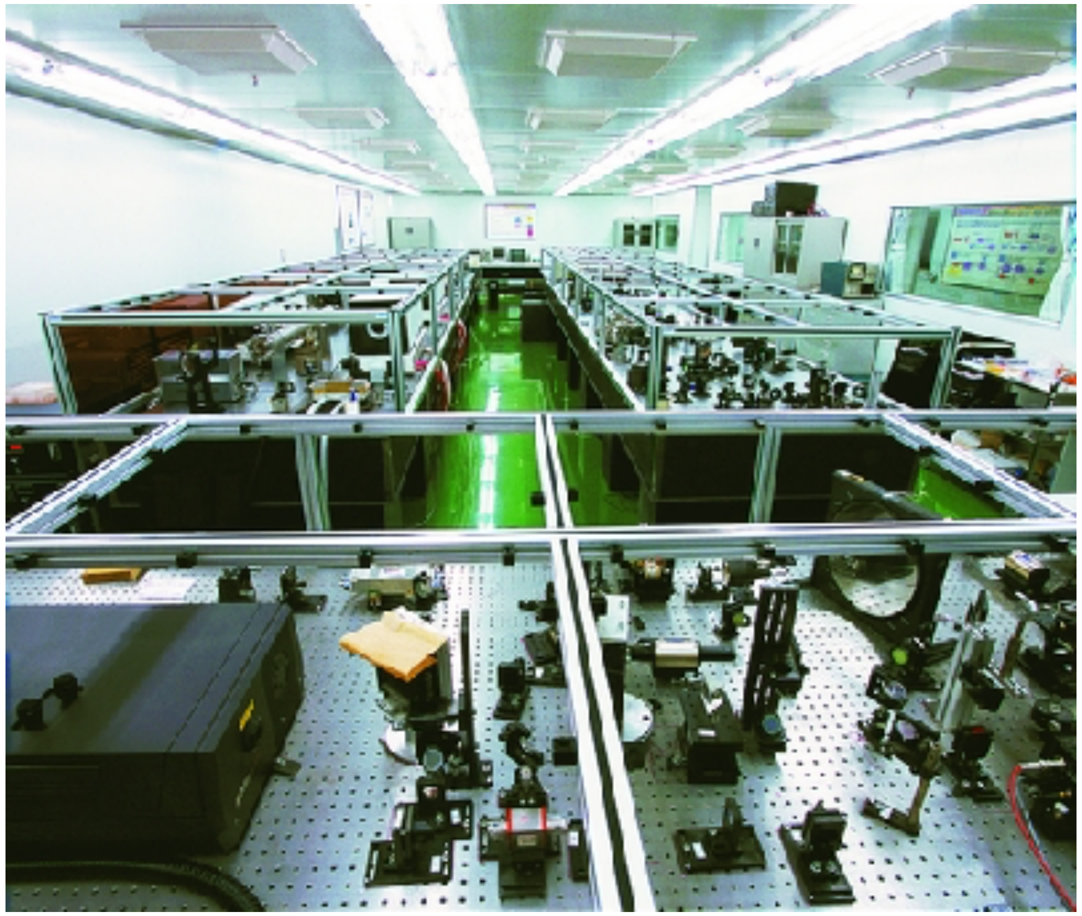
What are the next big directions going to be? – more power, more energy





- CoRels Korea
  - 30 fs, 1.5 PW dual laser system

What are the next big directions going to be? – more power, more energy



- SULF, Shanghai China
  - 5.3 PW, 120 fs
- Station of Extreme Light, 100 PW expected online 2023

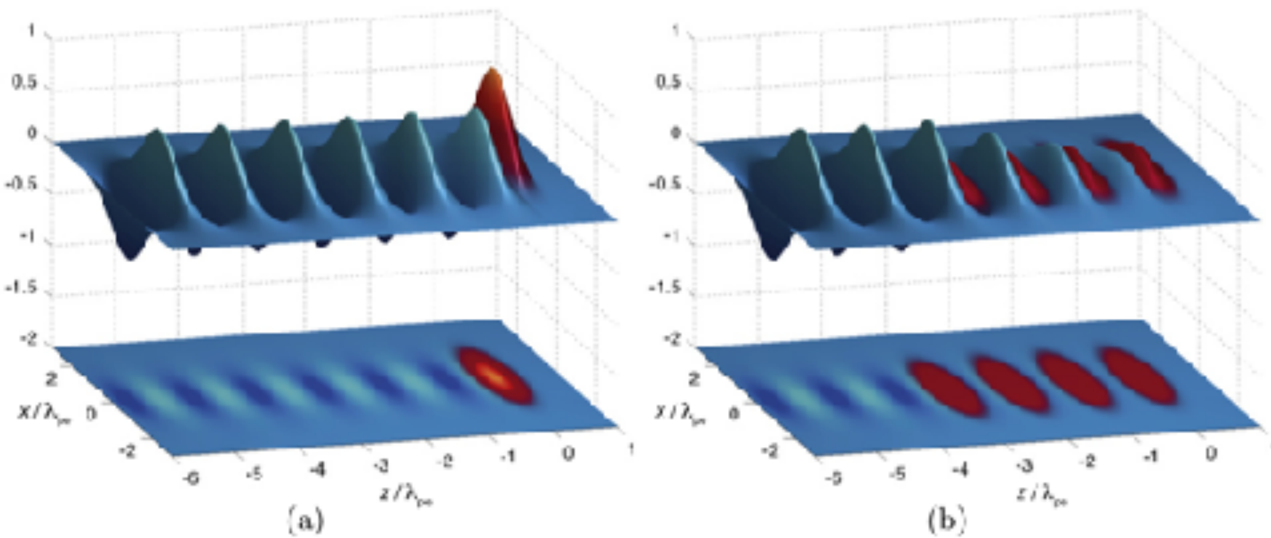
What are the next big directions going to be? – applications, applications, applications

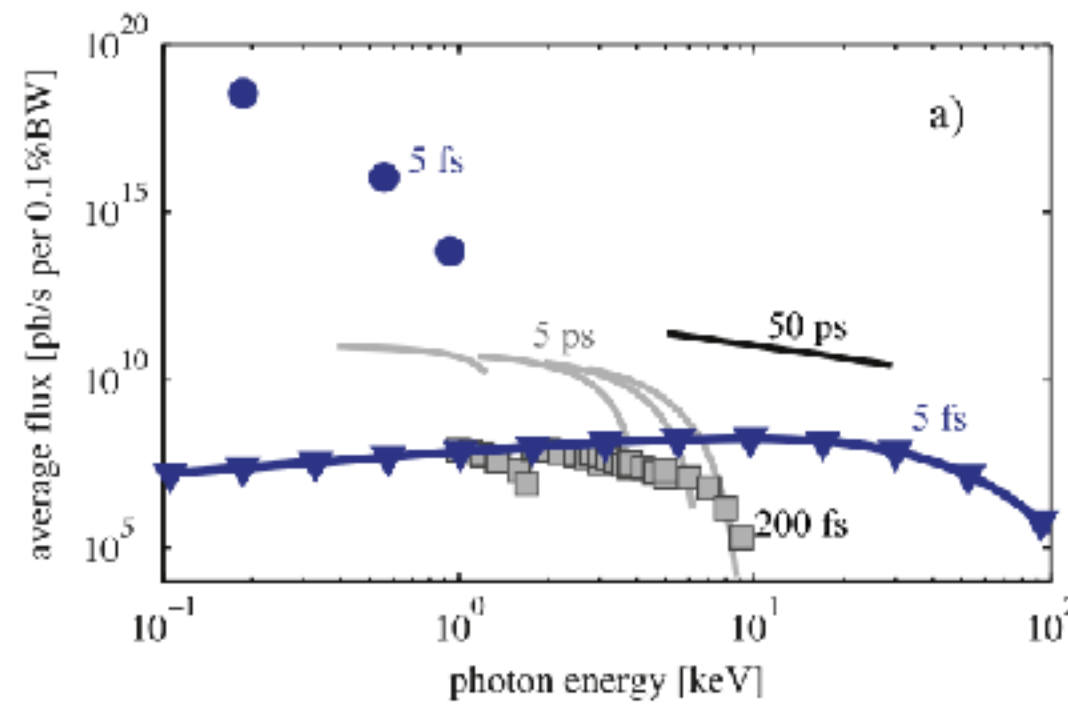
See talk by Zulfikar Najmudin!

What are the next big directions going to be? – increasing the repetition rate

- very high repetition rates needed for many applications
  - (parameter scans, statistics, accumulation of low signals)
- e.g. lights sources, colliders
  - can we every get to > 10 kHz needed at the very high laser powers needed?
  - Ti:Sapph and OPCPA lasers are $< 0.1\%$ efficient, at > 10 kHz that is an expensive electricity bill
- is it time for a new approach?

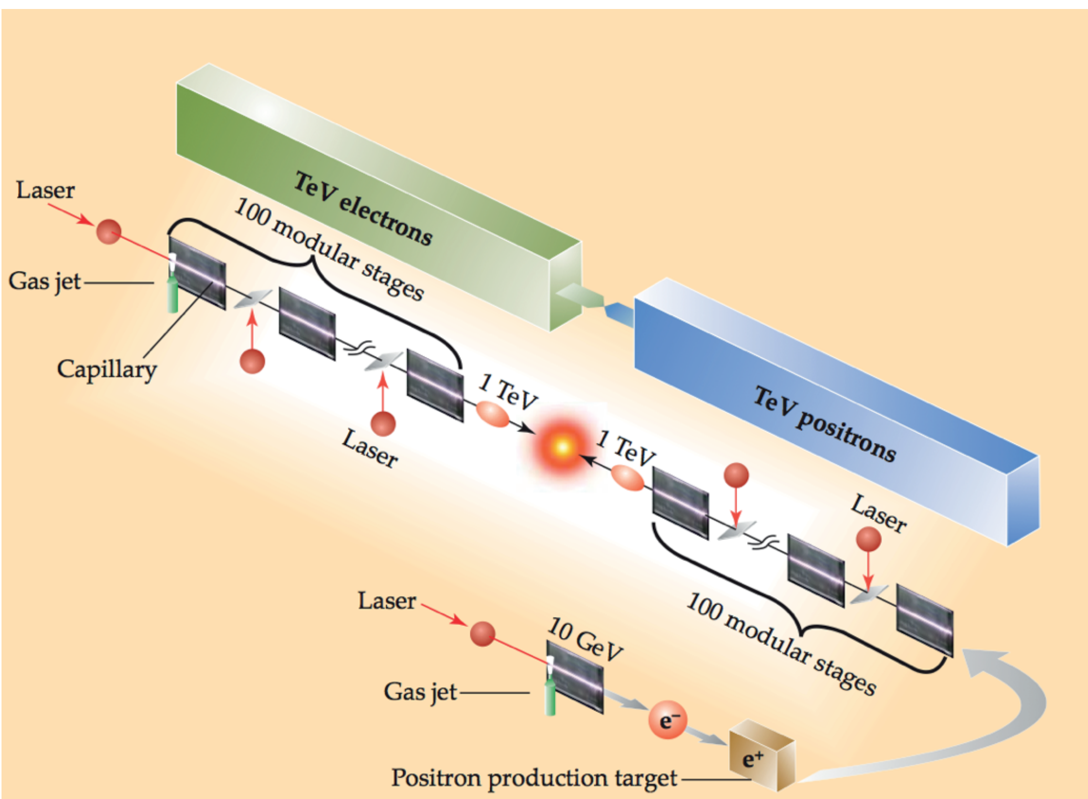
What are the next big directions going to be? – increasing the repetition rate





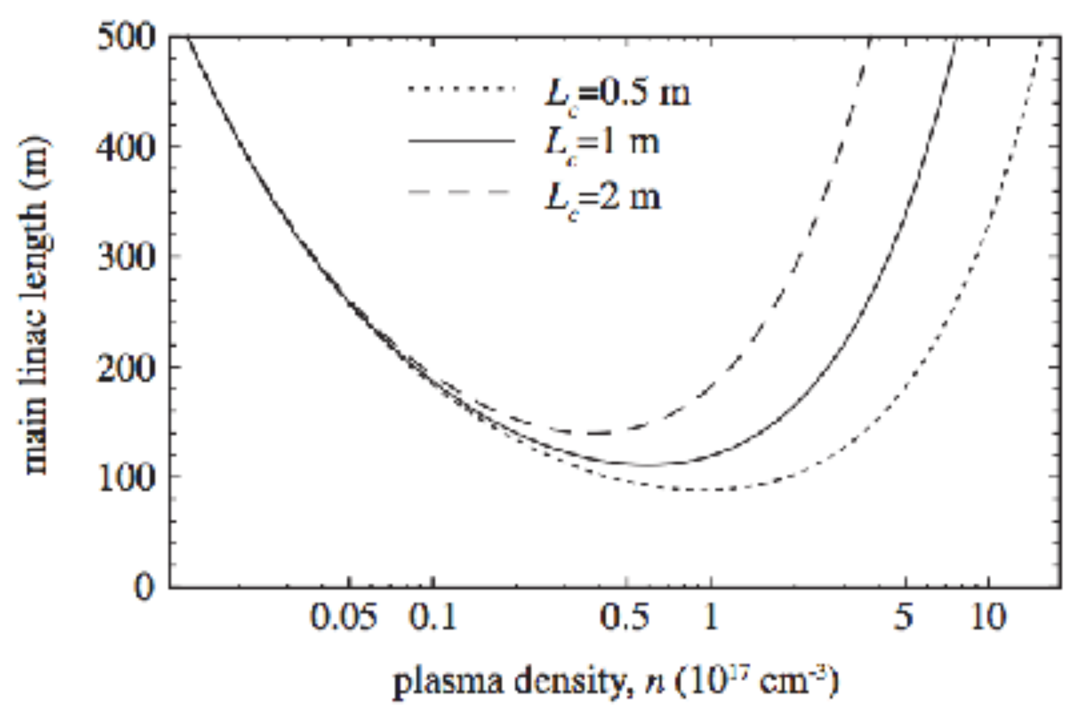
- High rep rates are easier for lower pulse energies
  - can we combine many lower energy pulses to get make a high rep rate LWFA?
  - highly efficient diode pumping can be used, e.g. fibre lasers can have > 20%
- Three approaches (that I know of)
  - Coherent combination (N lasers coherently combine to make one big pulse) [ICAN project]
  - Incoherent combination (N lasers incoherently combine to make one big pulse) [LBNL, Schroeder et al Phys Plasma 2014]
  - Resonant excitation (separate pulses buy plasma period) [JAI + Jena, Hooker et al J Phys B 2014]

What are the next big directions going to be?
– staging to beat depletion: a TeV collider?



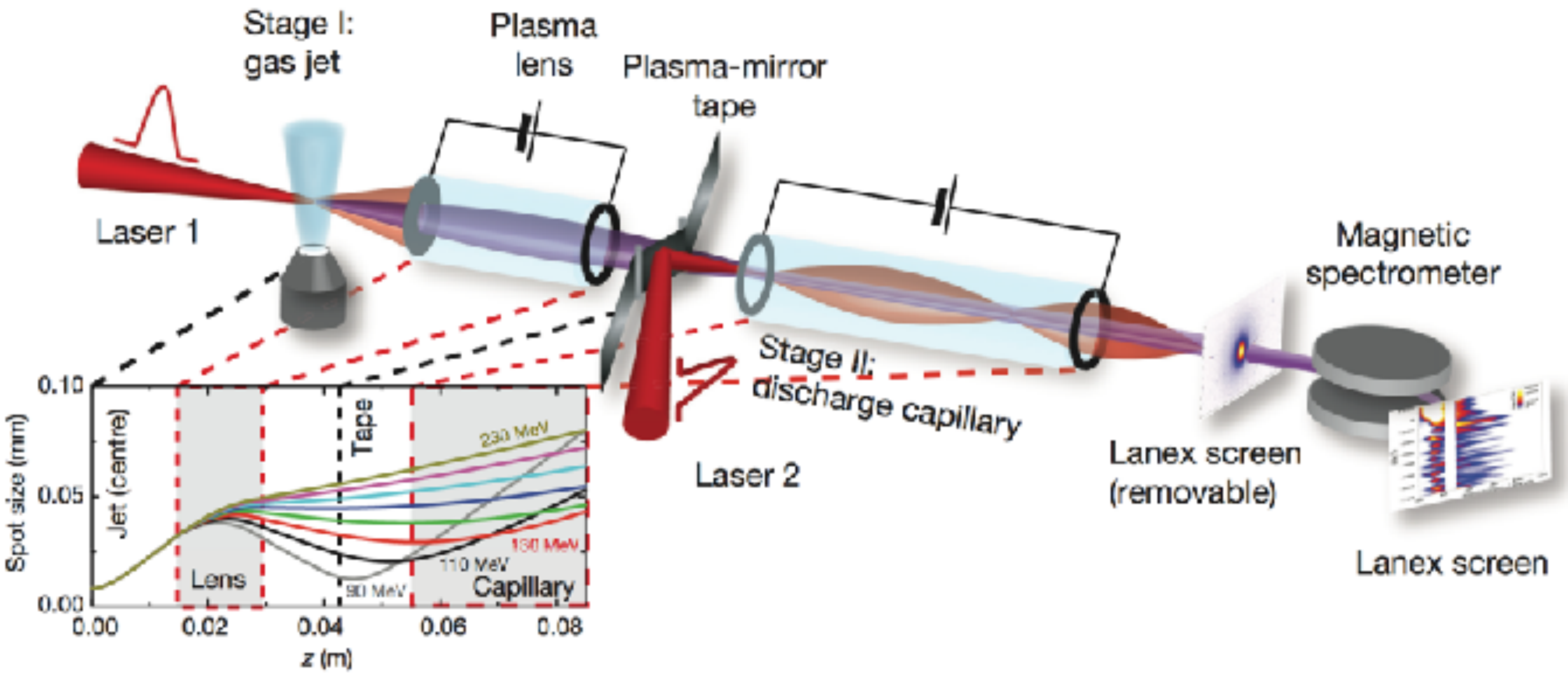
Leemans & Esarey, Physics Today 2009

Length of a 1 TeV (CoM) laser plasma collider

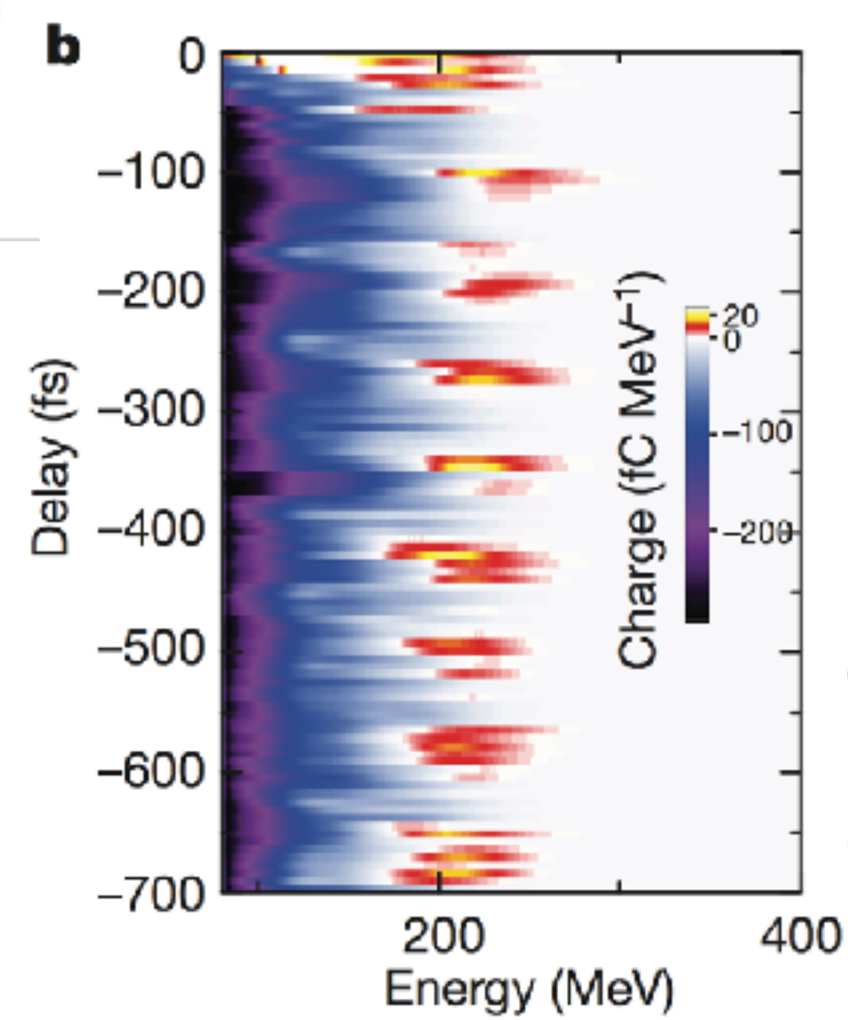


Schroeder et al PRSTAB 2010

What are the next big directions going to be? – staging to beat depletion: a TeV collider?



Steinke et al Nature 2016



- "low" energy staging demonstrated in 2016
  - » 120 MeV beam from gas jet accelerated to 200 MeV in second stage

Summary

- LWFA are a rapidly growing area
  - I gave you an overview of the high energy frontier
    - there's much more to LWFA than that though (see other talks on diagnostics, applications etc)
  - I showed you some of the trends in the experimental data
    - higher energy beams needs lower density plasma, longer accelerator & higher power laser
  - Future directions:
    - energy
    - repetition rate
    - applications
    - staging -> colliders