Multi-GeV electron acceleration with self-guided laser wakefield accelerators

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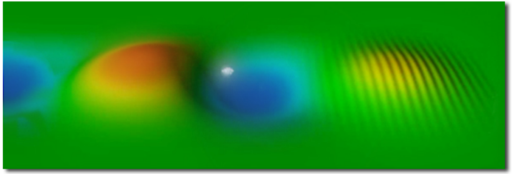
Plasma accelerators

100s GV/m accelerating fields in bubble moving with $\gamma_p^2 \simeq n_c/n_e$

Femtosecond bunch duration yielding kA current[1]

Bright, coherent betatron x-rays suitable for imaging[2]
(Also see J. Wood talk Fri 12:00 and J. Cole talk, Tue WG4 16:30)



$$E_0 = 96\sqrt{\frac{n_e}{10^{18}\mathrm{cm}^{-3}}}\ \mathrm{GV/m}$$

[1] Lundh *et al.*, Nat Phys **7**, 2011
[2] Cole *et al.*, Sci Rep **5**, 2015

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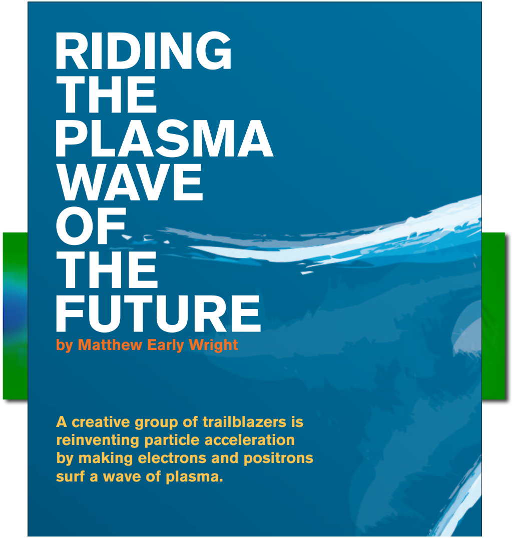

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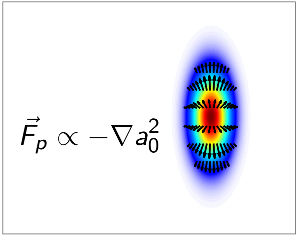
[1] Lundh *et al.*, Nat Phys **7**, 2011
[2] Cole *et al.*, Sci Rep **5**, 2015

How do laser wakefield accelerators work?

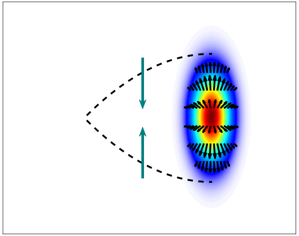


$$\vec{F}_p \propto -\nabla a_0^2$$

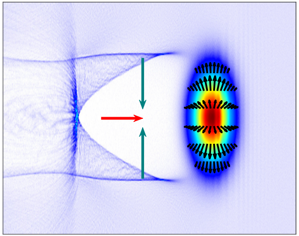
$$\vec{a}_0 = \frac{q_e \vec{E}}{m_e c \omega_L}$$

$$\vec{F}_p \propto -\frac{q_{e,i}^2}{m_{e,i}} \nabla (I \lambda^2)$$

$$\nabla^2 \phi = -\frac{q_e (n_i - n_e)}{\epsilon_0}$$



$$\vec{E}_z \propto \frac{\delta n}{n_e}$$



Energy scaling in laser wakefield accelerators

Linear theory[3] gives

$$\Delta W \propto n_e^{-1}$$

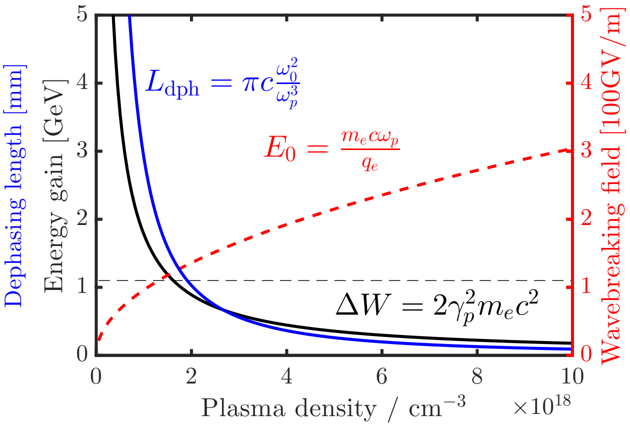
But dephasing length

$$L_{\mathrm{dph}} \propto n_e^{-3/2}$$

With lowering plasma density

$$L_{\mathrm{dph}} \gg z_R$$

Need guiding!



[3] Tajima, Dawson, PRL **43**, 1979

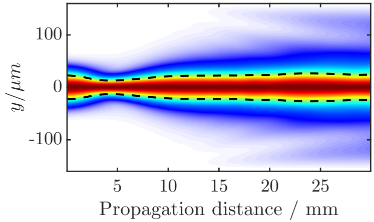
Self-guiding

Can derive an envelope equation[4] for the laser spot size R:

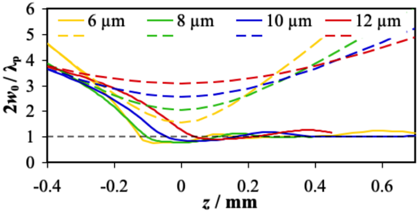
$$\frac{\mathrm{d}^2 R}{\mathrm{d}z^2} + \overbrace{\frac{\langle K^2 \tilde{r}^2 \rangle}{R}}^{\textit{Self focussing}} - \underbrace{\frac{\epsilon^2}{R^3}}_{\textit{Diffraction}} = 0$$

Increasing R reduces diffraction, allowing self-guiding at lower $n_e \rightarrow$ increasing ΔW

$P/P_c = 25,\ n_e = 3 \times 10^{18}\ \mathrm{cm}^{-3}$



$P/P_c = 2,\ n_e = 1.7 \times 10^{19}\ \mathrm{cm}^{-3}$



From Thomas *et al*, PRL **98**, 2007

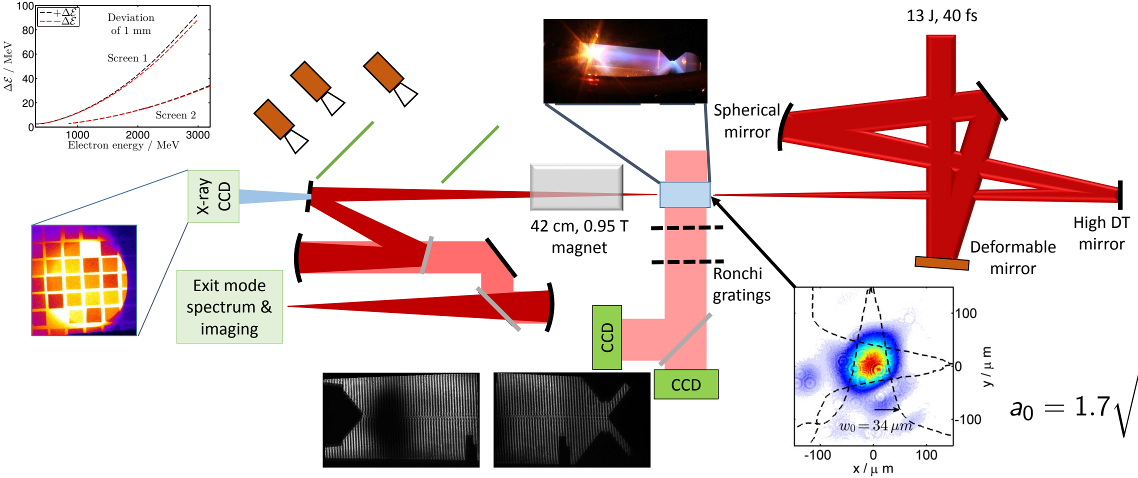
[4] Sprange *et al.*, IEEE T Plasma Sci, **15** 1987

The Gemini laser

- 15 J at 800 nm in 2 independently compressed and timed beams
- Pulselength < 40 fs
- 20 s repetition rate
- $f/20$ for LWFA setups ($a_0 \sim 4$)
- $f/2$ for ion acceleration setups ($a_0 \sim 20$)
- $f/2 - f/20$ combination for pump-probe experiments[5]

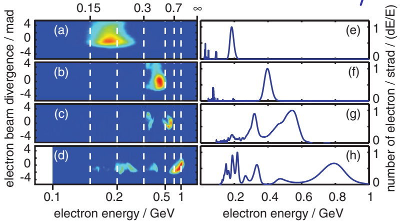
[5] Sarri *et al*, PRL **113**, 2014

Experimental setup for F/40

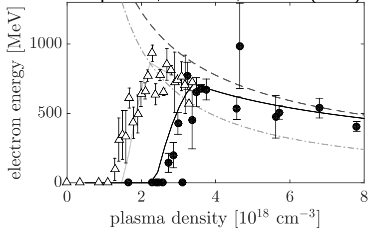


$$a_0 = 1.7\sqrt{\frac{E_L}{10}}$$

Electron acceleration with F/20

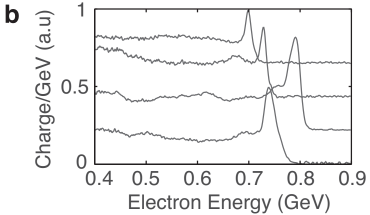


Kneip *et al.*, PRL 103, 035002 (2009)



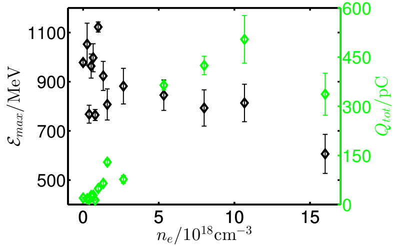
M. Bloom, PhD thesis, in preparation

Gas
jet

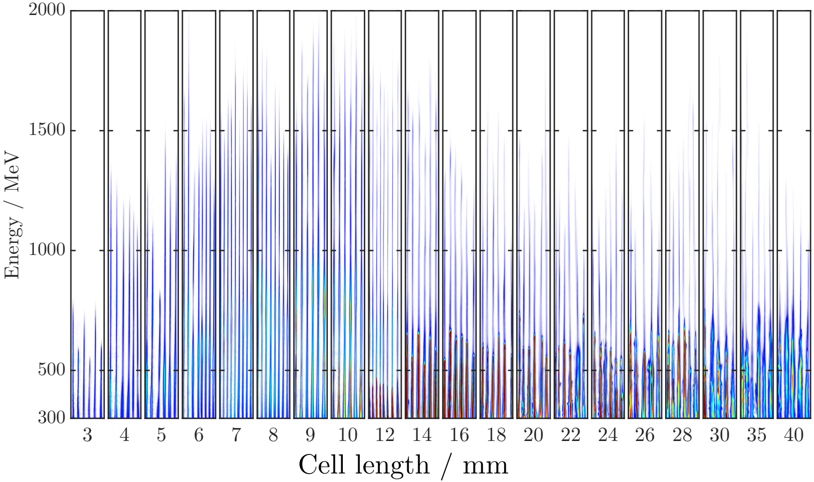


J. M. Cole *et al.*, Sci. Rep. 5, 13244 (2015)

Gas
cell

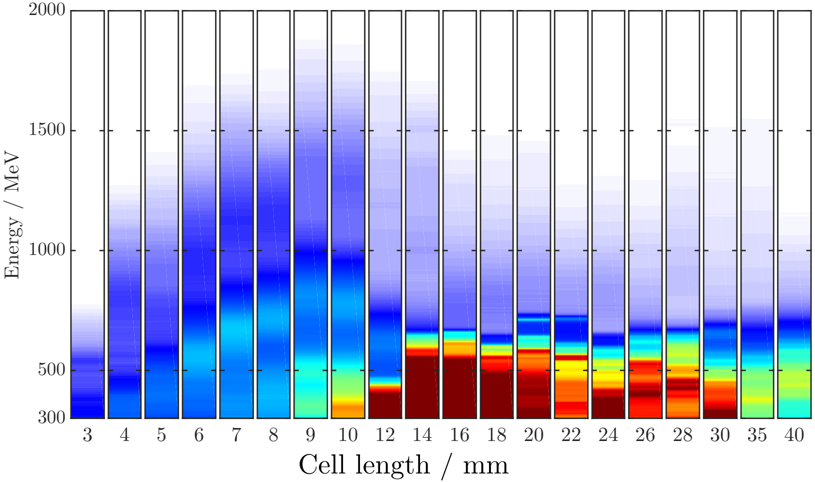


Length scans probe injection and acceleration



Energy on target
5.0 ± 0.7 J
Plasma density
$2.3 \cdot 10^{18}\ \mathrm{cm}^{-3}$

Length scans probe injection and acceleration



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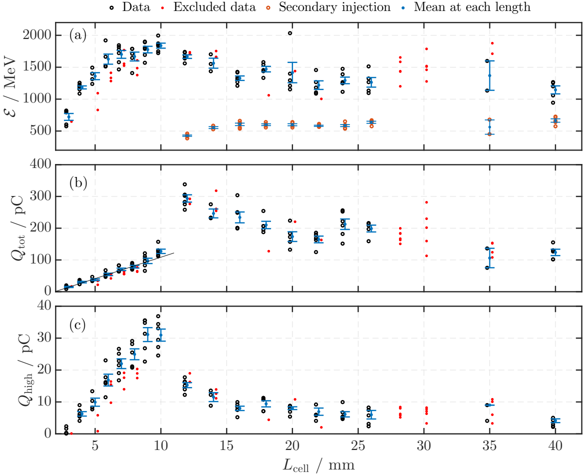
Length scans probe injection and acceleration

Nearly 2 GeV electron energies with $P_L = 125\,\text{TW}$!

Linear increase with charge up to 10 mm with $\nu_i = (13.5 \pm 0.5)\,\text{pC}\,\text{mm}^{-1}$

Secondary injection at 10 mm leads to reduced maximum energy and reduced charge at highest energies



Measuring acceleration gradient from length scan

In a nonlinear bubble[6],

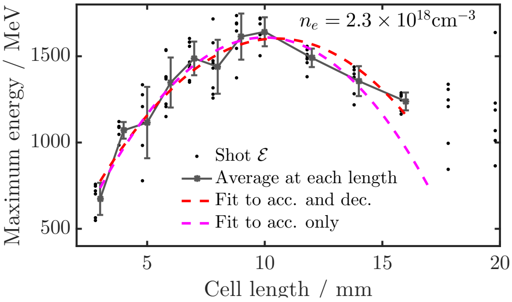
$$E_a(x) = E_p - \frac{E_p}{L_d}x; 0 \leq x \leq 2L_d$$

Thus electron energy is

$$\mathcal{E}(x) = \int_0^{x_C} E_a(x)\,\mathrm{d}x + \mathcal{E}_0$$

And at length x_C

$$\mathcal{E}_{x_C} = -x_C^2\frac{E_p}{2L_d} + x_c E_p + \mathcal{E}_0$$



	E_p/GVm^{-1}	L_d / mm
Full scan	349 ± 39	10.3 ± 1.0
Acceleration	362 ± 27	10.4 ± 1.7
1D Linear theory	146	2.7
3D NL theory	336	6.4

[6] Cardenas *et al*, ArXiv:1505.05732v2

Experimental scan of peak E-field

In 3D nonlinear theory[7]

$$E_{\text{peak}} = \sqrt{a_0} E_0$$

and

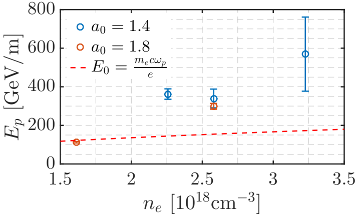
$$L_{\text{dph}} = \frac{4}{3} \frac{c}{\omega_p} \frac{\omega_0^2}{\omega_p^2} \sqrt{a_0}$$

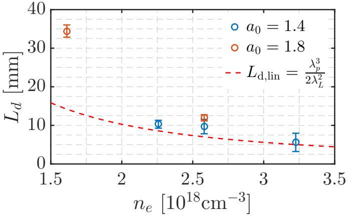
Matched spot size

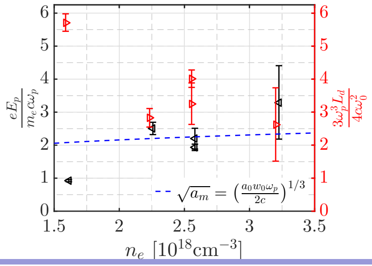
$k_p w_m = 2\sqrt{a_0}$ yields

$$a_m = \left(\frac{a_0 w_0 \omega_p}{2c} \right)^{2/3}$$

Data suggests $\sqrt{a_0} \simeq 3$

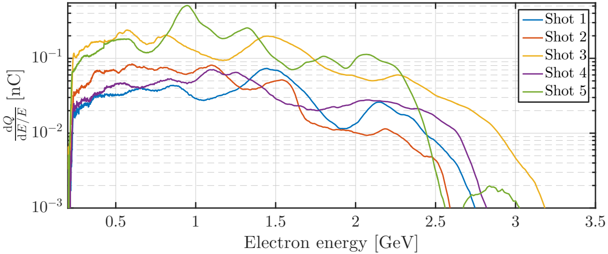






[7] Lu *et al*, PRL **96**, 2006

Multi-GeV electron energies from 250TW laser



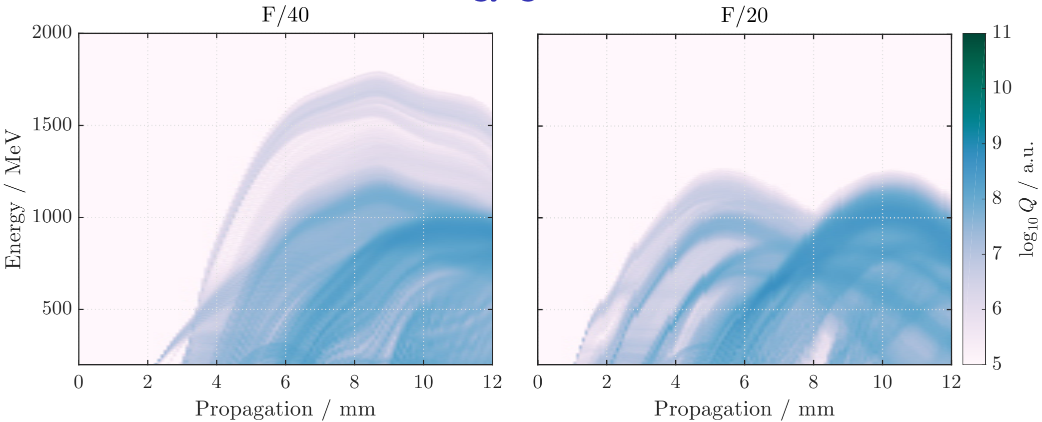
Shot	$\mathcal{E}_L$ J	Beam charge pC			Beam energy mJ		
		> 2 GeV	> 1 GeV	> 0.25 GeV	> 2 GeV	> 1 GeV	> 0.25 GeV
1	11.29	4.4	31.0	77.5	9.9	47.5	73.6
2	11.31	2.0	31.5	122.2	4.5	42.8	93.4
3	11.42	14.9	98.9	343.4	34.8	154.2	286.3
4	11.31	6.4	35.7	92.1	14.6	53.6	85.7
5	11.31	15.2	127.8	373.9	33.0	182.1	335.1

3D PIC Simulations examine physics of increased energy gain

- Using EPOCH 3D PIC code[8]
- Exact phase front of laser unknown $\implies$ simulations to study underlying physics and not to reproduce exact results
- $n_e = 3 \times 10^{18}\,\mathrm{cm}^{-3}$ plasma, $\tau_{\mathrm{laser}} = 45\,\mathrm{fs}$
- Gaussian laser with $w_y = 37\,\mu\mathrm{m}$ and $w_z = 48\,\mu\mathrm{m}$ and $a_0 = 2$ to mimic the $f/40$ results
- Gaussian laser with $w_y = 18.5\,\mu\mathrm{m}$ and $w_z = 24\,\mu\mathrm{m}$ and $a_0 = 4$ to compare to $f/20$ focussing

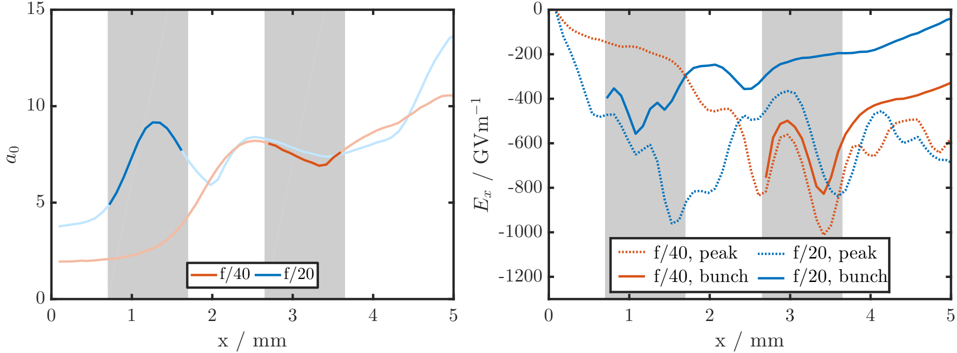
[8] Arber *et al.*, PPCF **57**, 2015

3D PIC Simulations: enhanced energy gain



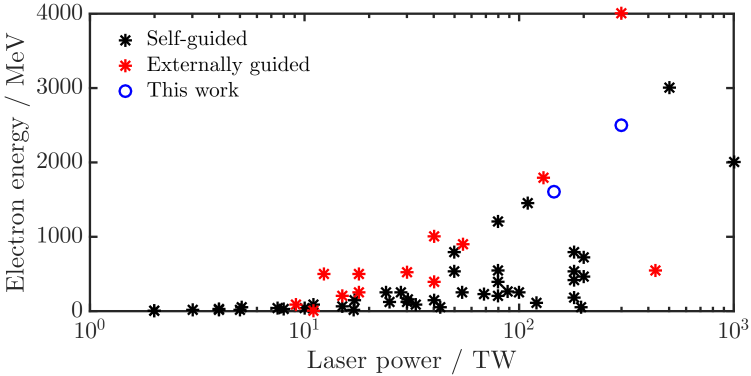
Longer focal length leads to higher energy gain for the the same laser power!

3D PIC Simulations: origins of enhanced energy gain



Large variations in laser intensity afer injection lead to rapid dephasing from high field
Higher energy gain seen due to more stable bubble structure

Enhanced energies and empirical scalings



Compilation of data[9] from $\sim$ 70 results published between 2004-2015

[9]S. Mangles, CERN Yellow Reports, **1**, 289.

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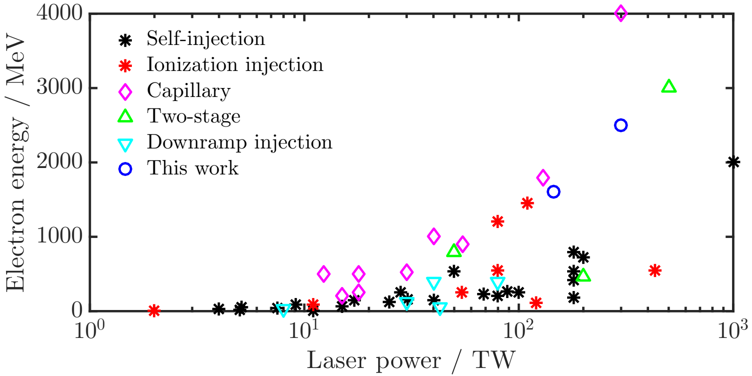

Compilation of data[9] from ~ 70 results published between 2004-2015

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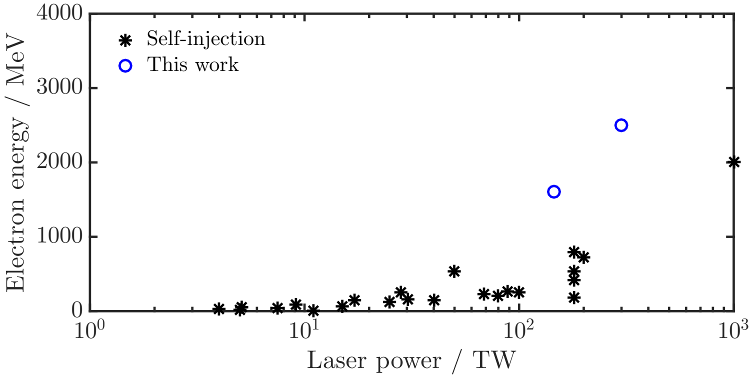

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Conclusions

- Experimentally measured peak accelerating fields of 100s GV/m
- Extended electron energy beyond 2 GeV with 250 TW laser in self-guided, self-injected regime by employing $f/40$ focussing
- Simulations imply optimised bubble dynamics avoiding dephasing during bubble evolution