Laser pulse evolution in non-linear plasma wakefield accelerators

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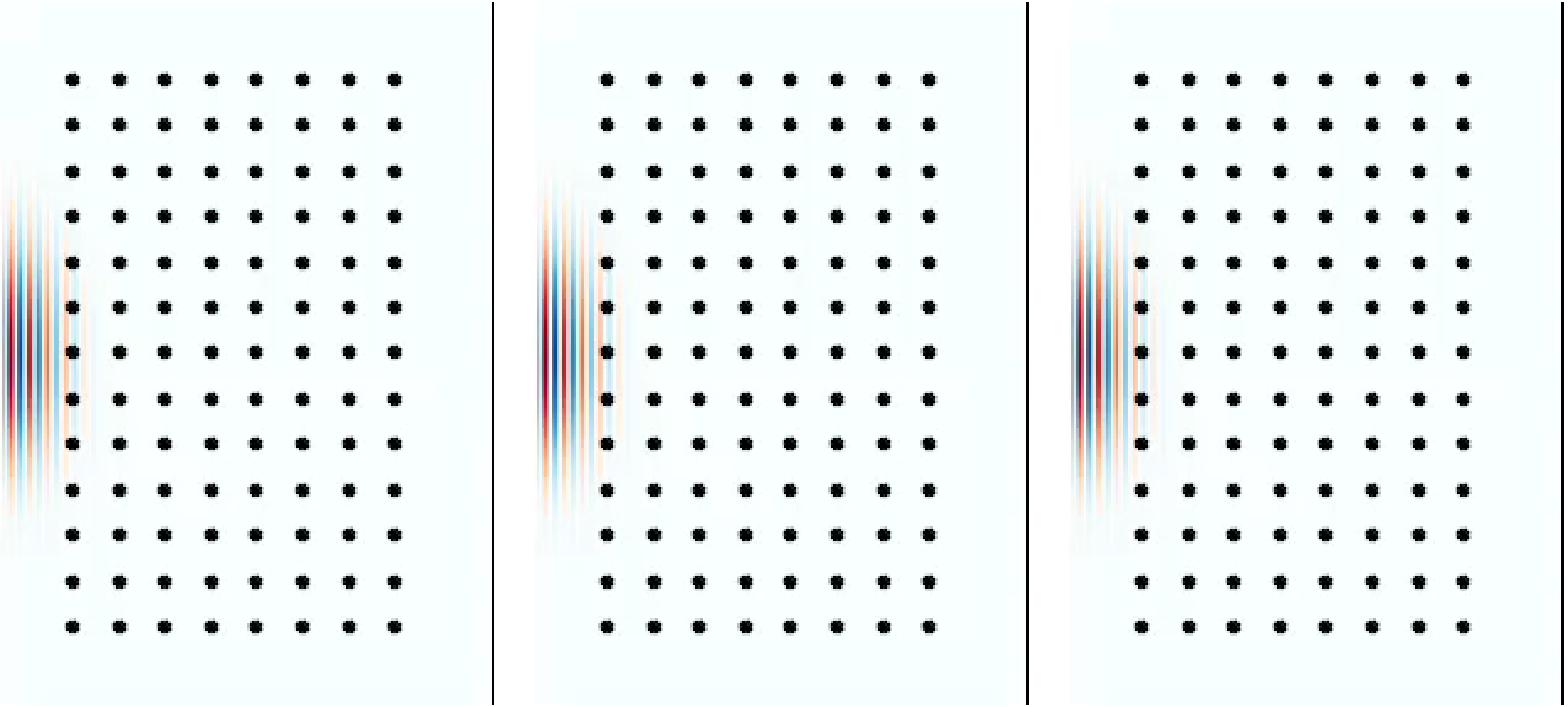
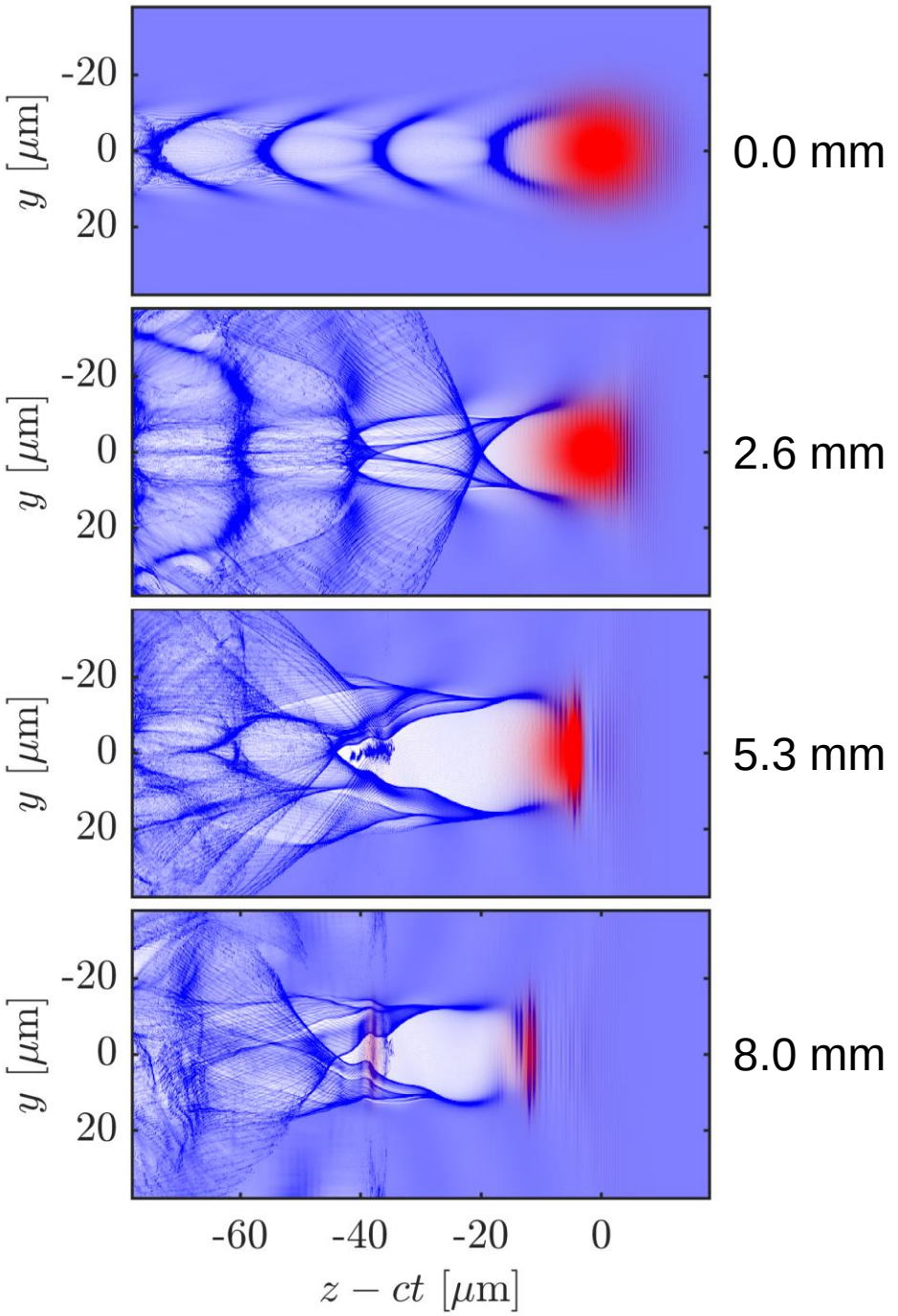
Stating the obvious….
The plasma wave is generated by the drive laser

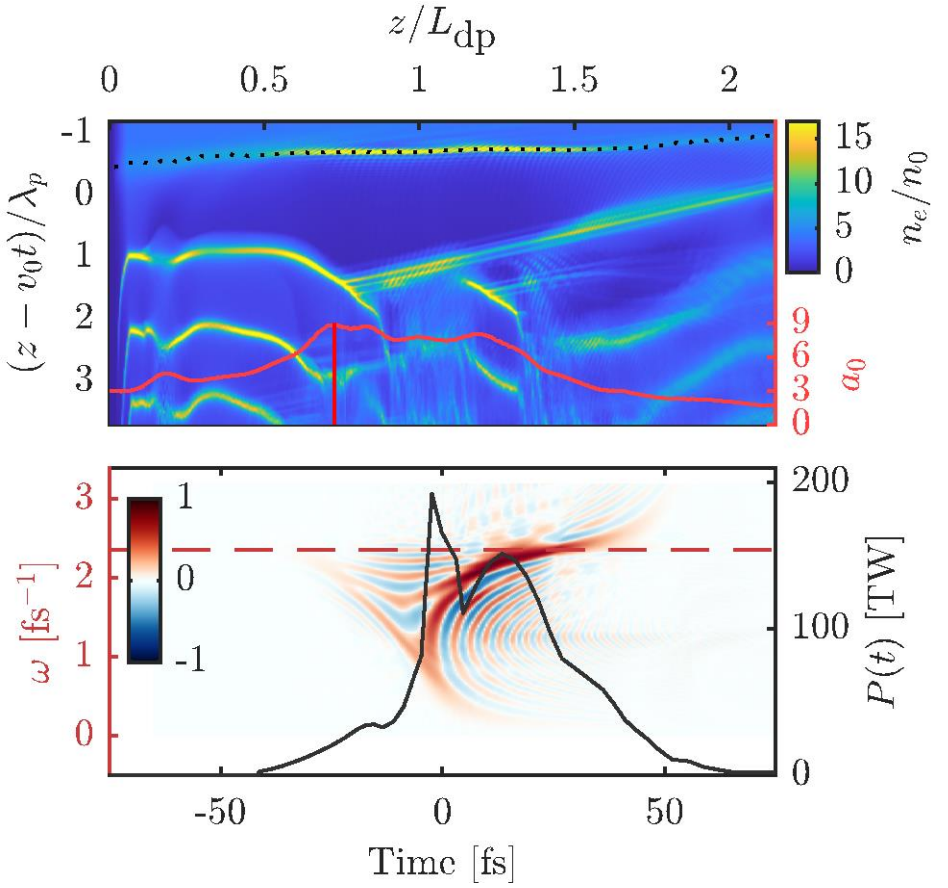
$$a_0 = \frac{eE_0}{\omega m_e c}$$

$a_0 = 1$ $a_0 = 2$ $a_0 = 4$



The plasma response modifies the laser pulse



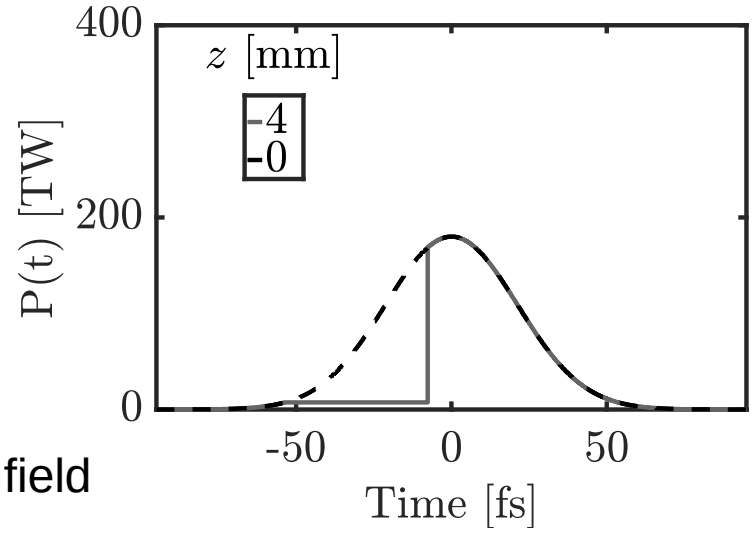


Redshifted photons travel slower than the pulse front and cause power amplification

Group velocity of far redshifted photons can be less than the reduced group velocity of the laser $v_g(1) = v_g(0) - v_{\text{etch}}$

$$c\sqrt{1 - \frac{{\omega_p}^2}{{\omega_1}^2}} = c\sqrt{1 - \frac{{\omega_p}^2}{{\omega_0}^2}} - \frac{{\omega_p}^2}{{\omega_0}^2}$$

$$\omega_1 = \frac{\omega_0}{\sqrt{3}}$$

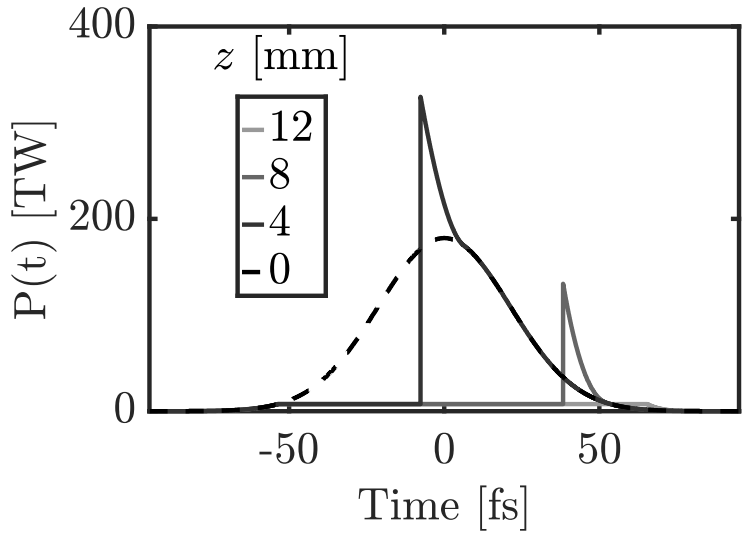


These photons drift backwards and contribute to field behind the depletion region

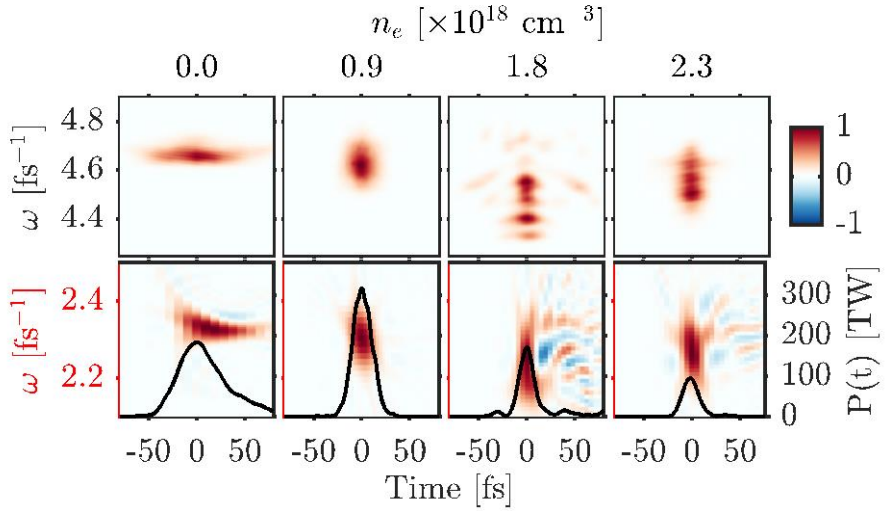
Pre-Injection Pulse Evolution length
For a gaussian pulse=:

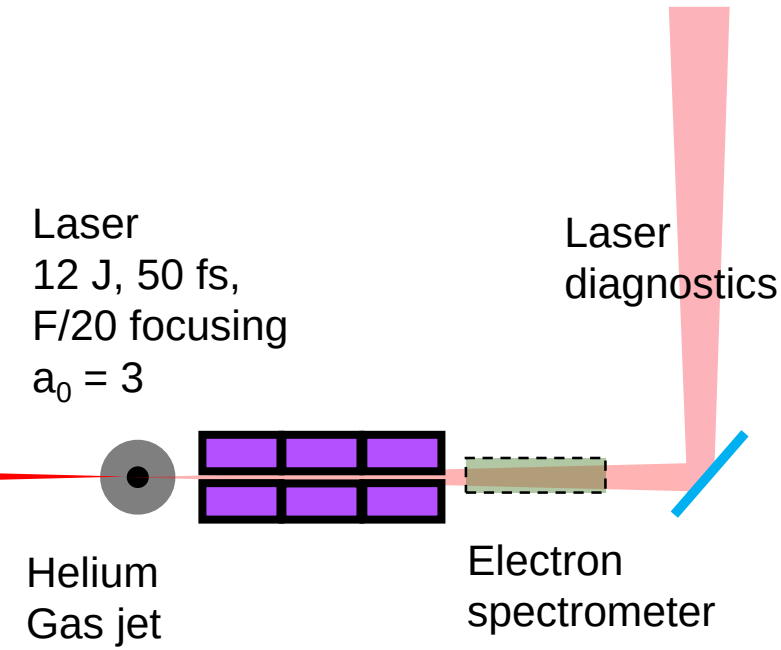
$$L_{\text{evol}} \approx \sigma_t c \left(\frac{2}{3}\frac{{\omega_0}^2}{{\omega_p}^2}\right)\sqrt{\frac{1}{2}\ln\left(\frac{P_0}{P_c}\right)}$$

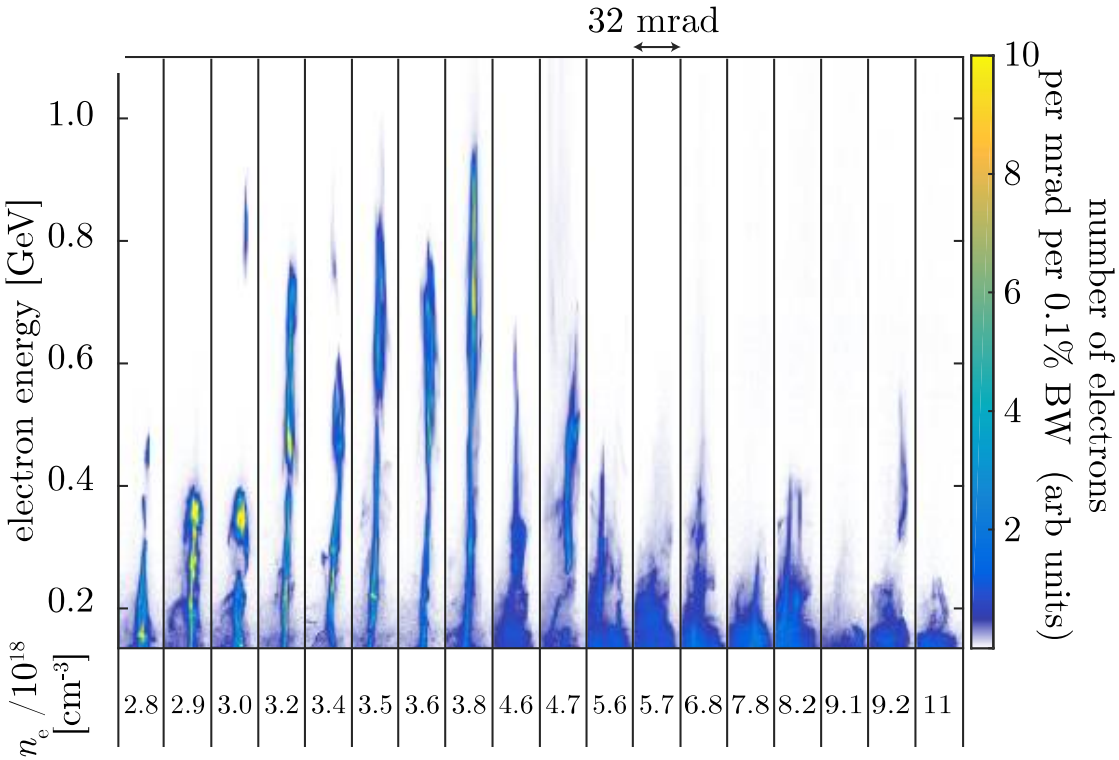
$$L_{\text{dp}} \approx 2L_{\text{evol}}$$



An experiment to study laser, electron and x-ray beams simultaneously



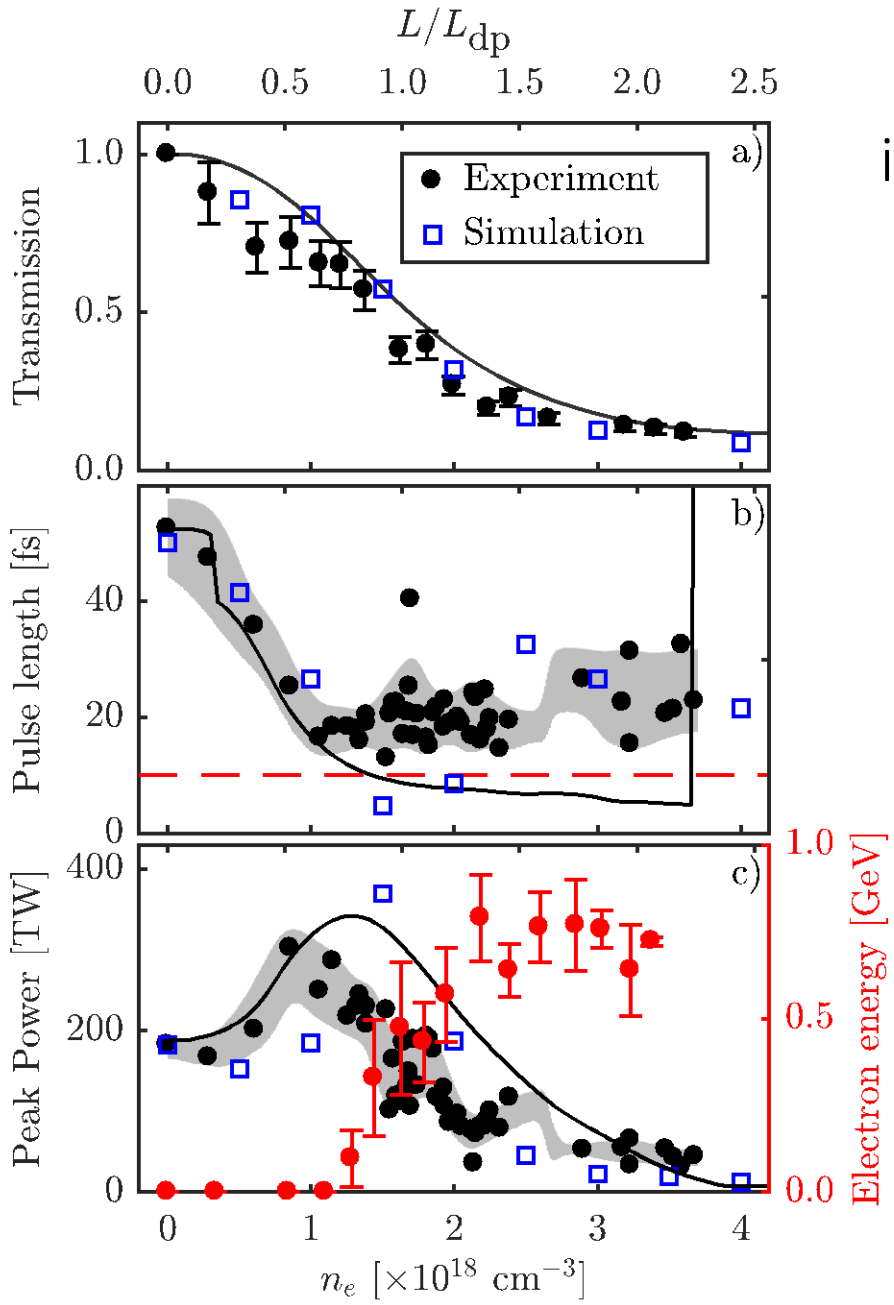




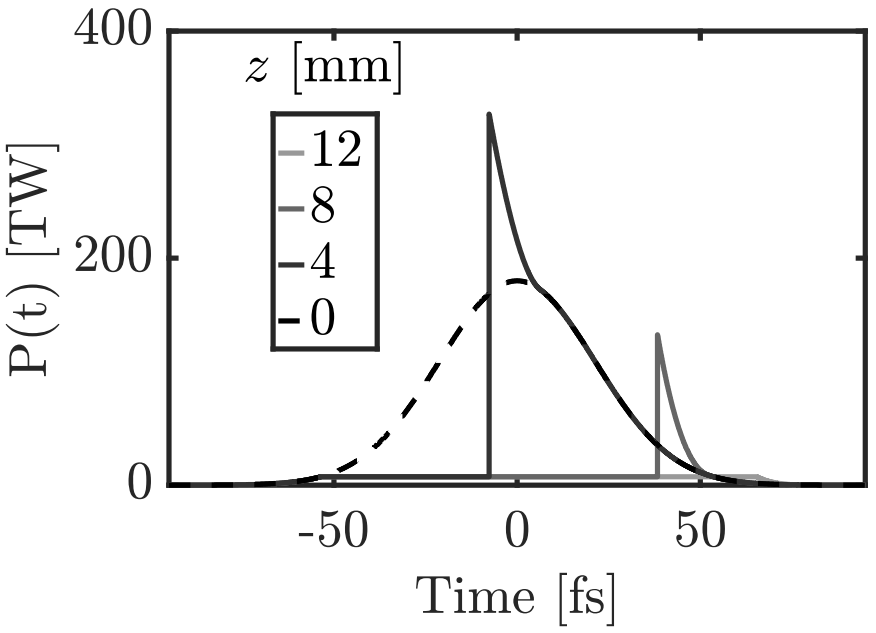
Streeter, M. J. V., et al. (2018) *Physical Review Letters*, *120*(25), 254801. https://doi.org/10.1103/PhysRevLett.120.254801

Bloom, M. S., et al. (2018). https://arxiv.org/abs/1710.05740

Laser evolution determines self-injection and acceleration behavior



Model of laser evolution



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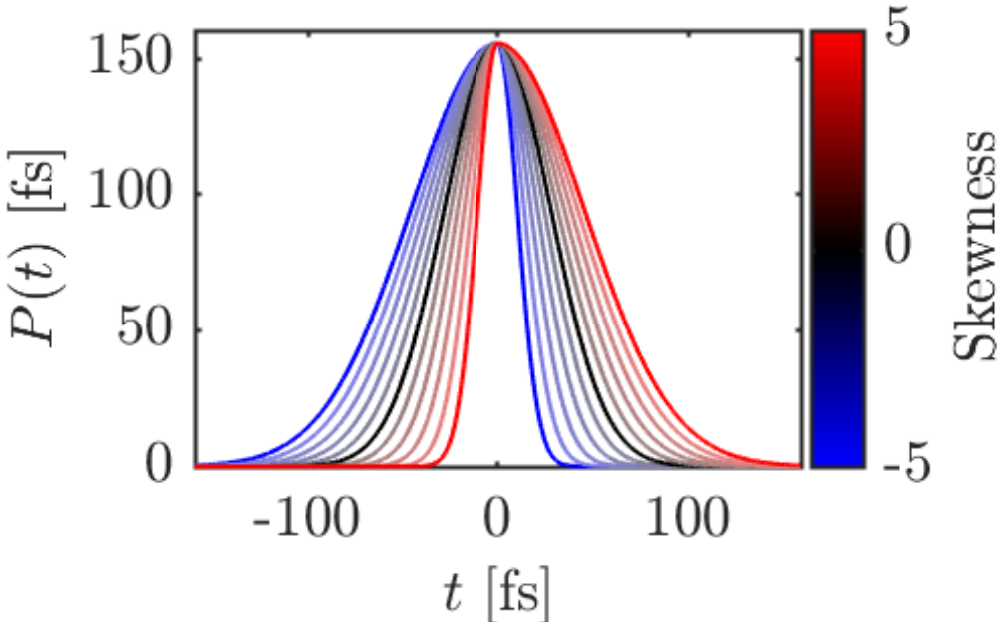
Controlling the laser evolution by shaping the initial pulse profile

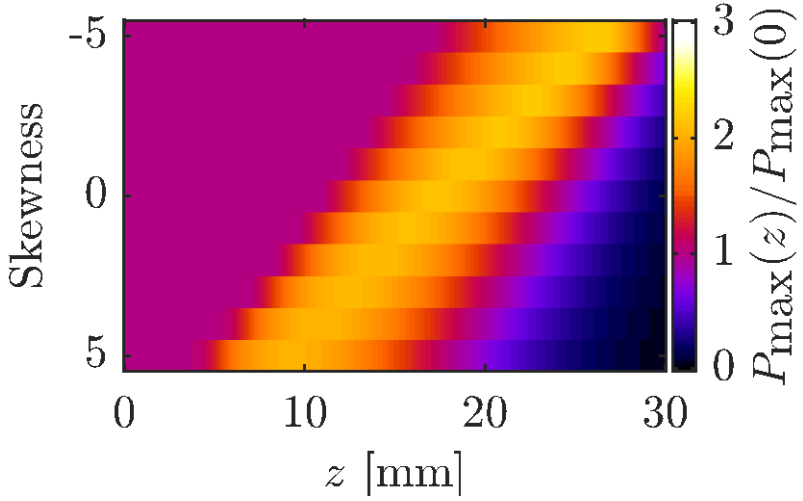
Input laser pulse shapes



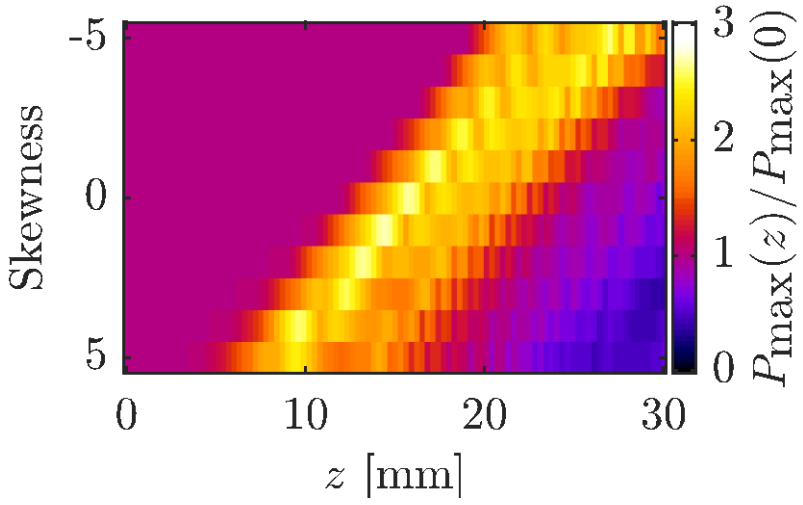
Electron density for calculations and simulations

$$n_e = 2 \times 10^{18}\ \mathrm{cm}^{-3}$$

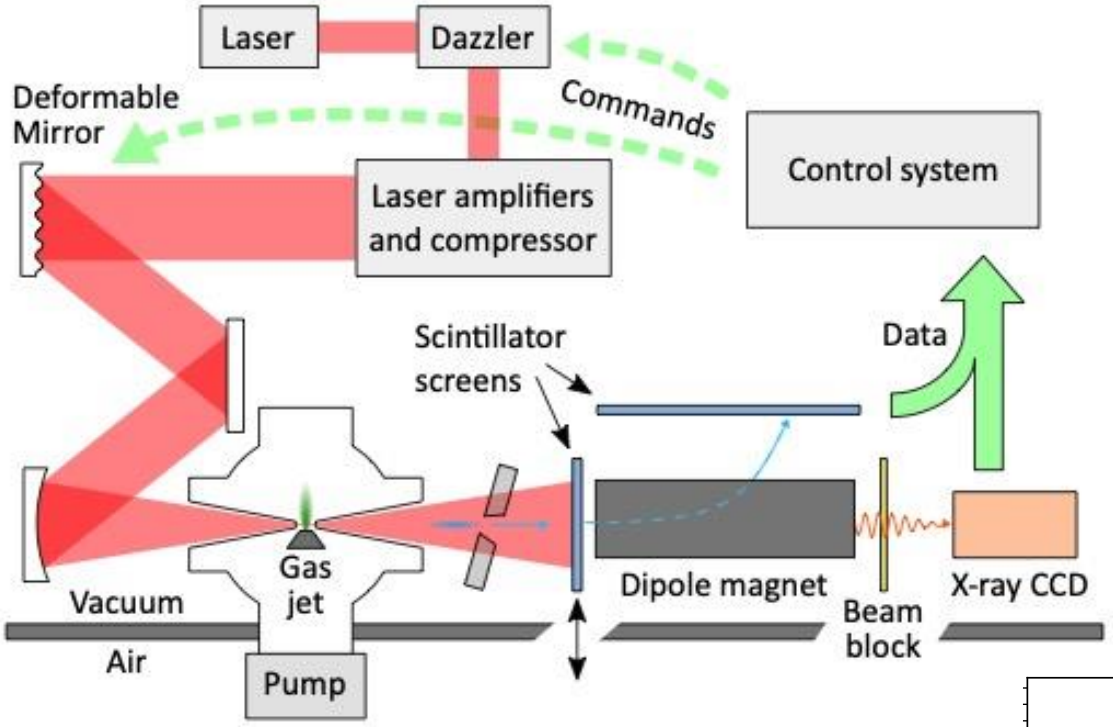
Model prediction

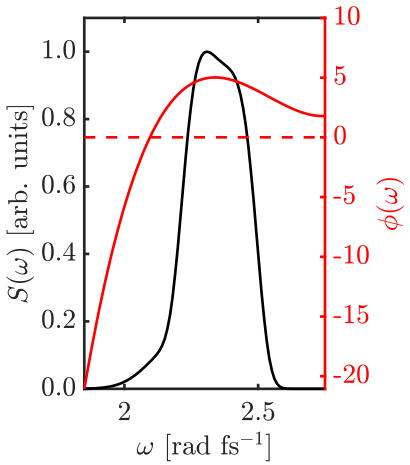


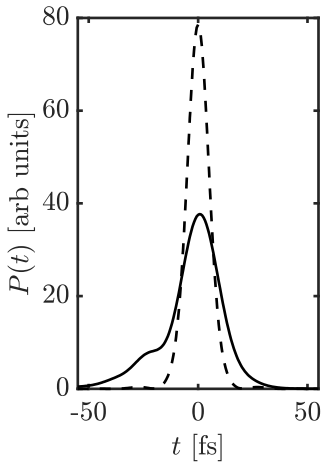
1D PIC simulations

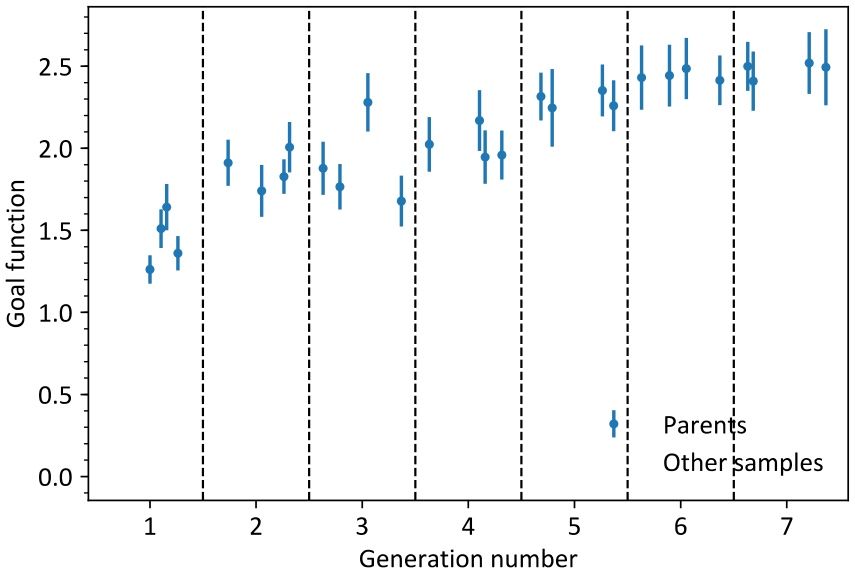


Using active feedback to optimize laser pulse shape





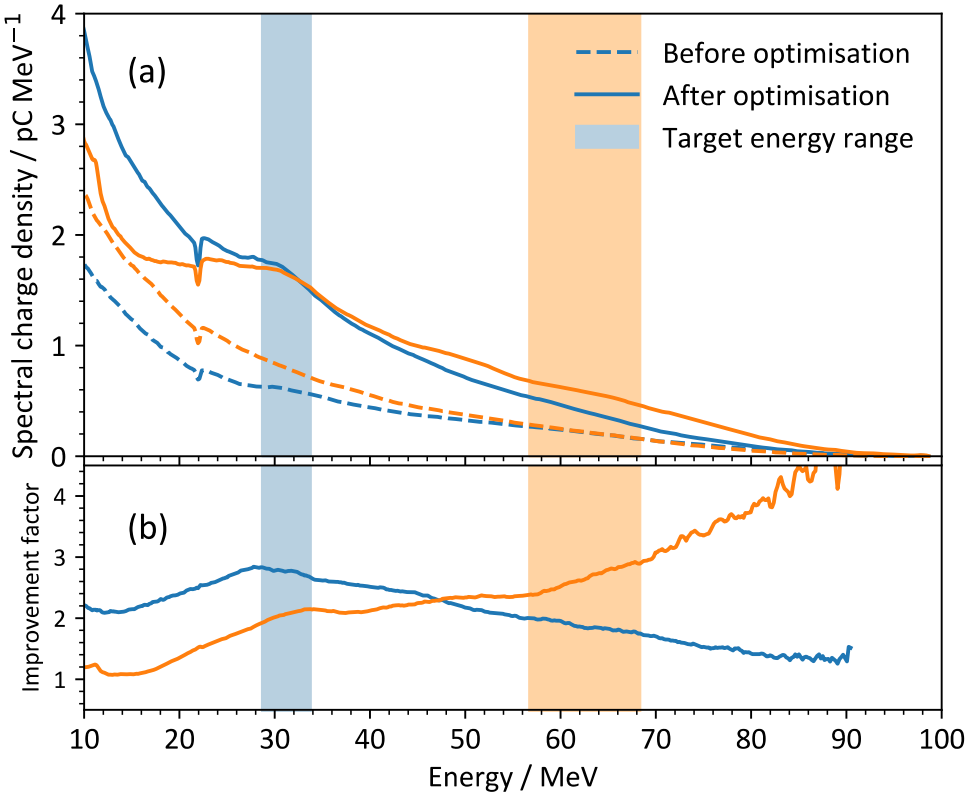




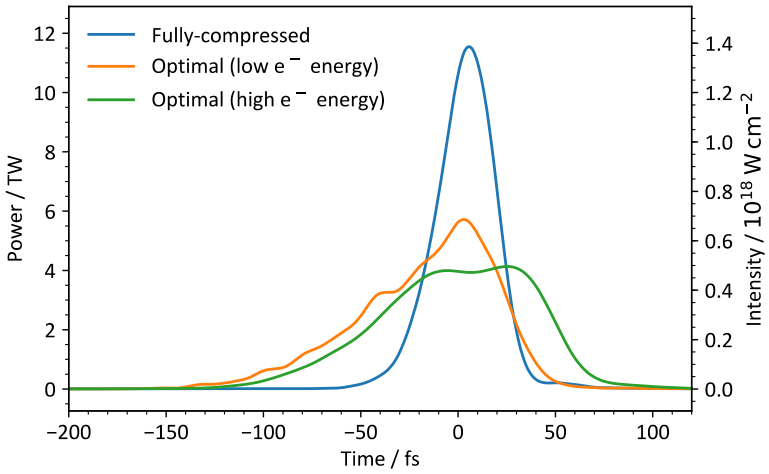
Streeter, M. J. V., et al. (2018). *Applied Physics Letters*, *112*(24), 244101. https://doi.org/10.1063/1.5027297
Dann, S. J. D. et al (2018) *In prep for submission*

Algorithm autonomously improved electron spectrum through control of initial pulse shape

Electron spectrum before and after



Fully compressed pulse shape and optimized cases



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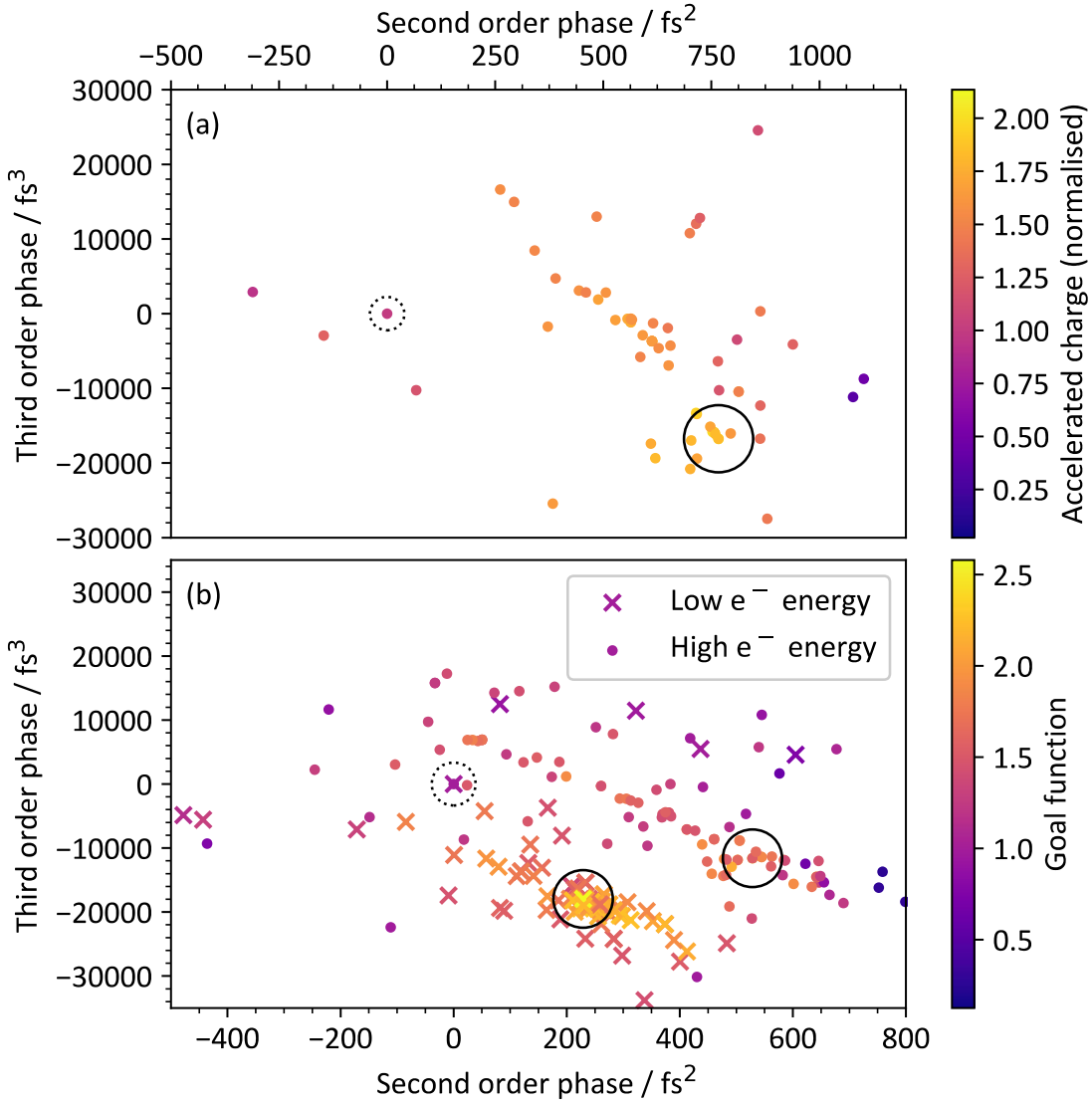
Machine learning used to explore multi-dimensional parameter space and identify interesting regions for further study



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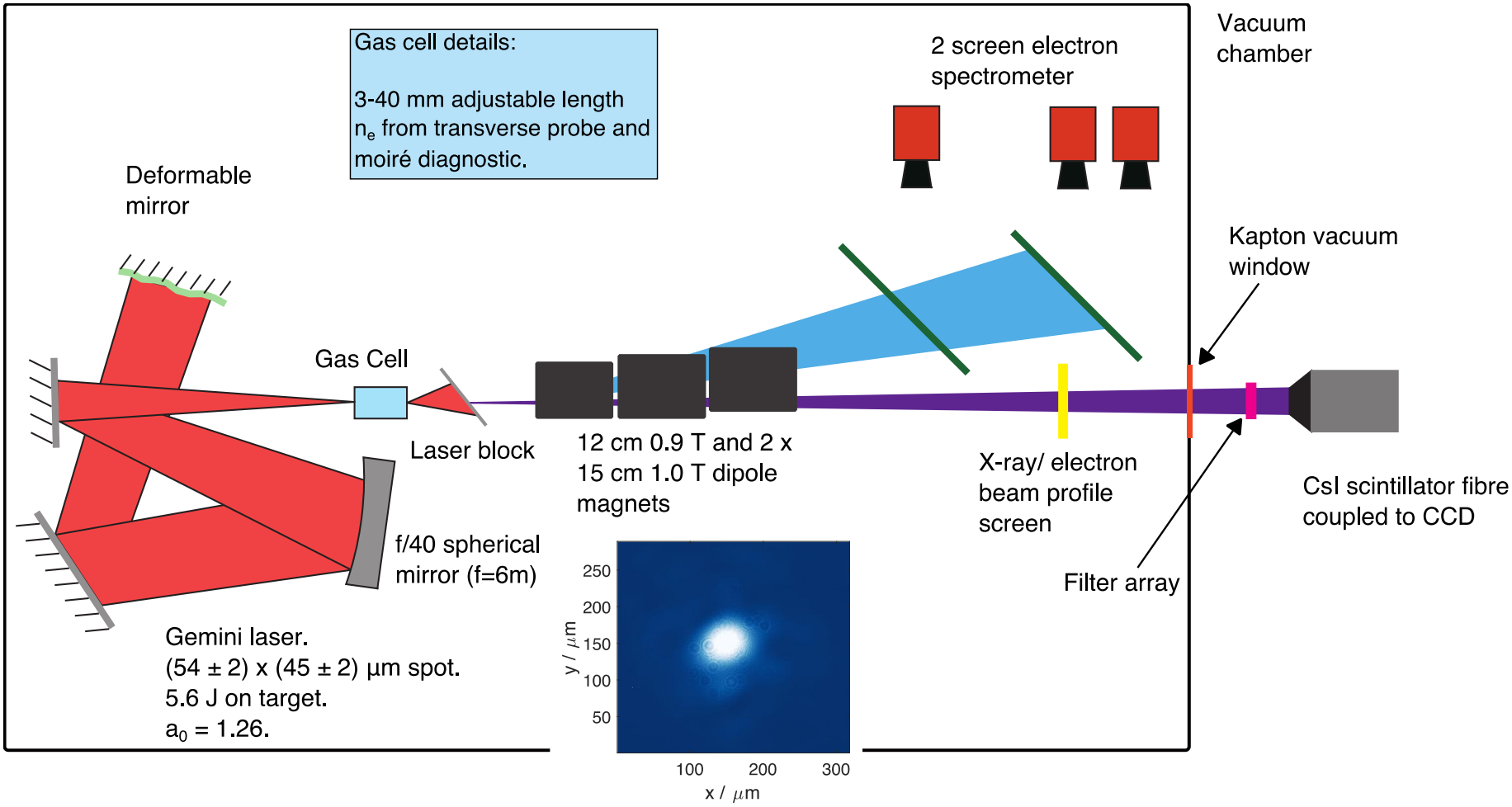
Experiment with Long Focal Length focusing optic and variable length gas cell



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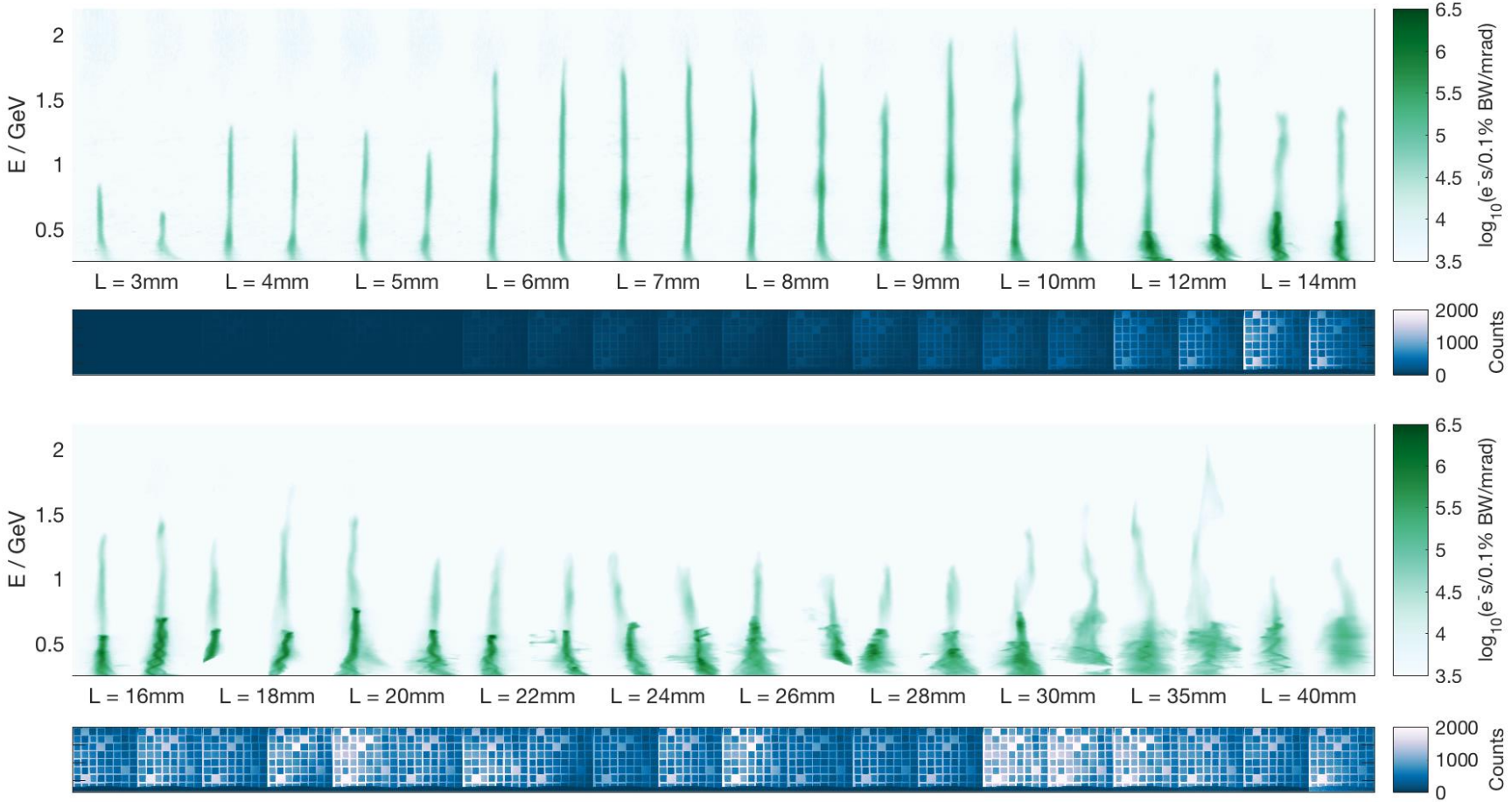
Large charge, high divergence electron beam injected at depletion length

For $n_e = 2.3 \times 10^{18}\ \mathrm{cm}^{-3}$ depletion length $L_d = \dfrac{{\omega_L}^2}{{\omega_p}^2} c\tau_L \approx 11\ \mathrm{mm}$



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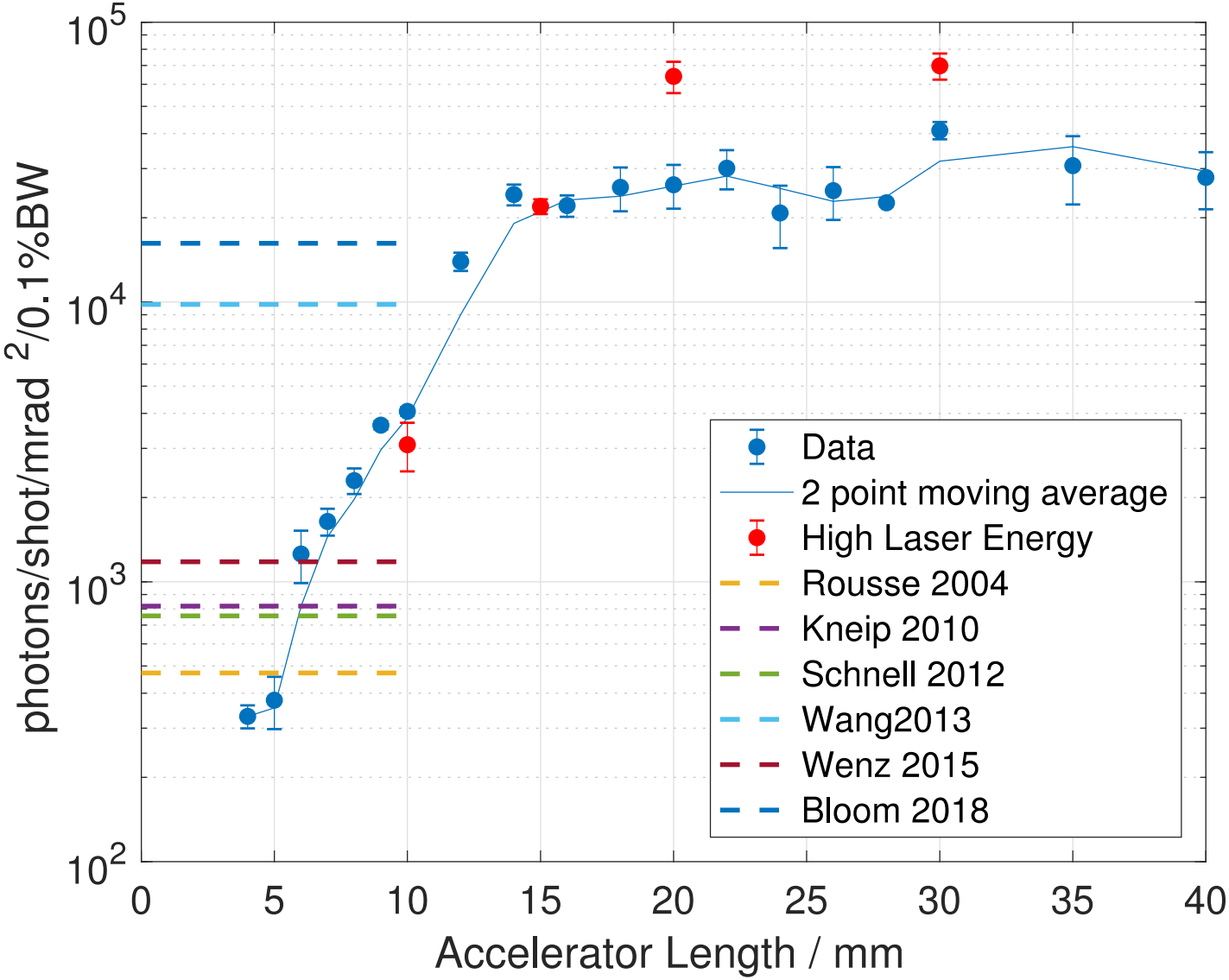
Extending interaction length as leads to a huge increase in x-ray flux



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Conclusion

- Detailed studies of laser pulse evolution are essential for understanding LWFA
- Wakefield amplitude and size can vary dramatically in a constant plasma density
- Great potential for optimization of electron and x-ray beams

Thank you to all co-investigators of this work...

C. D. Baird,[1] R.A. Bendoyro,[2] M.S. Bloom,[3] N. Bourgeois,[4] O. Chekhlov,[4] J. M. Cole,[3] A.E. Dangor,[5] S. J. D. Dann,[6,7,4] A. Döpp,[3,8,9] S. Eardley,[5] C. D. Gregory,[4] J.-N. Gruse,[3] J. Hah,[10] D. Hazra,[11] S. J. Hawkes,[4] J. Holloway,[12] C. J. Hooker,[4] J. Jiang,[2] S. Kneip,[3] K. Krushelnick,[10] N.C. Lopes,[3,2] S. P. D. Mangles,[3] V. A. Marshall,[4] C. D. Murphy,[1] Z. Najmudin,[3] H. Nakamura,[3] J. A. Nees,[10] P.A. Norreys,[4] J. Osterhoff,[13] C.A.J. Palmer,[6,7] B. Parry,[4] P. Pourmoussavi,[13] S. V. Rahul,[14] P. P. Rajeev,[4] S. Rozario,[3] J. Schreiber,[3,8,9] J. D. E. Scott,[6,7] R. A. Smith,[5] E. Springate,[4] Y. Tang,[4] S. Tata,[15] A. G. R. Thomas,[6,10,7] C. Thornton,[4] D. R. Symes,[4] M. J. V. Streeter,[6,7,3] M. Wing,[12] and J. C. Wood[3]

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