Shock Injection Producing Narrow Energy Spread, GeV Electron Beams from a Laser Wakefield Accelerator

Jason A Cardarelli[1], Matthew JV Streeter[2], Cary Colgan[2], Dominik Hollatz[3], Aaron Alejo[4,8], Christopher Arran[5], Chris Baird[6], Mario Balcazar[1], Tom D. Blackburn[7], Nicolas Bourgeois[6], Jason Cole[2], Elias Gerstmayr[2], Harsh[3], Yiftach Katzir[6], Brendan Kettle[2], Eva Los[2], Mattias Marklund[7], Christopher D. Murphy[5], Zulfikar Najmudin[2], Pattathil P. Rajeev[6], Christopher Ridgers[5], Christian Roedel[3], Felipe Salgado[3], Guillermo M. Samarin[8], Gianluca Sarri[8], Dan R. Symes[6], Alexander GR Thomas[1], Christopher ID Underwood[2], Matthew Zepf[3], and Stuart Mangles[2]

[1]The Gérard Mourou Center for Ultrafast Optical Science, University of Michigan; [2]Imperial College, London; [3]Helmholtz Institute, Jena; [4]Oxford University; [5]University of York; [6]RAL Central Laser Facility; [7]Chalmers University of Technology; [8]Queen's University, Belfast

Introduction: Laser Wakefield Acceleration (LWFA) & Injection

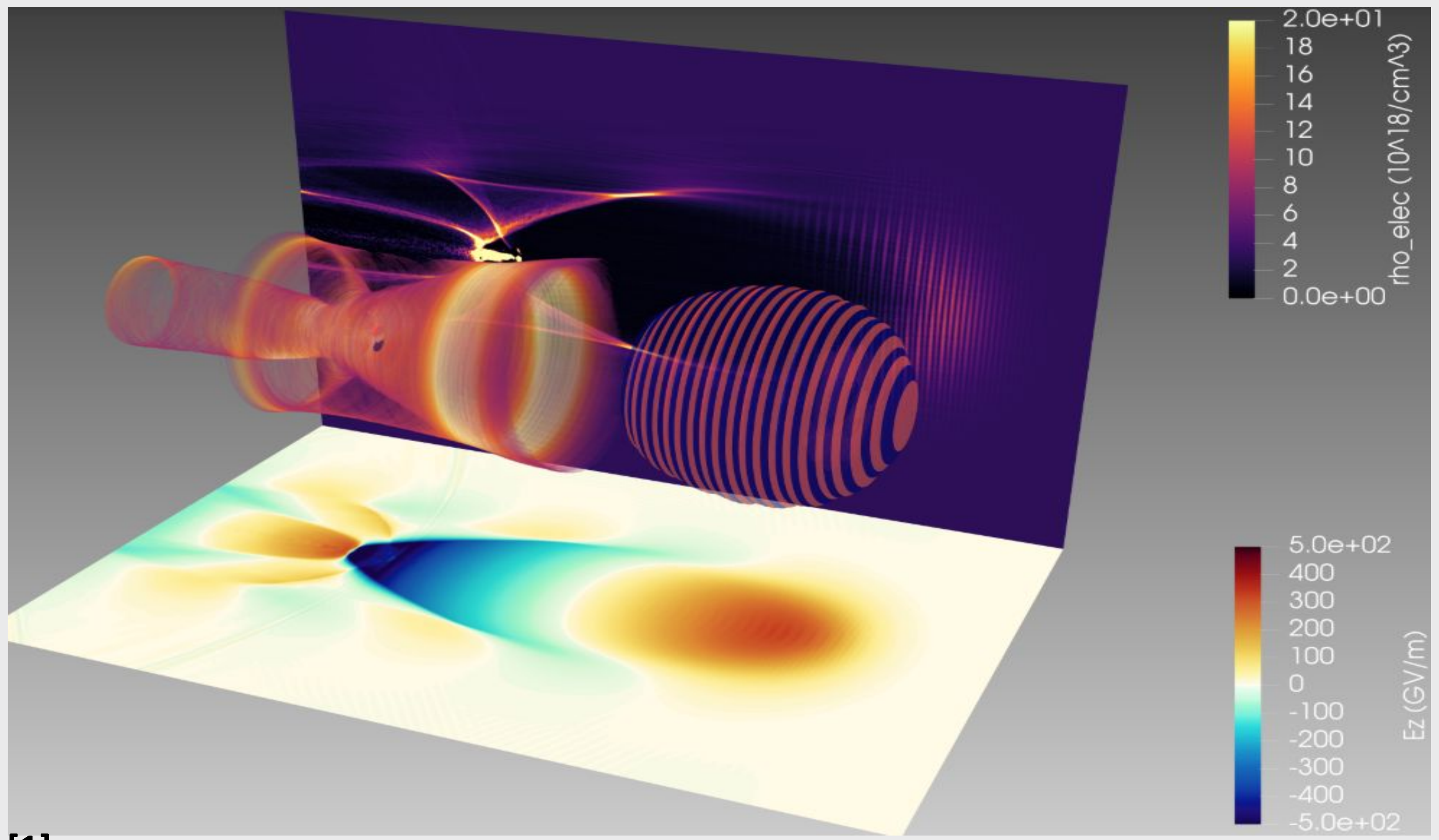
LWFA accelerates particles in field gradients of magnitudes > 10,000x the normal operating limit of conventional accelerators.

These high fields are generated via an intense laser/plasma interaction creating a nonlinear plasma wave bubble, which is set up by a time-averaged Lorentz force away from the laser axis, the 'relativistic ponderomotive force': $\mathbf{F}_p = \left\langle \frac{c}{2\gamma} \nabla \mathbf{a}^2 \right\rangle$

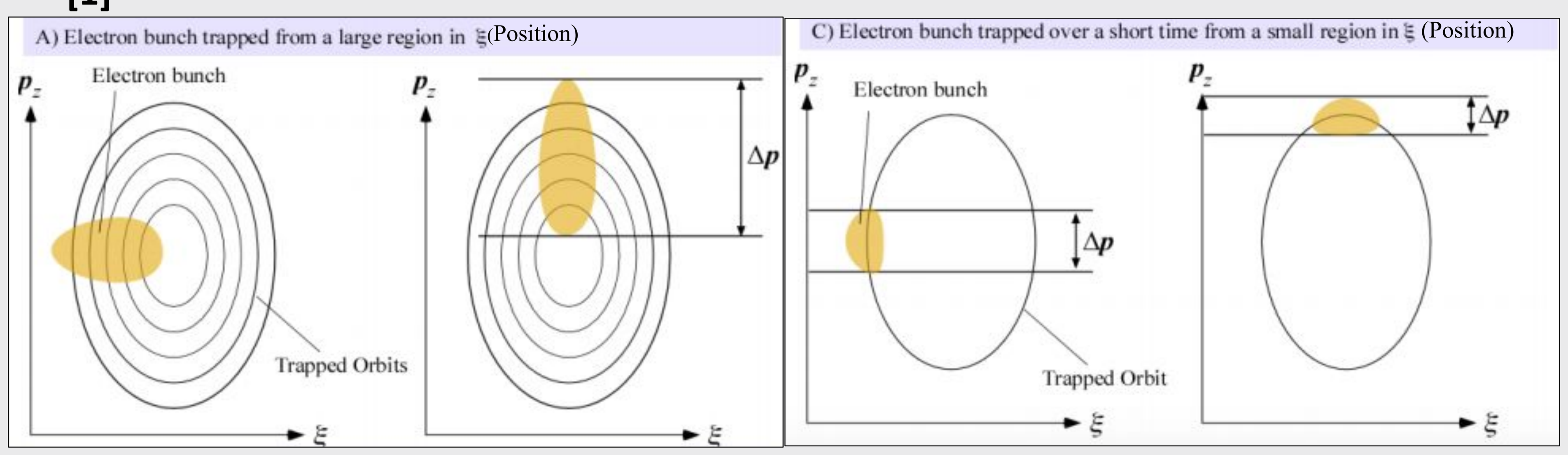
Electrons must have a longitudinal momentum within a range such that it is trapped in the bubble's accelerating fields. This is due to the phase velocity of the bubble, $v_{\Phi,p}=v_{g,L}<c$. This range is given by a phase-space orbits within the plasma wake.

The dominant injection mechanism describes the mechanics of how these particles are brought into a trapped phase-space orbit.

Applications of LWFA include high repetition-rate phase-contrast betatron imaging for industrial and medical purposes, injectors or amplifiers of particles in junction with conventional accelerators, and high energy density physics experiments.



[1]



[2]

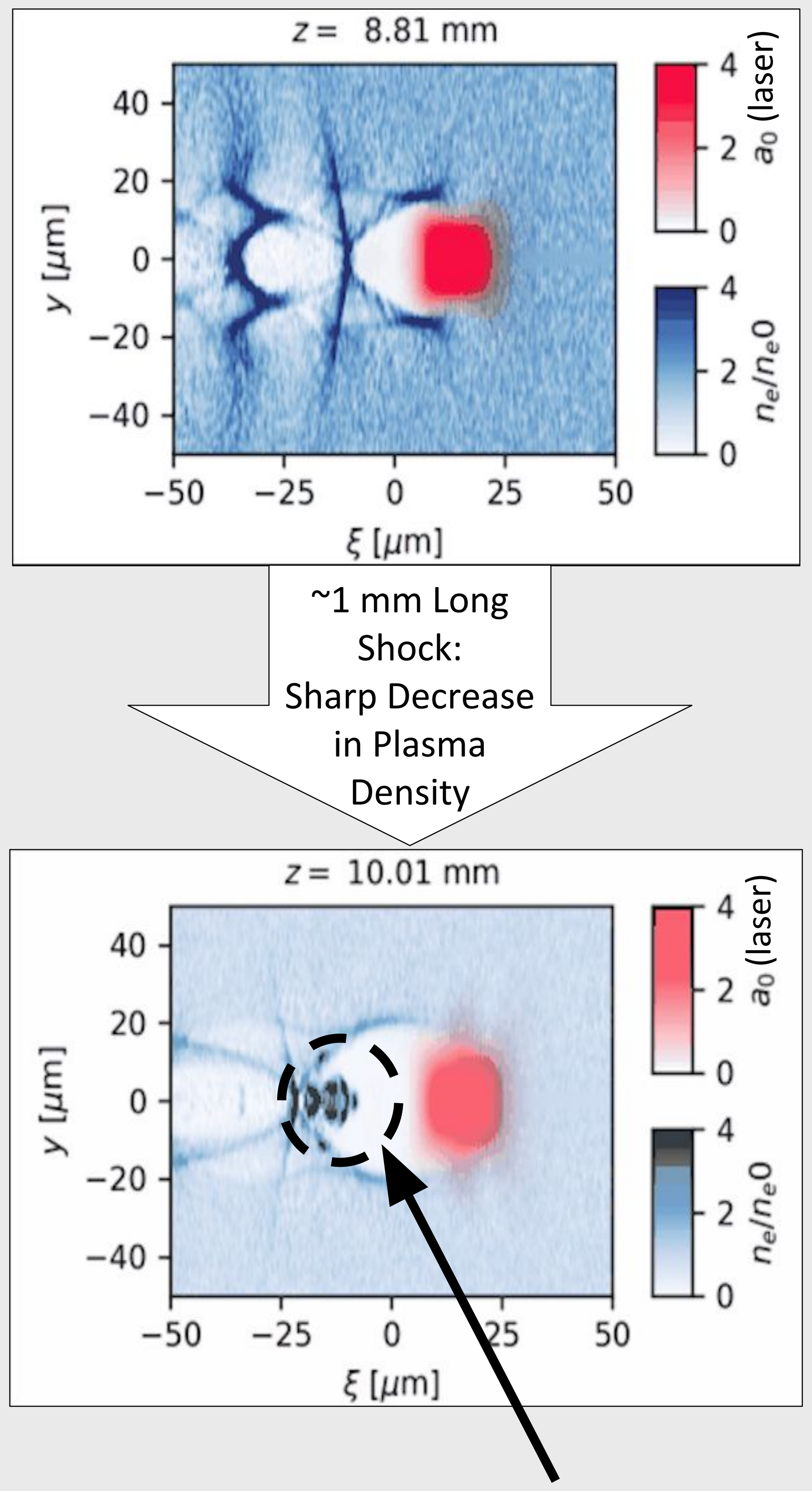
Shock Injection

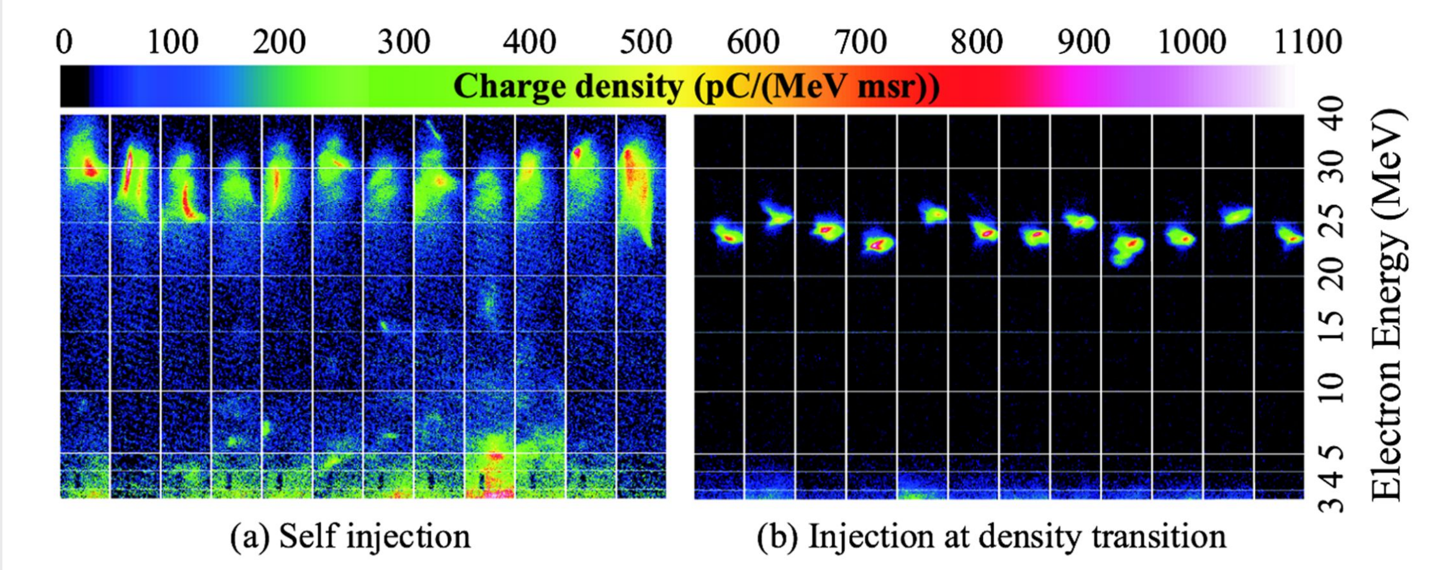
Shock injection (SI): particles injected suddenly via rapid expansion of wakefield bubble radius, resulting in monoenergetic electron bunches.

Compared to other injection mechanisms, SI yields low energy spread (ΔE), modest peak energy (E_p) electron beams.

High E_p, low ΔE particle beams are essential for most radiation reaction experiments, free electron (FEL) X-Ray sources, as well as other applications.

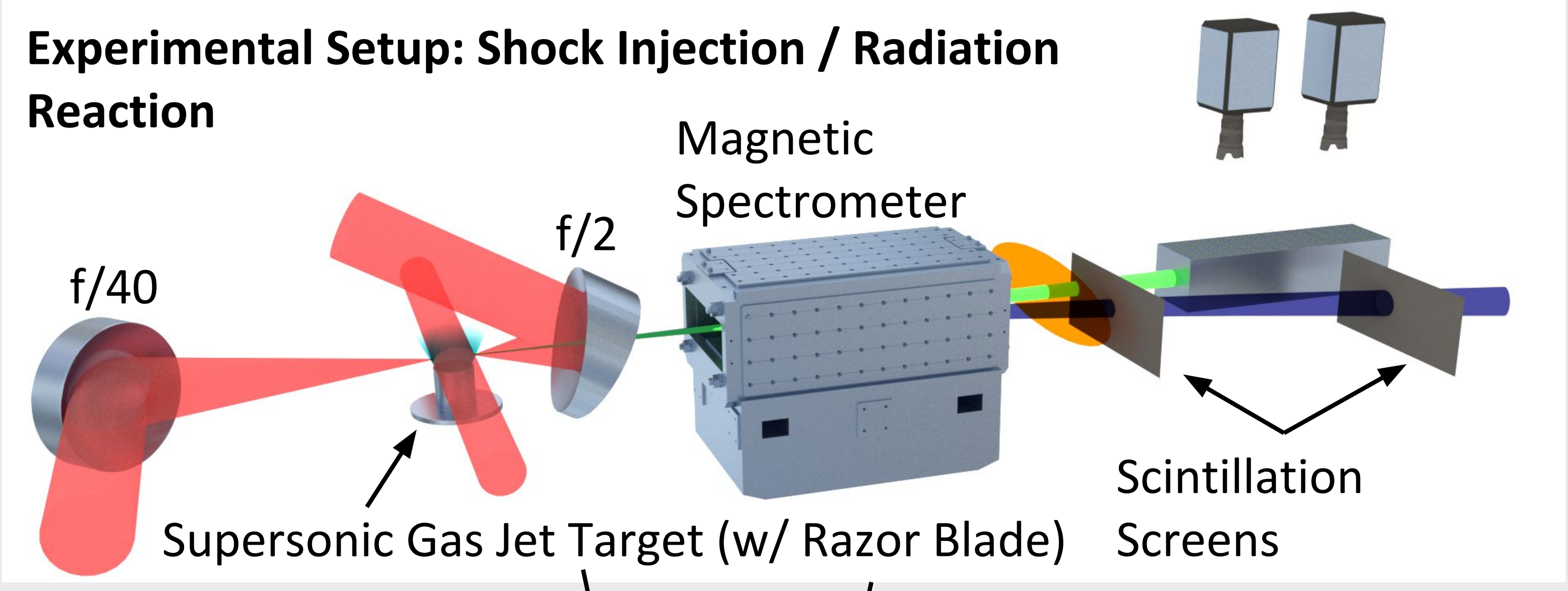
Goal: demonstrate GeV electron beams using SI with >150TW laser system, while preserving low ΔE.





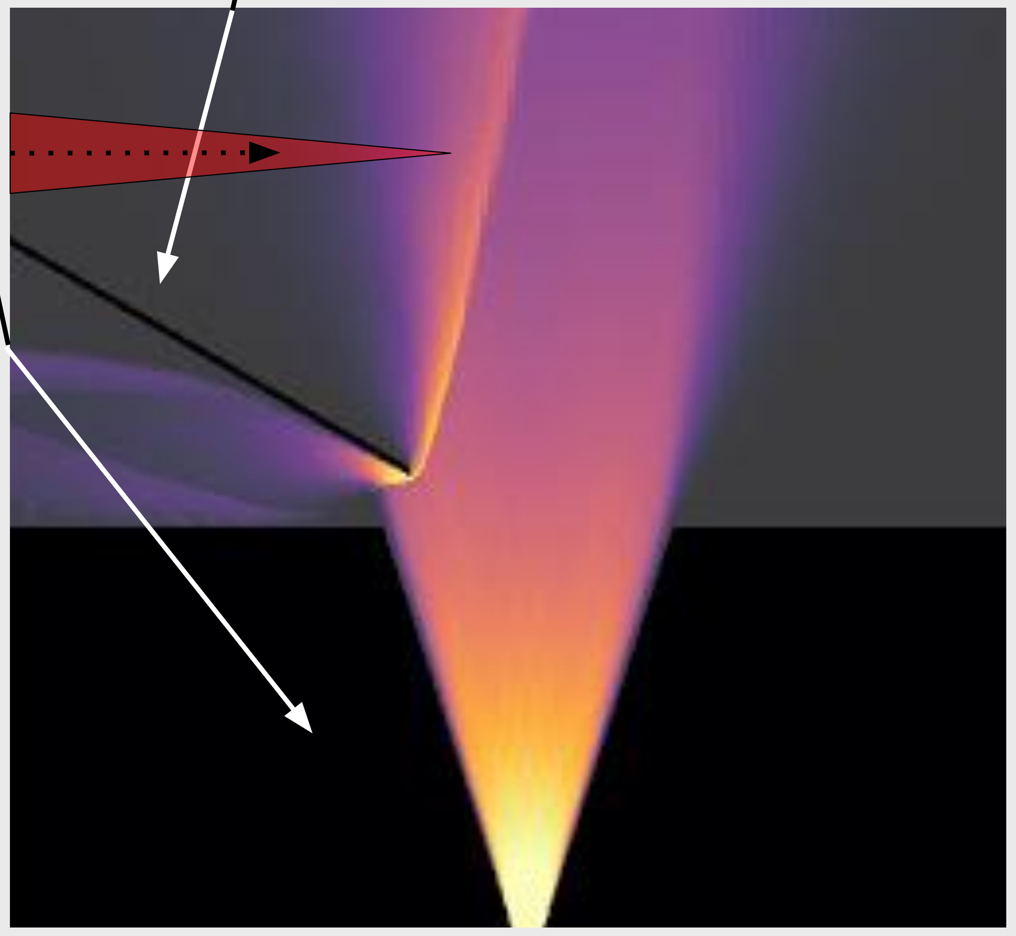
[3]

Experimental Setup & Results



Above: setup which the data in this abstract was recorded. Similar to previous SI experiments [3-5]. Experimental campaign both optimize shock injection and measure electron/photon radiation reaction at CLF Gemini laser.

Right: Gas jet / razor blade in fluid simulation to demonstrate shock-front in density profile.



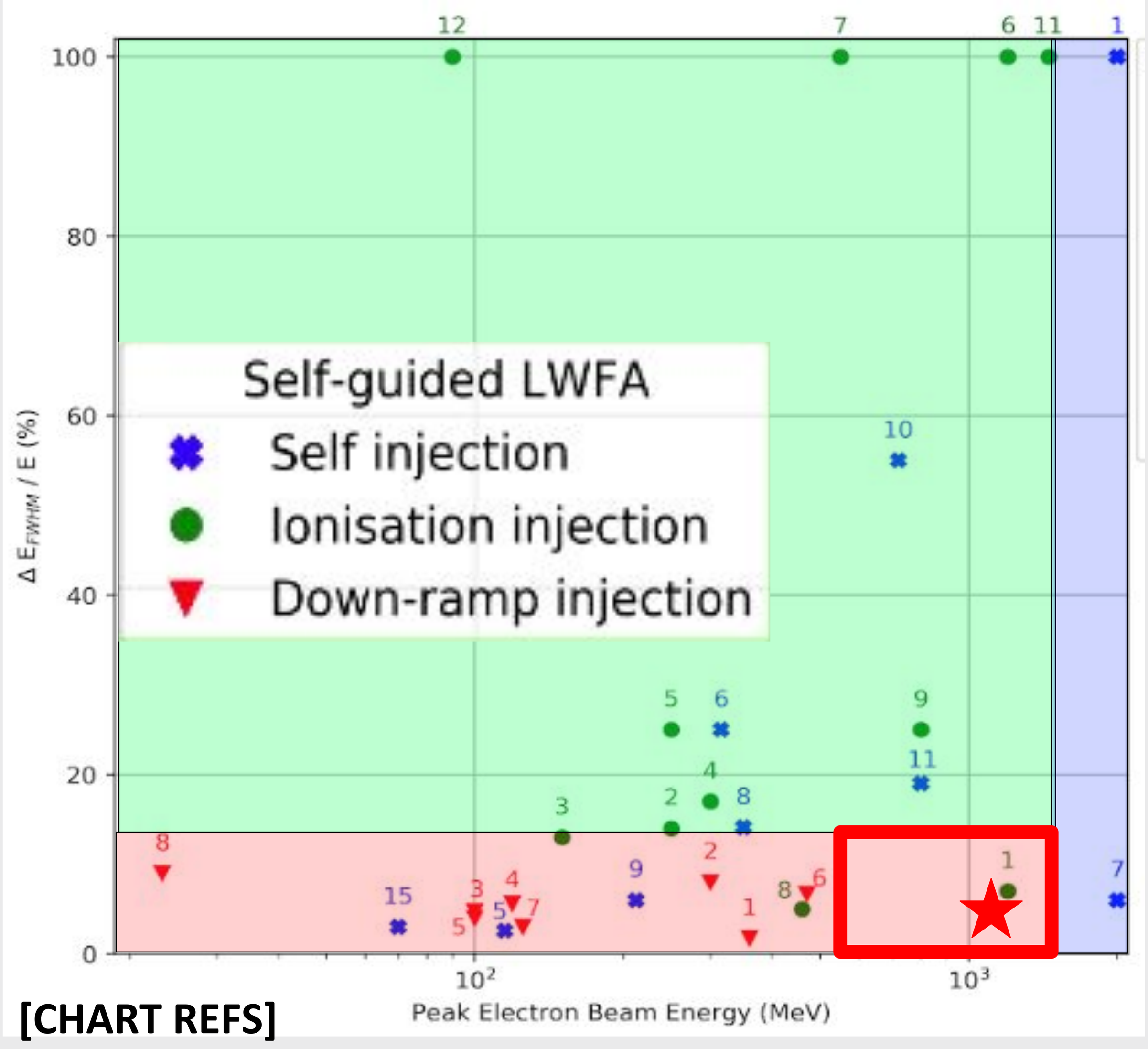
Results: GeV level, narrow ΔE electron beams from a shock injection LWFA, as has not been shown before.

For a sequence of 7 out of 11 consecutive laser shots:

Mean peak energy: 1.11 ± 0.05 GeV

Relative FWHM (ΔE): 6.1 ± 1.0%

Improving parameters toward those for applications like FEL lasers, QED experiments, and multi-stage beam loading.



[CHART REFS]

References & Support

[CHART REFS]

Self Injection
1 Poder et al. PRX (2018)
2 Ferri et al. SciRep (2016)
3 Ferri et al. SciRep (2016)
4 Ferri et al. SciRep (2016)
5 Schnell et al. JPP (2015)
6 Banerjee et al. PRSTAB (2013)
7 Wang et al. NatCom (2013)
8 Weingartner et al. PRSTAB (2012)
9 Kneip et al. PRSTAB (2012)
10 Froula et al. PRL (2009)
11 Kneip et al. PRL (2009)
12 Kneip et al. PRL (2009)
13 Kneip et al. PRL (2009)
14 Kneip et al. PRL (2009)
15 Mangles et al. Nature (2004)

Ionisation Injection
1 Mirzaie et al. SciRep (2015)
2 Couperus et al. NatComms (2017
3 Kuschel et al. PRAB (2016)
4 Golovin et al. PRSTAB (2015)
5 Powers et al. Natphot (2014)
6 Mo et al. APL (2013)
7 Mo et al. APL (2012)
8 Pollock et al. PRL (2011)
9 Liu et al. PRL (2011)
10 McGuffey et al. PRL (2010)
11 Clayton et al. PRL (2010)
12 Pak et al. PRL (2010)

Down-ramp Injection
1 Qin et al. PhysPlas (2018)
2 Tsai et al. POP (2018)
3 Swanson et al. PRSTAB (2017)
4 Buck et al. PRL (2013)
5 Burza et al. PRSTAB (2013)
6 Fourmaux et al. APL (2012)
7 Brijesh et al. POP (2012)
8 Schmid et al. PRSTAB (2010)

[1] - FBPIC Particle-in-Cell LWFA simulation, provided by Dr. Daniel Seipt

[2] - Thomas. Diss. Imperial College London (University of London), 2007.

[3] - Schmid, et al. Phys Rev Spec Top-AC 13.9 (2010): 091301.

[4] - Wenz, et al. Nat Phot 13.4 (2019): 263.

[5] - Tsai, et al. PoP 25.4 (2018): 043107.

Work supported in part by the National Science Foundation under grant #1804463.