Nearly collinear optical injection of electrons into wakefield accelerators

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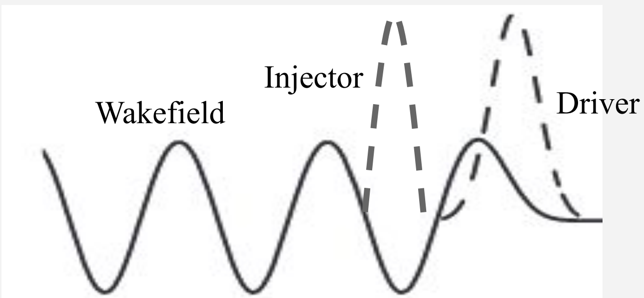
- Goals and objectives
- Experiment methods & results
- Simulation results
- Outlook and conclusions

Optical injection and colliding pulse injection (CPI) for laser wakefield accelerators (LWFA)

Single intense injector optical injection

Umstadter, Kim, et al. , 1996



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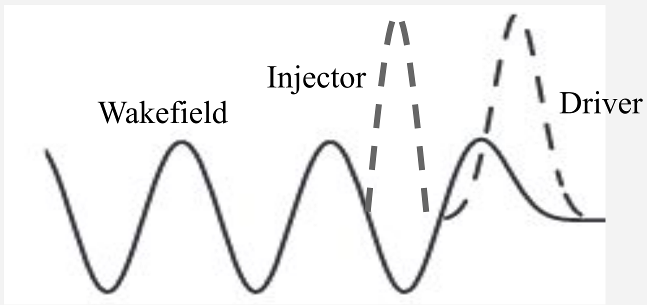
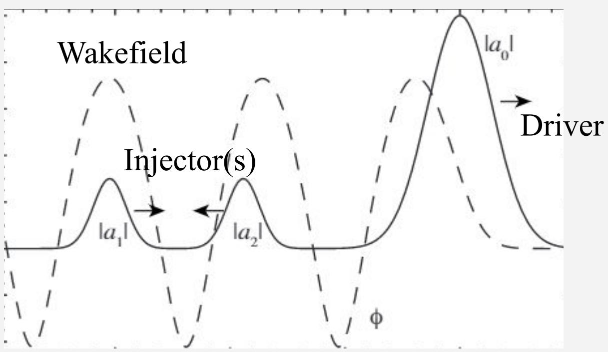


Colliding pulse injection

Esarey, Hubbard, et al. , 1997; Fubiani, Esarey, et al. , 2005



Less intense injector(s)

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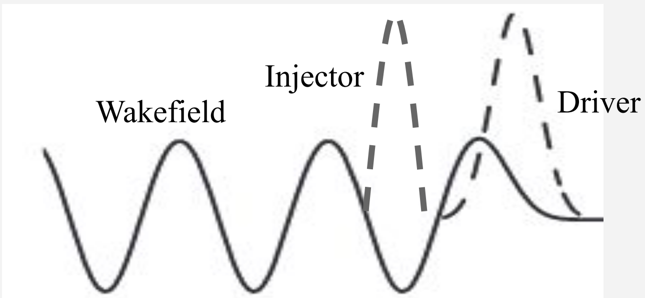

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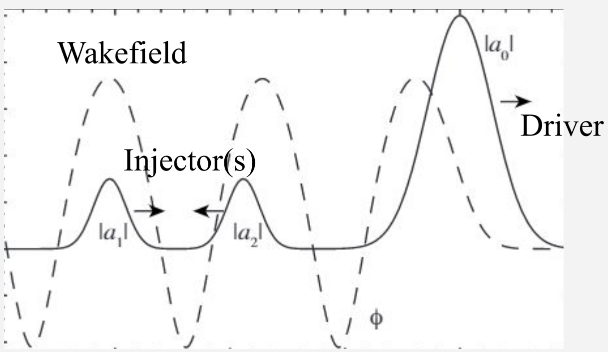
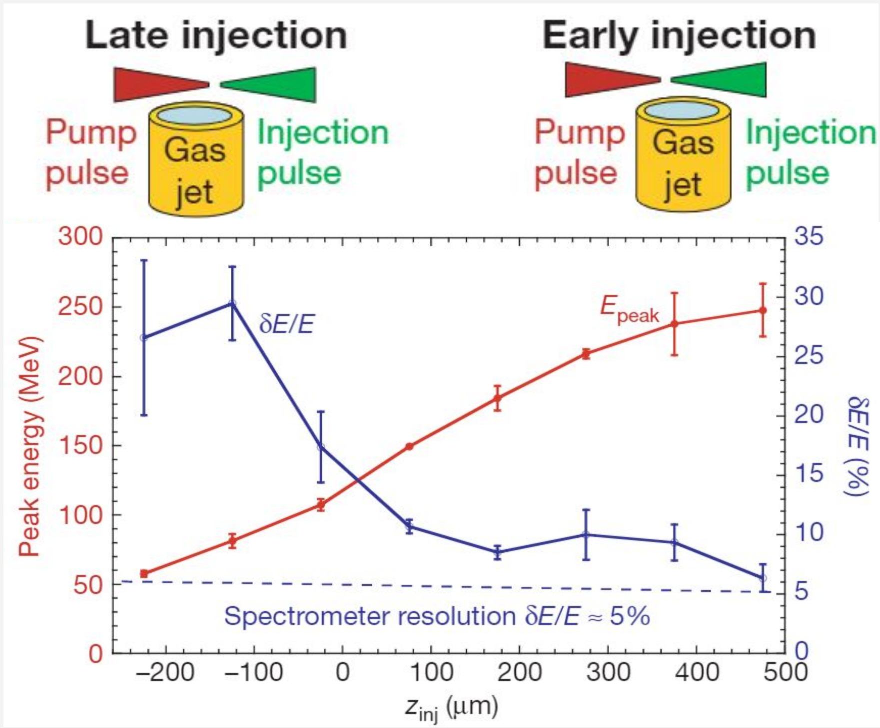


Less intense injector(s)

1st experiment demonstration of CPI

Faure, Glinec, Malka, et al. , 2006

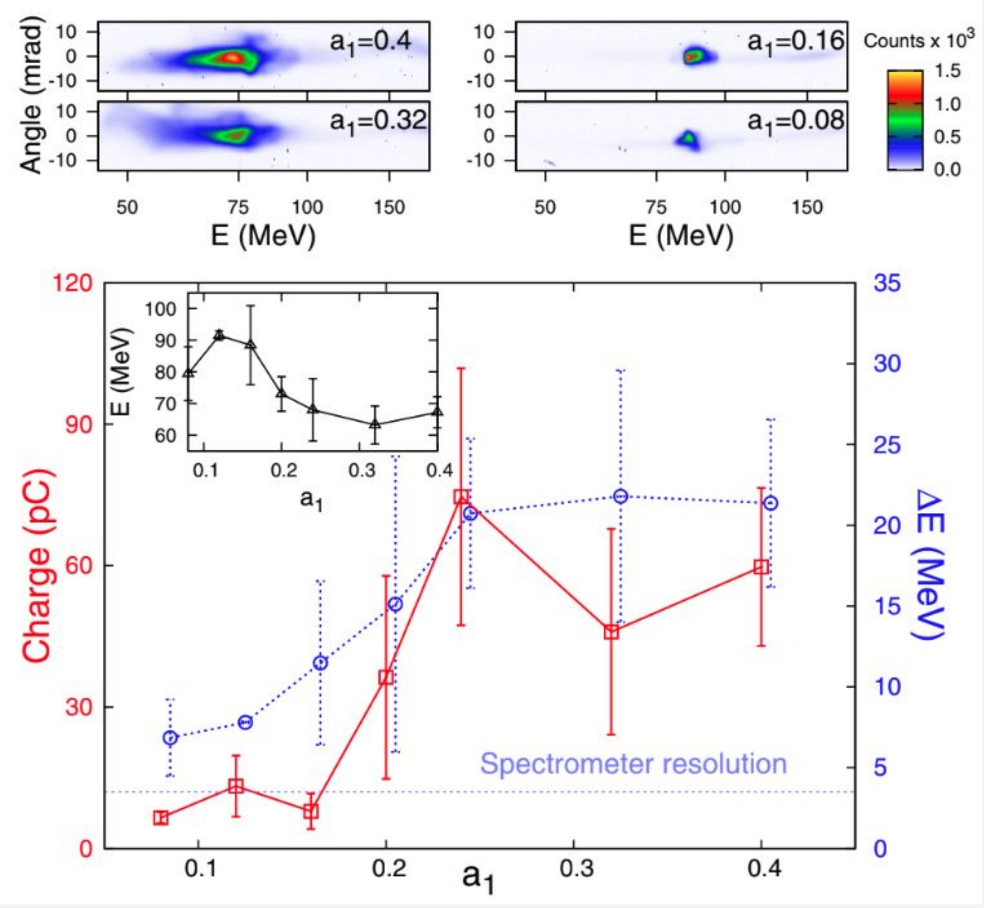


Tunable peak energy and small energy spread

Some other systematic parameter scans for a better control of the colliding pulse injection

Experiment electron spectra for different injector intensity

Rechatin, Faure, Malka, et al., 2009



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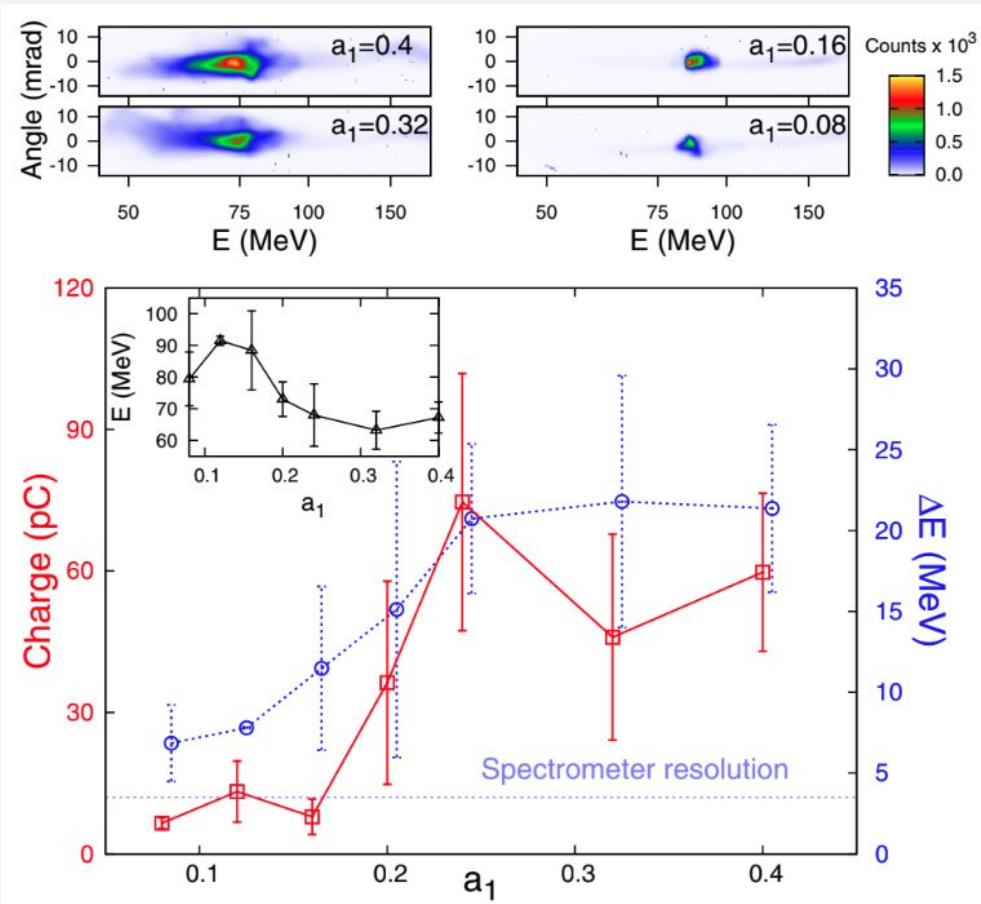
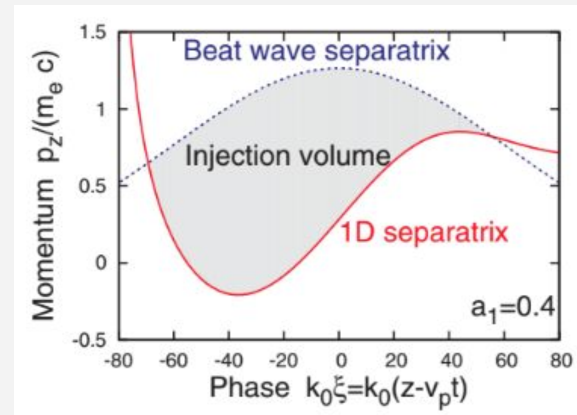
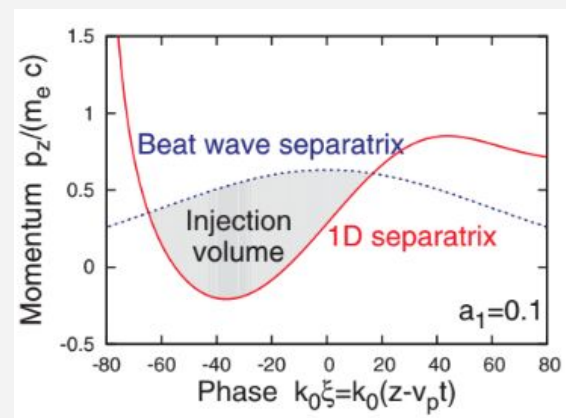


1D schematic for evolution of injection volume with a_1 = 0.4 and a_1 = 0.1.





Explore the untested nearly collinear scheme of the colliding pulse injection

Nearly counterpropagating CPI
(experiments)

Faure, Malka, Kotaki, et al, 2006, 2007, 2009, …
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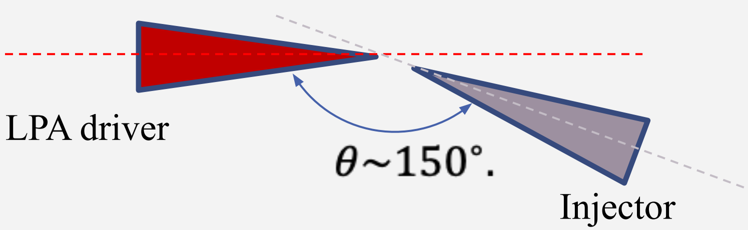

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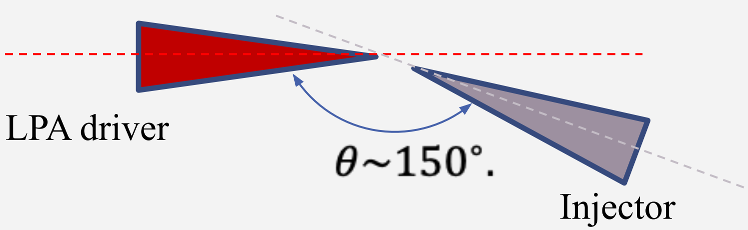
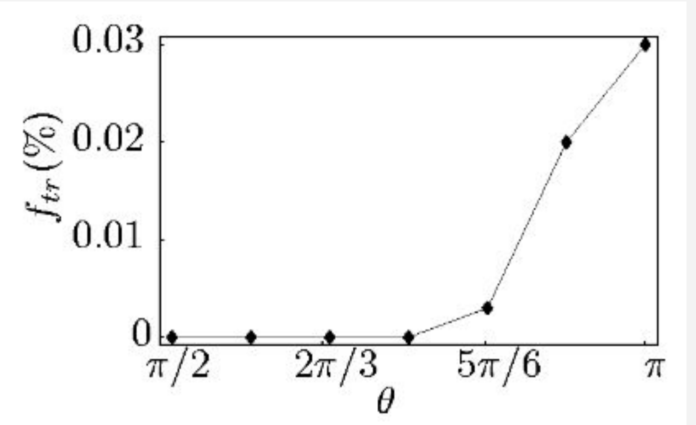


Trapping versus angle
(simulations)

Fubiani, Esarey, et al. , PRE, 2004



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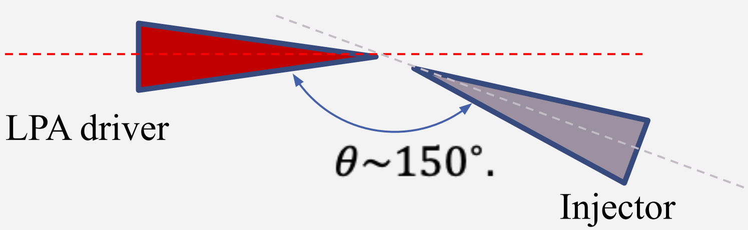

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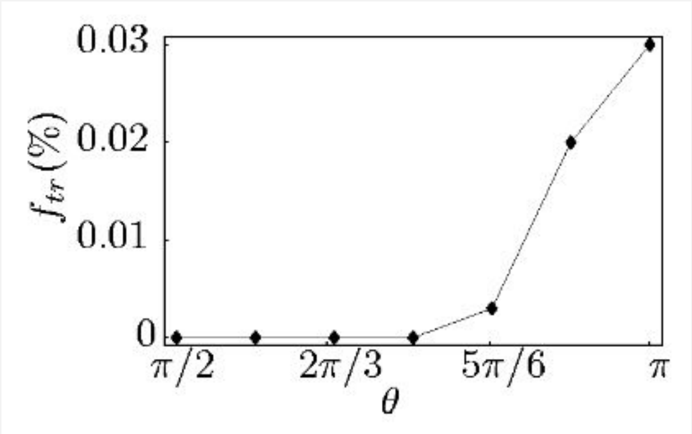


For smaller angles (and even smaller than 90deg):

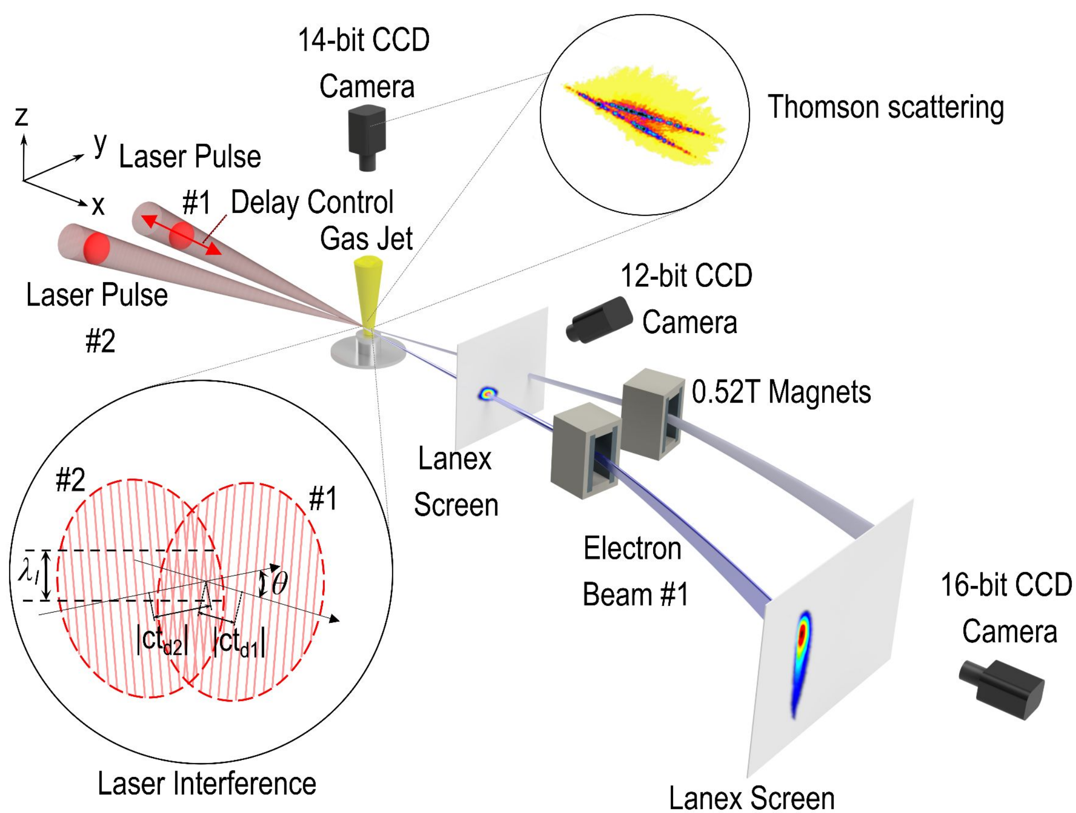
1. What if the injector is as strong/relativistic as the driver? If so, is the trapping possible and observable?
2. What does the transverse component of the beat wave do and what follows?

Experiment schematic and laser parameters

Experiment Schematic

Chen, Maslarova, Wang, Li, Horný, and Umstadter (2022)

Chen, Maslarova, Wang, Li, and Umstadter (2022)

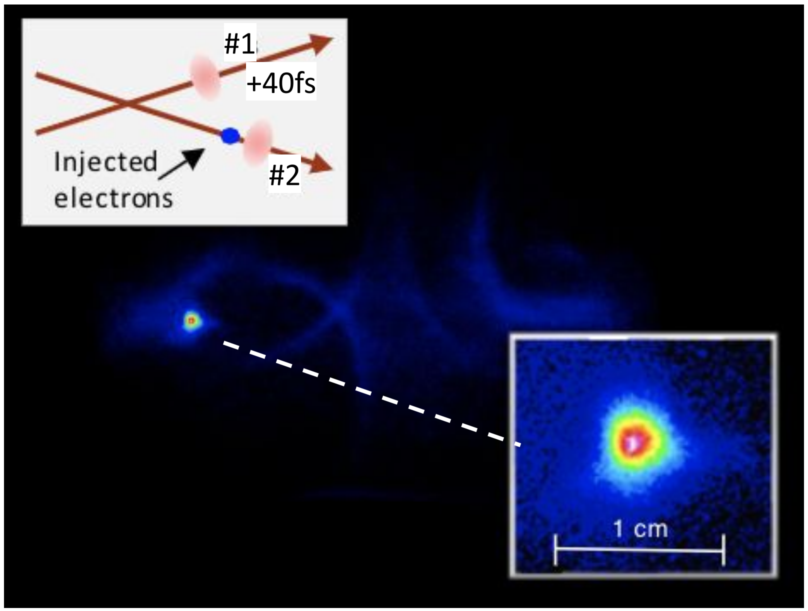


Laser Parameters

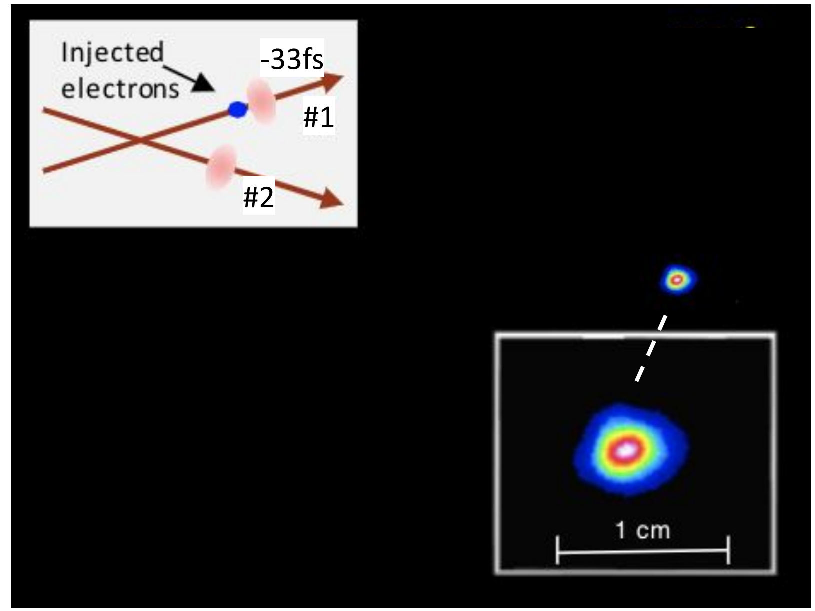
	Parameters	Driver	Injector
Input (Measured)	Lambda (um)	0.8	0.8
	Total Energy (J)	**0.84**	**0.762**
	FWHM Duration (fs)	35	39
	FWHM Diameter (um)	18	18
	Strehl Ratio	0.8	0.8
Output (Estimated)	Waist (um)	15.29	15.29
	Peak Intensity (W/cm2)	4.91E+18	4.00E+18
	Peak Power (TW)	18.03	14.68
	a_0	**1.52**	**1.37**
	Electric Field (TV/m)	6.09	5.49

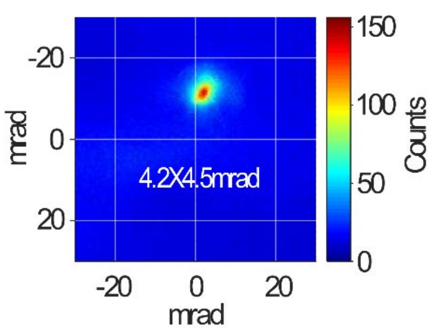
Colliding pulse injection into either laser wakefield accelerators

Injection into wakefield #1

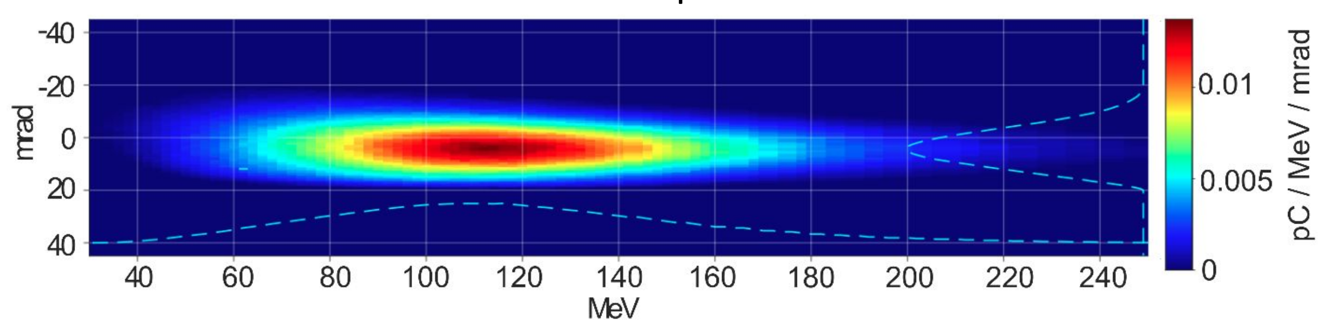


Injection into wakefield #2

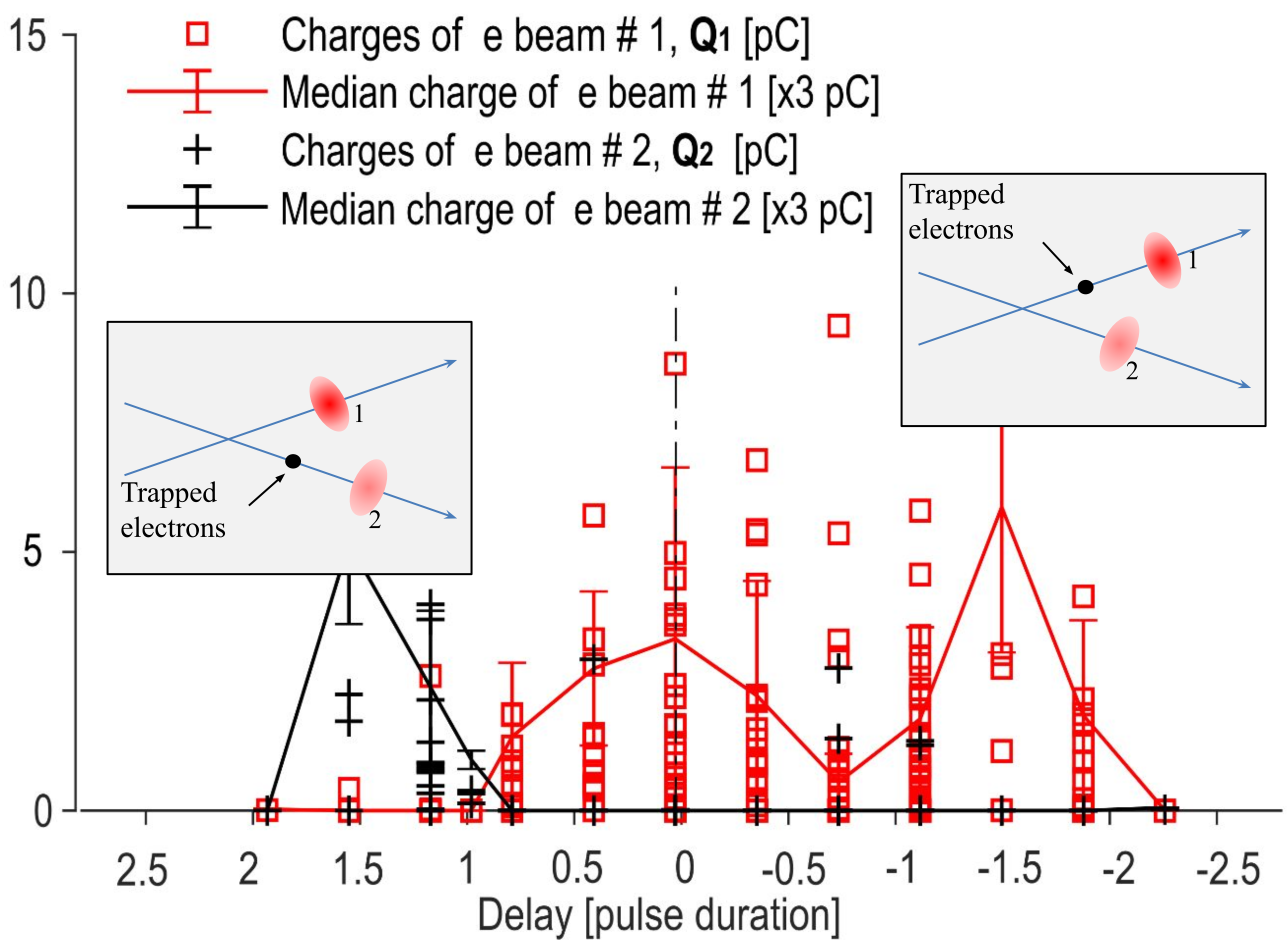




Electron beam spectrum

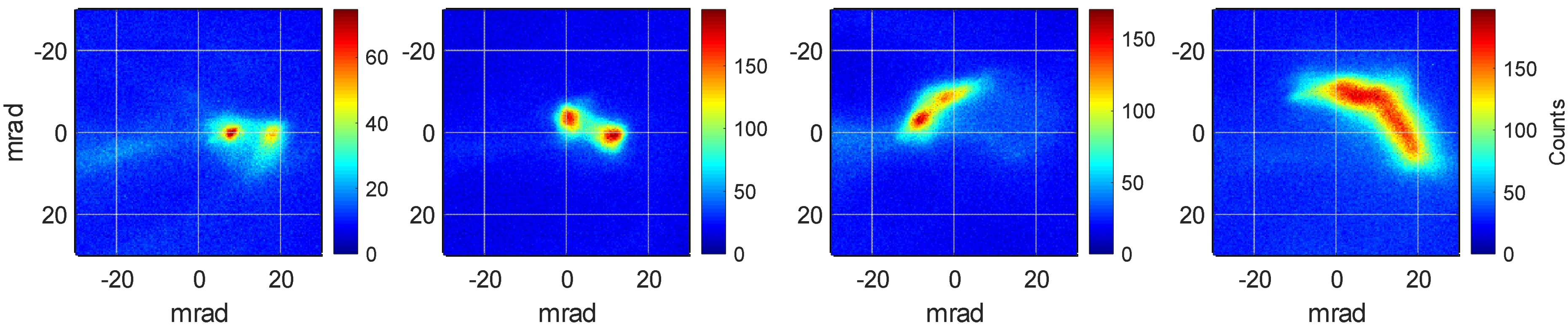


Electron charge versus the delay between two laser pulses

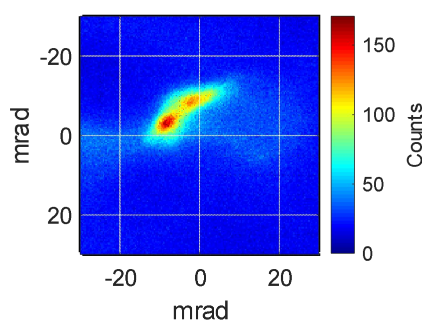


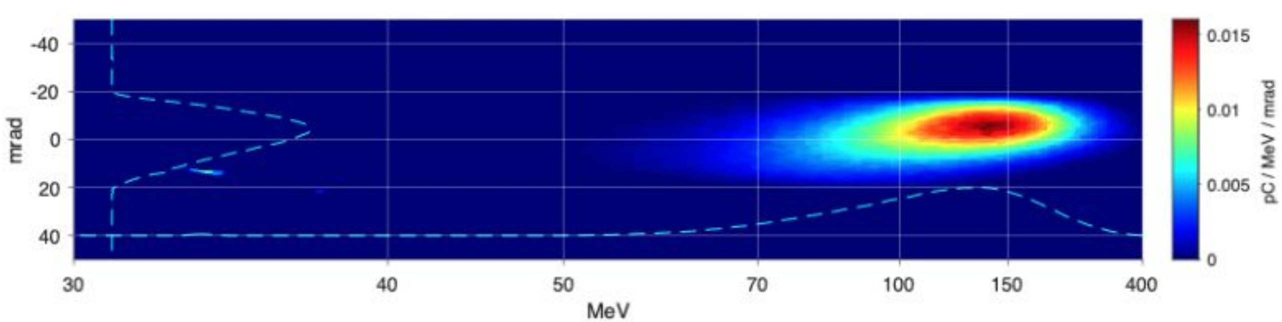
Electron beam splitting and different splitting patterns at ~40fs delay

Different splitting of the electron beam



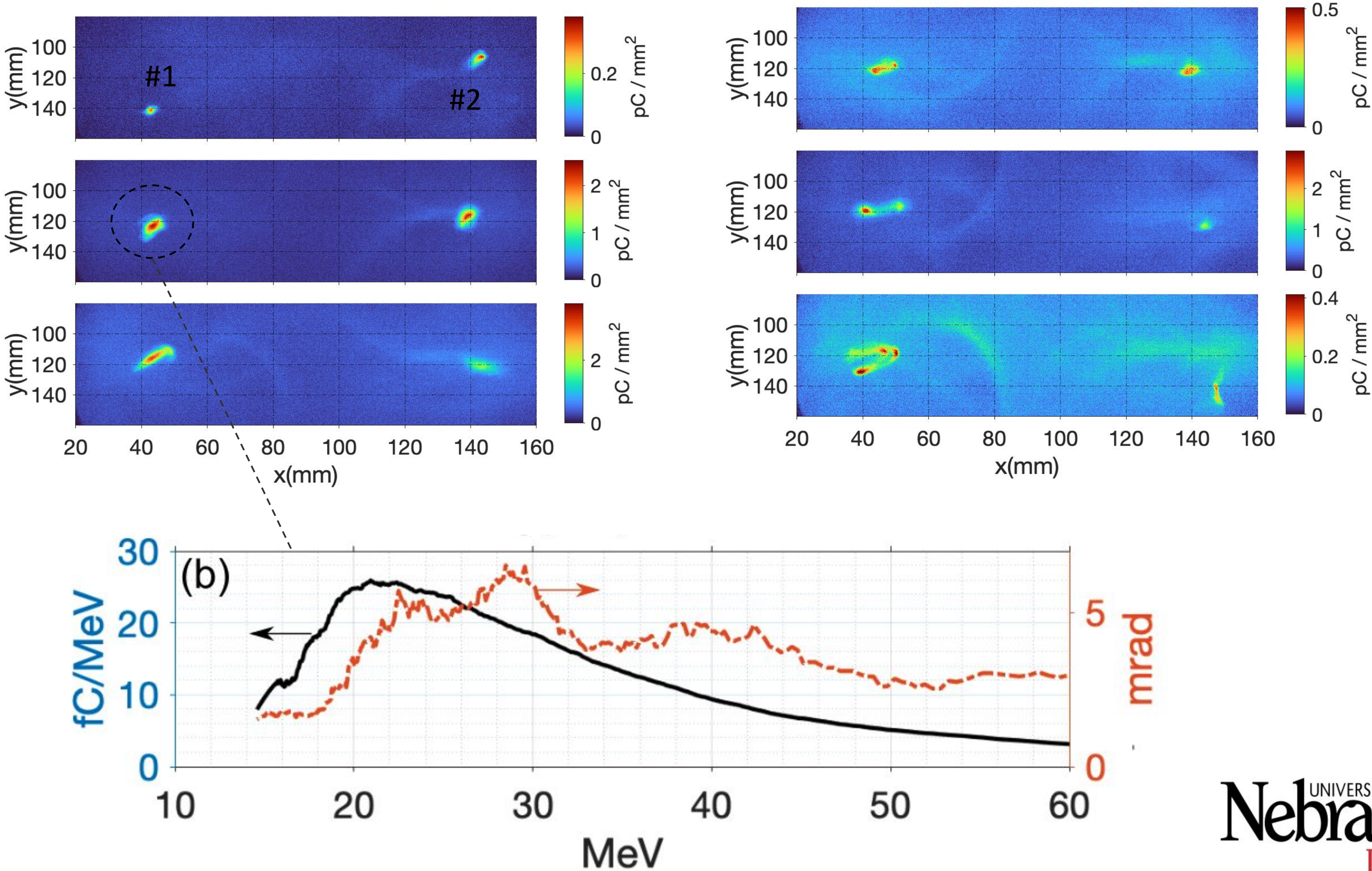
Spectrum of the split beam





Mutual injection of electrons onto both wakefields

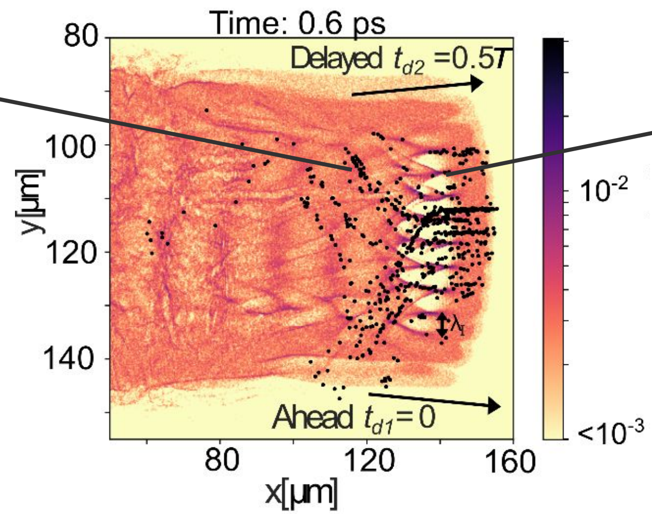
Electron beam spatial profiles



2D particle-in-cell simulations using Smilei)

electron density evolution and injection

Eventually trapped electron macro-particles.



Transient relativistic plasma grating.

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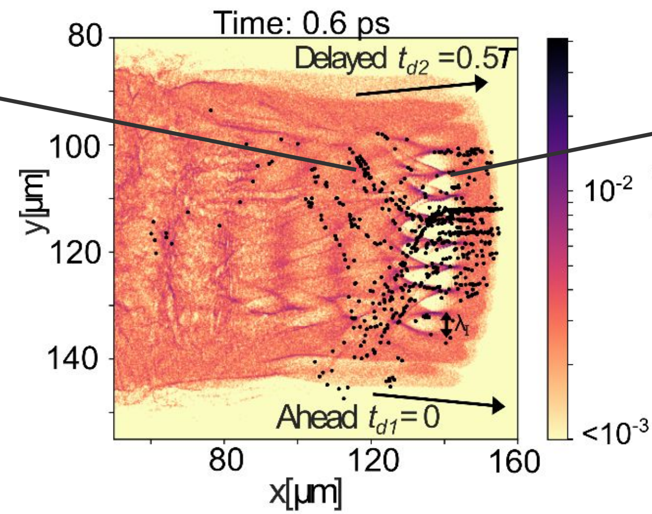

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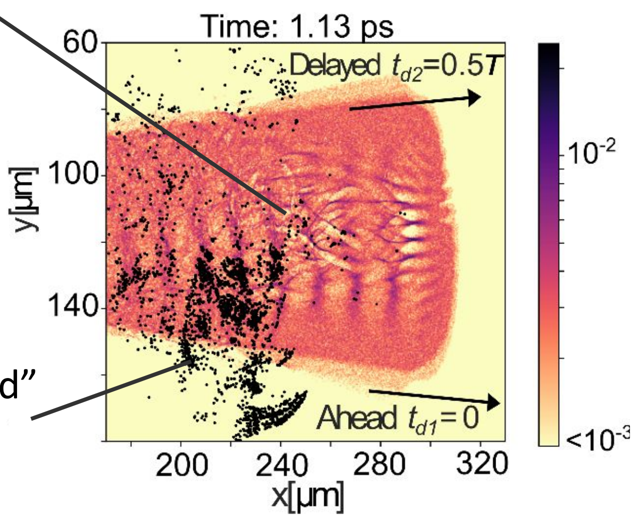
Dual-beam-driven wakefield



“Scattered” electrons

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Transient relativistic plasma grating.

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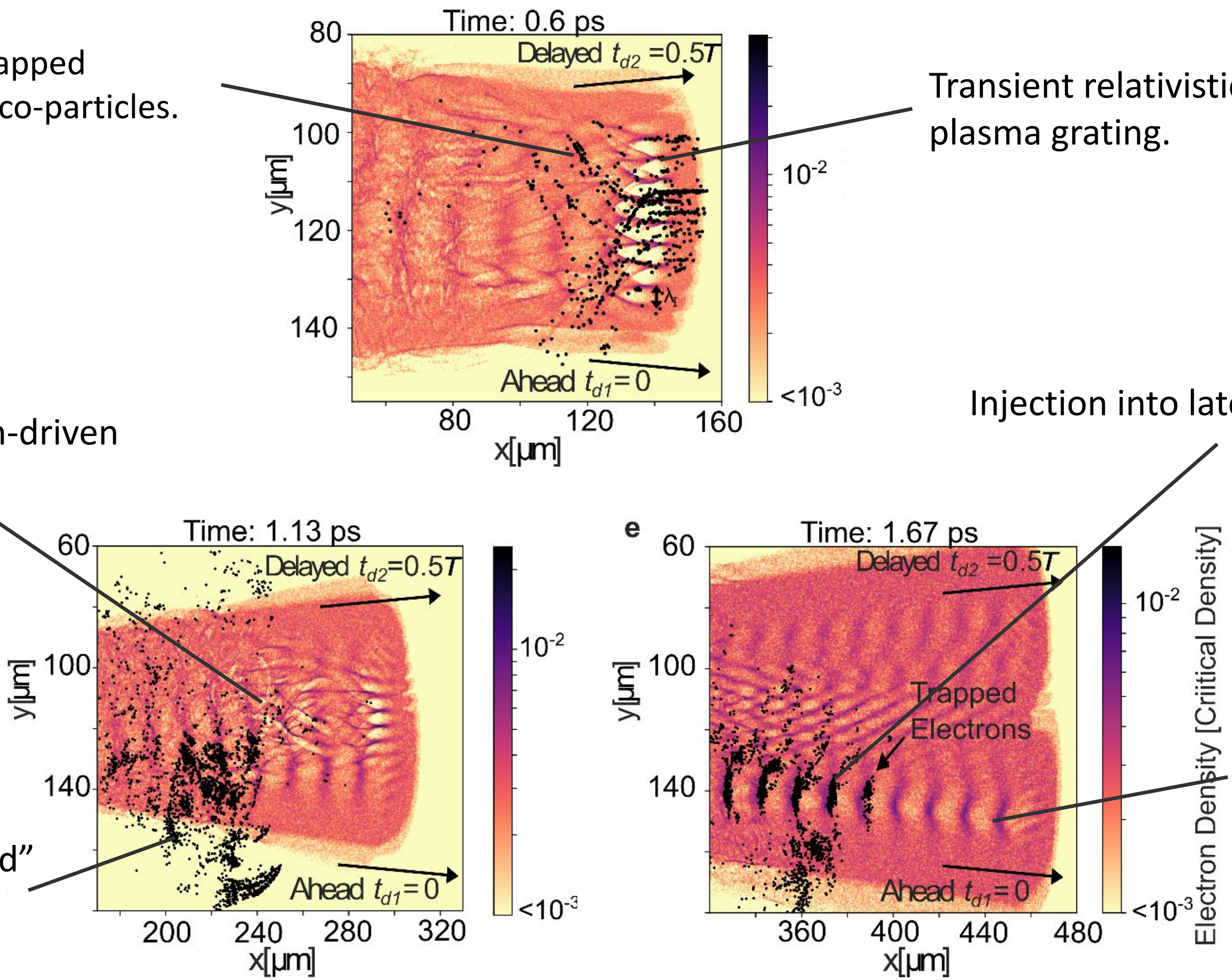
Injection into later buckets

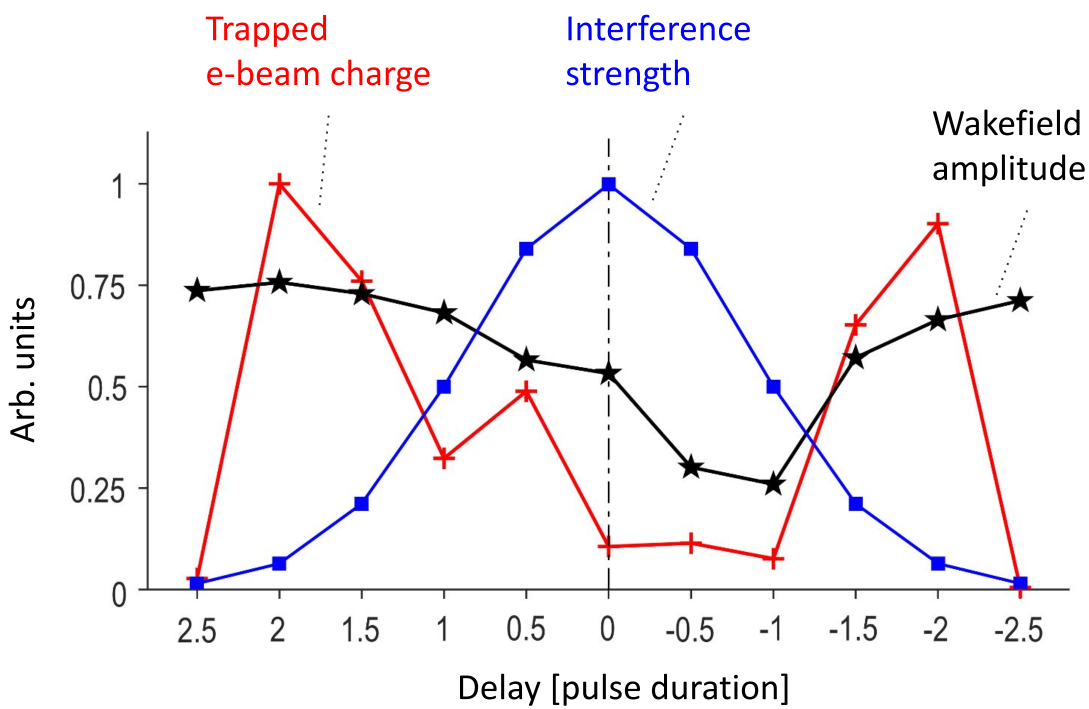


Each bucket recovers

“Scattered” electrons

2D particle-in-cell simulations using Smilei

Strong interference effects



Strong interference → **Strong plasma grating** → Weak wakefield → Low e-beam charge

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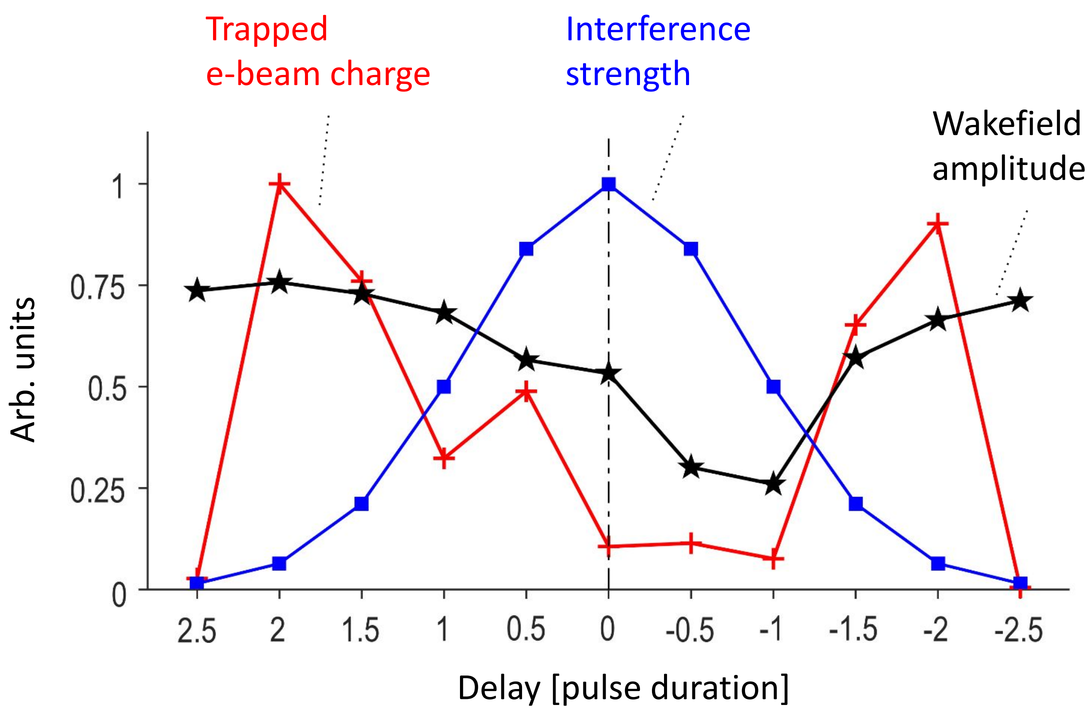

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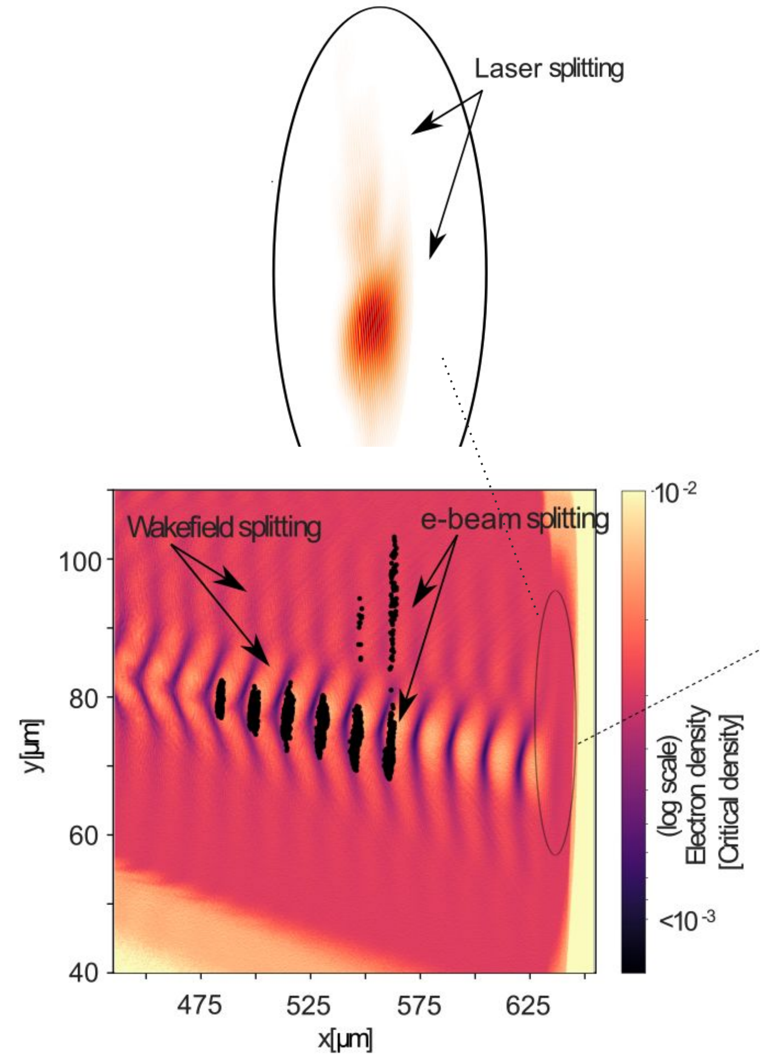
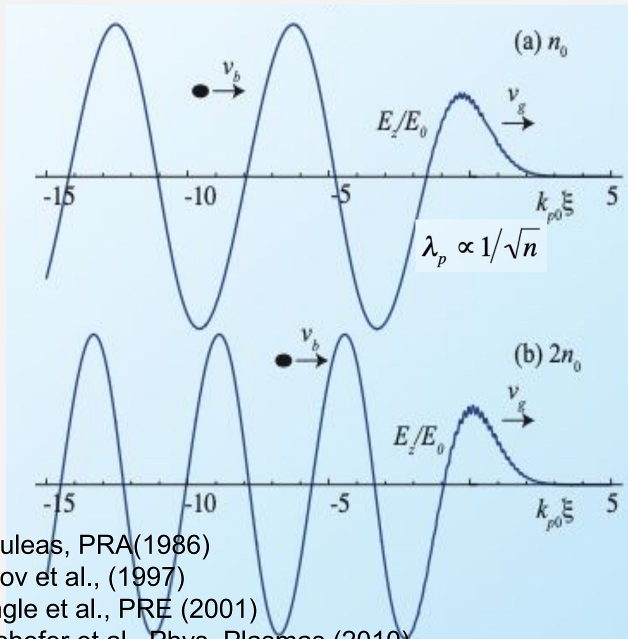


Outlook for future high-energy, compact, high-repetition LWFA and LWFA-based applications using **colliding pulses**

Mitigating dephasing in later-buckets

n_e tapering (neglecting laser propagation effects)



Katsouleas, PRA(1986)
Bulanov et al., (1997)
Sprangle et al., PRE (2001)
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$$\Delta\gamma_N^{\max}/\Delta\gamma_{\rm hom} \approx \pi(2N-1)$$

With N = 5 and suitable n_e tapering, there could be 30x more energy gain for LWFA electron beams.

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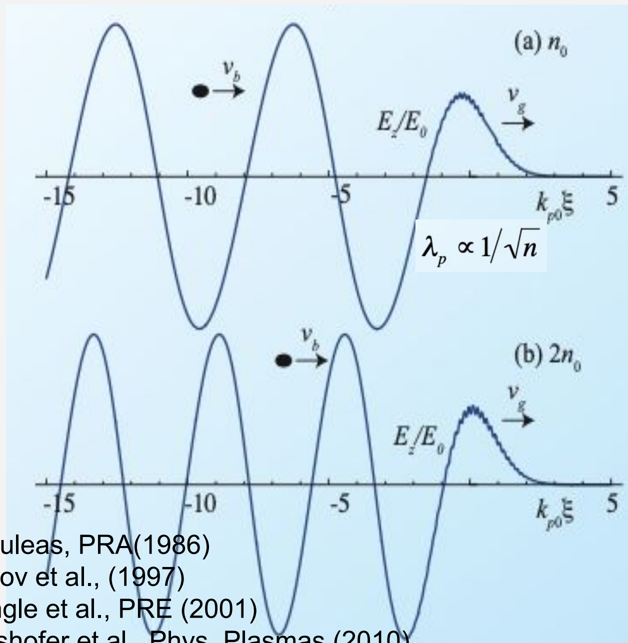

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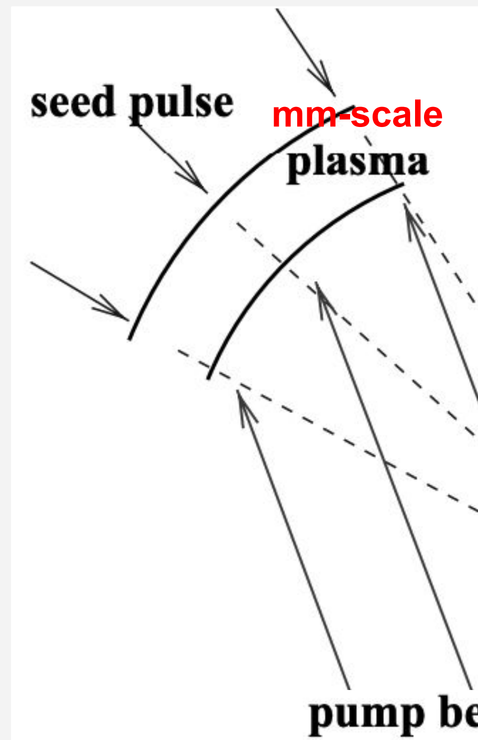
Compact, high repetition plasma compressor

Conceptual schematic via Raman amplification



Malkin, Shvets, and Fisch (1998)
Mourou, Fisch, Malkin, Toroker, Khazanov, Sergeev, Tajima (2011)
Ping, Cheng, Suckewer, Clark, and Fisch (2004)
Wu, Chen, Morozov, Suckewer (2019)

Conclusions

(Experiment) Nearly collinear colliding pulse injection was demonstrated, with the injector as intense as the LWFA driver.

(Experiment) The injection was sensitive to the delay between two laser pulses and various e-beam splitting was observed.

(Simulations) Transverse interference initiated the injection process, by kicking electrons to form a relativistic plasma grating.

(Simulations) Strong interference caused a strong plasma grating, which splits lasers, plasma wakefields and e-beams.

Thank you for your attention!

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Simulation parameters

Angle of collision θ	10°
Laser wavelength λ_l	0.8 µm
Duration Pulse #1 & #2	τ=29 fs FWHM
Intensity Pulse #1 & #2	3.6×10^{18} W/cm^2 (a_0 = 1.3)
Spot size Pulse #1 & #2	18 µm FWHM
Delay between pulses τ_{d2}-τ_{d1}	-72.5 to 72.5 fs
Gas type	100% He
Electron density	5×10^{18} cm^{-3}
Macroparticles per cell	2 He
Cell size	0.033 x 0.05 µm^2

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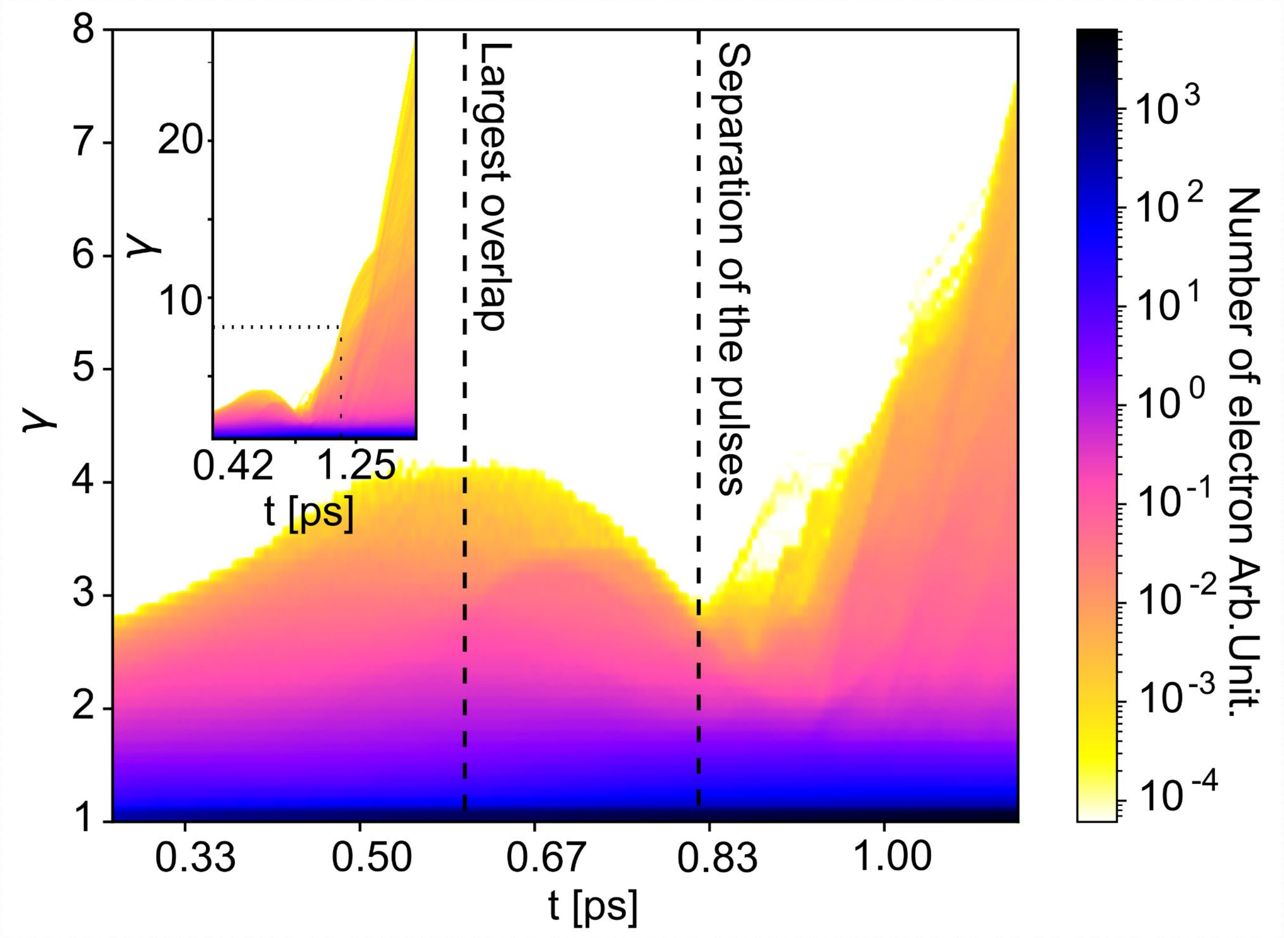
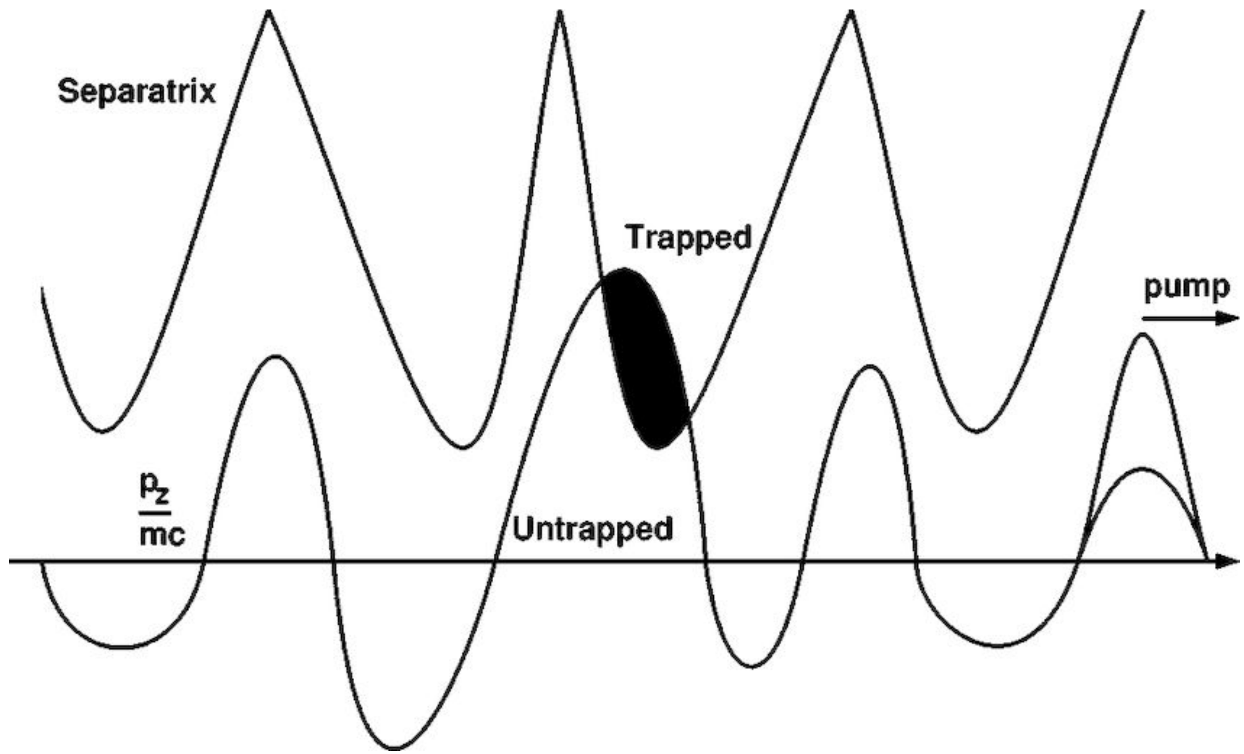
2D particle-in-cell simulations using Smilei

electron energy evolution




Separatrix
Trapped
pump
$\frac{p_z}{mc}$
Untrapped