Modeling LWFA with the Quasi-3D Version of OSIRIS

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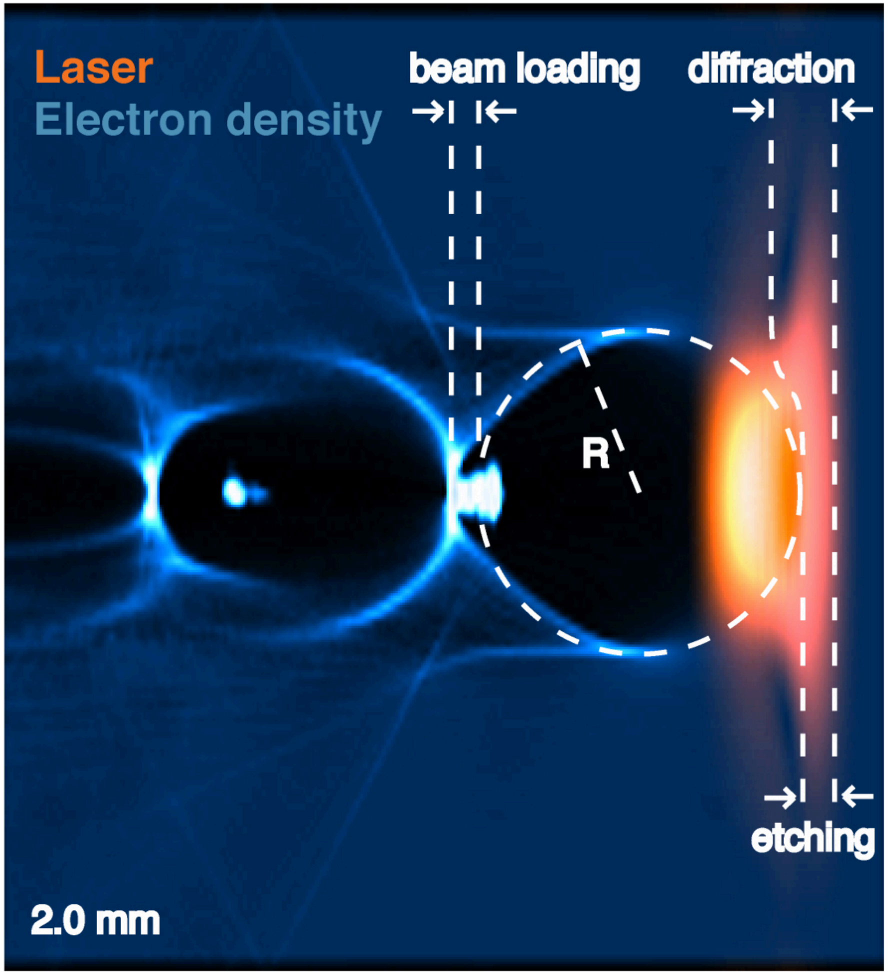
The Blowout Regime

Spot Size Matching[†]



(Courtesy of Lu et al.)

- In order for transverse profile of the laser to remain stable over many Rayleigh lengths, an ideal spot size must be chosen, where the transverse ponderomotive force on the plasma balances the force of the ion channel

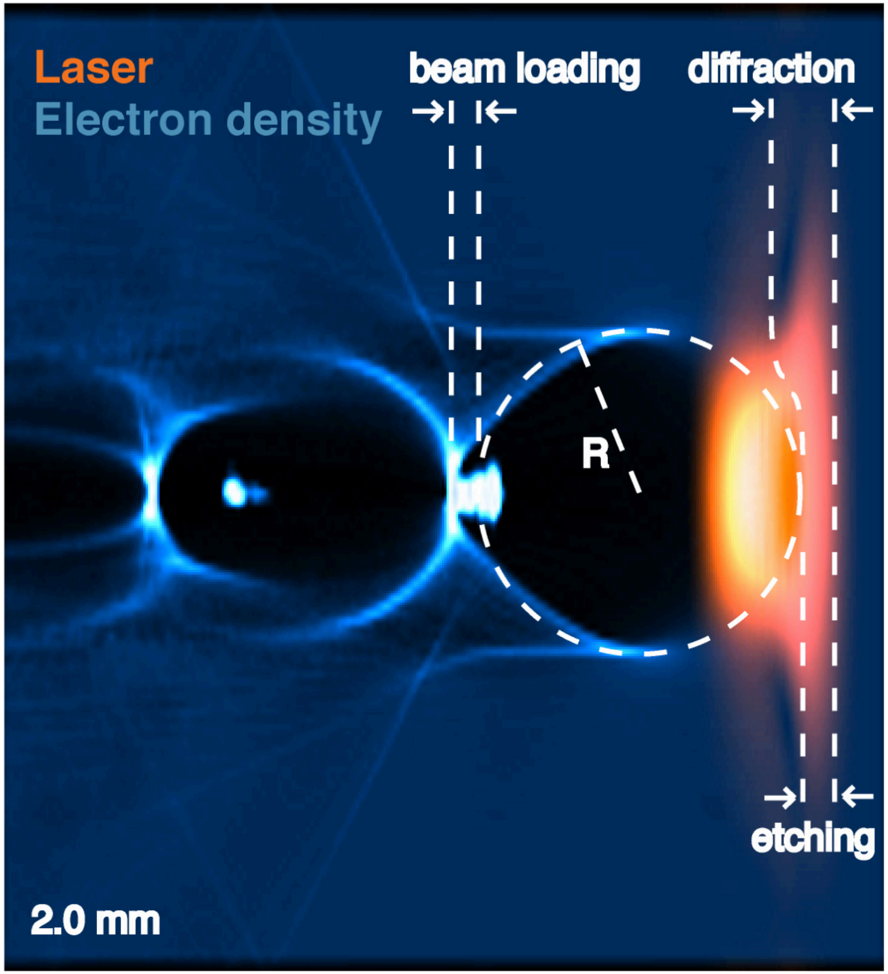
$$W_0 = \frac{2}{k_p}\sqrt{a_0}$$

$$a_0 = 2\left(\frac{P}{P_c}\right)^{1/3}$$

$$P_c = 17\omega_0^2/\omega_p^2[GW]$$

The Blowout Regime

Phenomenological Scaling Law[†]



(Courtesy of Lu et al.)

- Given that the laser has a matched spot size, a scaling law can be derived
- The maximum accelerating distance is estimated as

$$L_d \simeq \frac{2}{3}\left(\frac{\omega_0}{\omega_p}\right)^2 W_0$$

- The particle energy estimated as

$$\Delta E = \frac{2}{3}mc^2\left(\frac{\omega_0}{\omega_p}\right)^2 a_0$$

[†] W. Lu et al., PRSTAB 10 (2007) 061301

The Laser Wakefield Accelerator

- Lu et al. results in an expression for the estimated energy of the trapped particles given the power of a laser, the plasma density, and the laser wavelength

$$\Delta E[\mathrm{GeV}] \simeq 1.7\left(\frac{P[\mathrm{TW}]}{100}\right)^{1/3}\left(\frac{10^{18}}{n_p[\mathrm{cm}^{-3}]}\right)^{2/3}\left(\frac{0.8}{\lambda_0[\mu\mathrm{m}]}\right)^{4/3}$$

- **How far does it scale?**

Pushing the Theory Further

by Scaling to Higher Acceleration Distances

estimated CPU hours (3D)	P (TW)	n_p (cm^{-3})	W_0 (μm)	L_d (cm)	a_0	ΔE (GeV) Estimated	ΔE (GeV) Simulated
100,000	200	1.5×10^{18}	19.5	1.5†	4.0	1.58	1.55†
430,000	324	1.0×10^{18}	22.0	2.62	4.44	2.52	???
3,200,000	649	5.0×10^{17}	31.7	7.37	4.44	5.28	???
26,000,000	1298	2.5×10^{17}	44.8	20.8	4.44	10.57	???
120,000,000	2162	1.5×10^{17}	57.8	44.8	4.44	17.6	???
340,000,000	3280	1.0×10^{17}	71.2	83.8	4.44	26.7	???

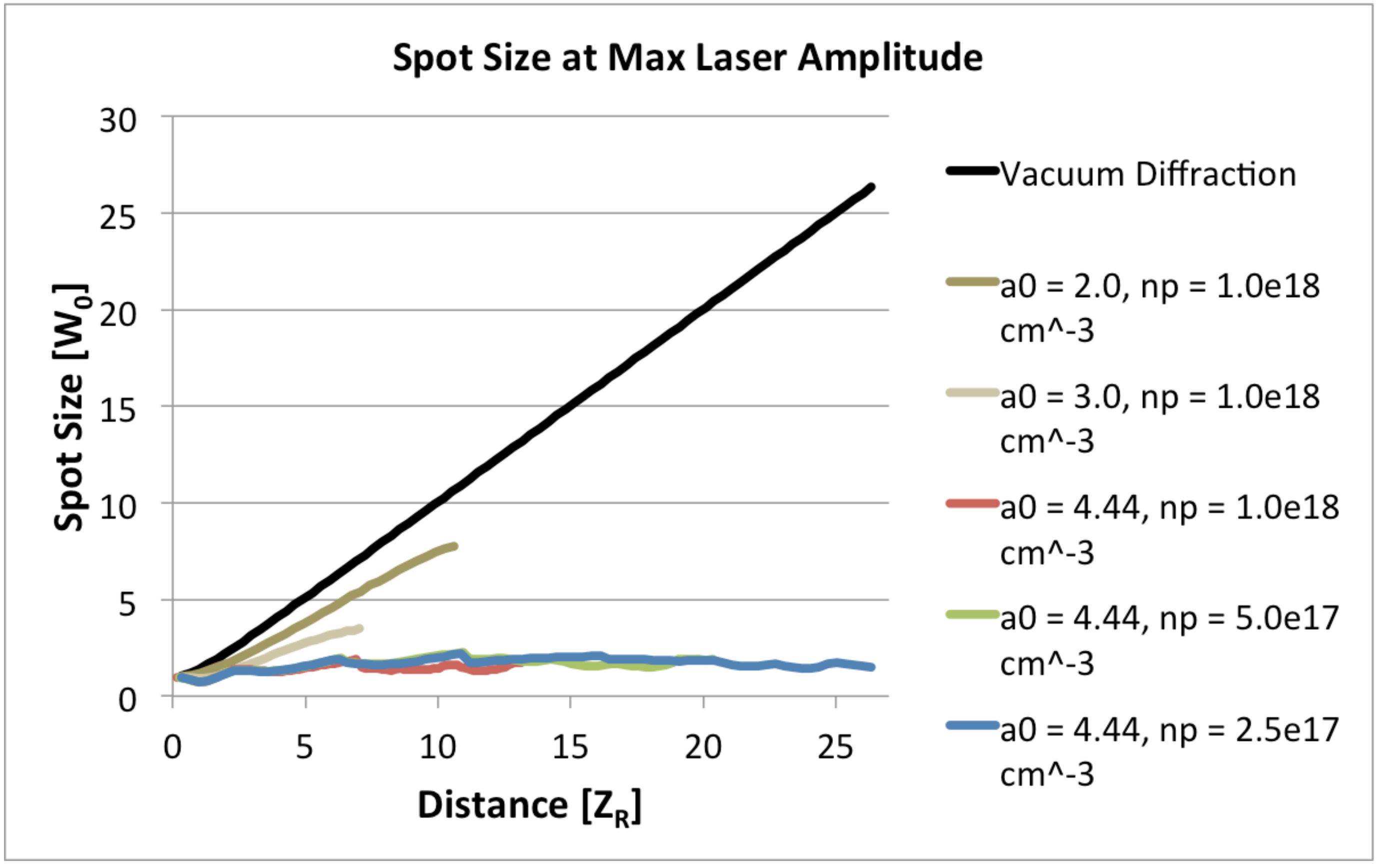
We implement the quasi-3D geometry to attain hundreds of times of speedup

†Lu et al. Conducted this simulation over 0.75cm, not the entire L_d

Scaling Laws in Nonlinear Regime

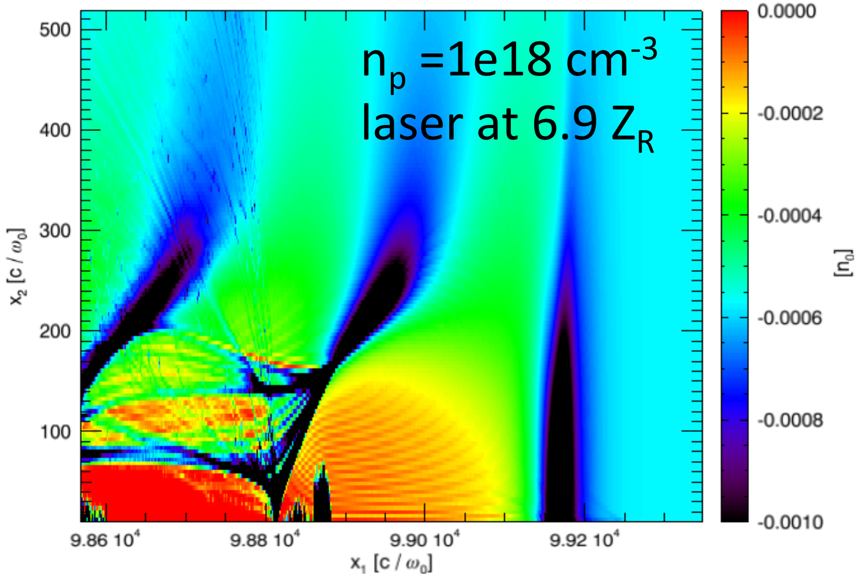
Scaling Laws in the Nonlinear Regime

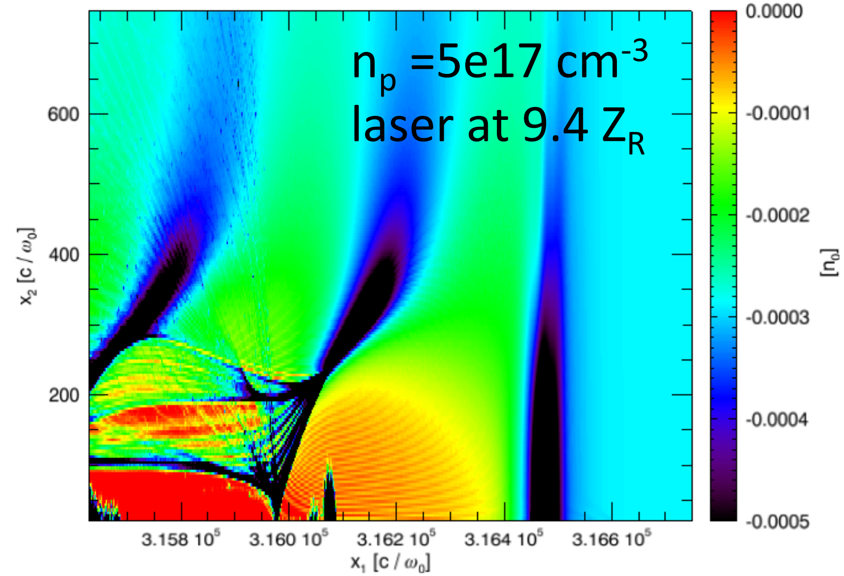
Higher Laser Energies in the Nonlinear Self-Guided Regime

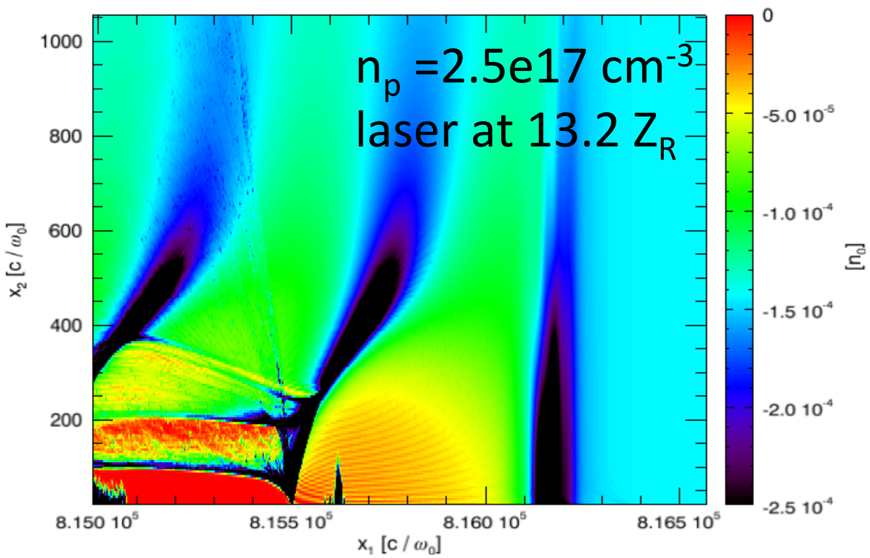


- These simulations spanned up to 26 Rayleigh lengths, clearly demonstrating that self guiding does occur

Scaling Laws in Nonlinear Regime



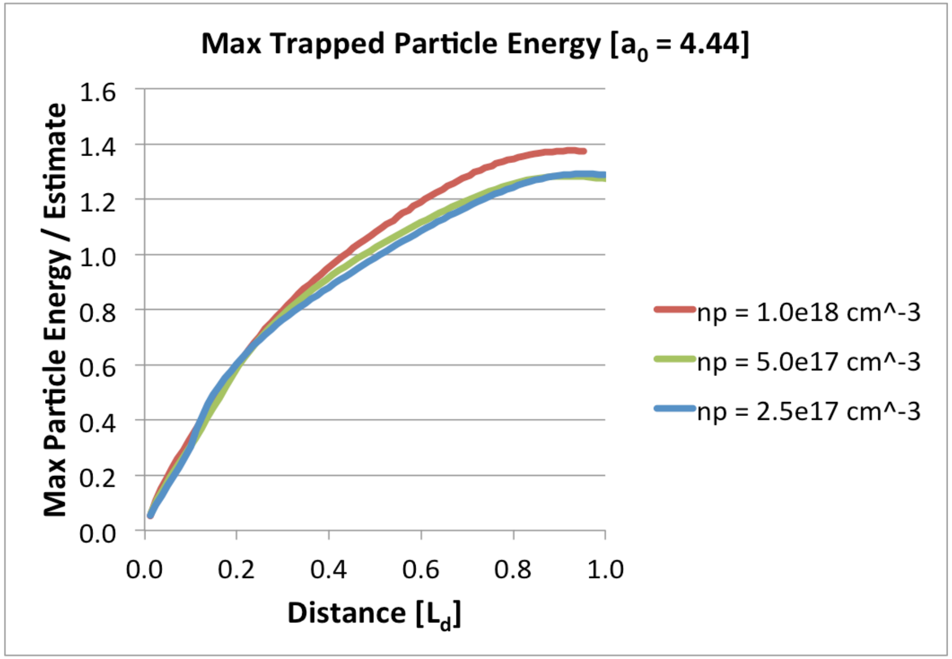


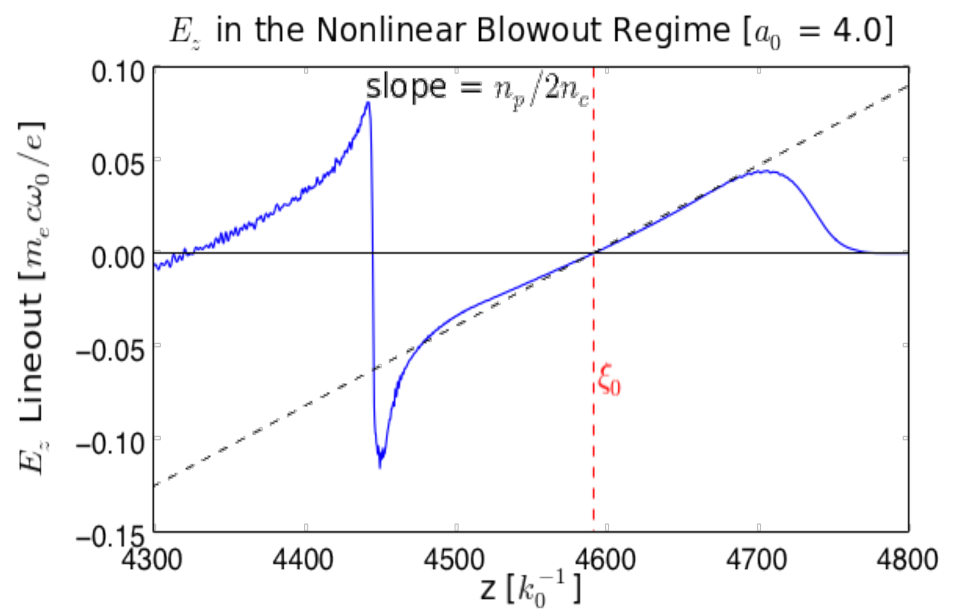


- The plasma densities are compared at a laser traversal distance of 0.5 L_d
- The qualitative feature of Wei Lu's scaling laws work well, given that a_0 remains fixed

Scaling Laws in Nonlinear Regime

We get a Higher Energy than Estimate





- Lu et al.'s particle energy estimate is based on a perfectly linear ramp in the accelerating field
- However, the evolution of the energy gain is very close when scaled to the appropriate parameters

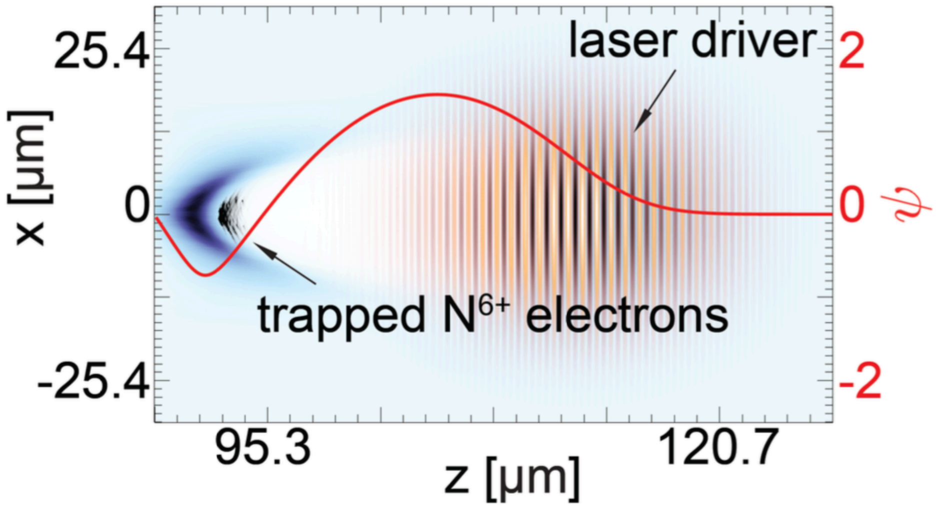
Scaling Laws in Nonlinear Regime

Faster Methods Means Physics in Farther Regimes

Laser Energy (J)	P (TW)	n_p (cm^{-3})	W_0 (μm)	L_d (cm)	a_0	ΔE (GeV) Estimated	ΔE (GeV) Simulated
6	200	1.5×10^{18}	19.5	1.5	4.0	1.58	1.55
16	**324**	$\mathbf{1.0 \times 10^{18}}$	**22.0**	**2.62**	**4.44**	**2.52**	**3.46**
47	**649**	$\mathbf{5.0 \times 10^{17}}$	**31.7**	**7.37**	**4.44**	**5.28**	**6.63**
133	**1298**	$\mathbf{2.5 \times 10^{17}}$	**44.8**	**20.8**	**4.44**	**10.57**	**13.6**
290	2162	1.5×10^{17}	57.8	44.8	4.44	17.6	???
542	3280	1.0×10^{17}	71.2	83.8	4.44	26.7	???

Ionization-Injection

Implemented in Quasi-3D



- Ultra-relativistic high quality beams by Ionization-Injection
- Lower trapping threshold for ionized elections
- Tunneling Ionization

$$W(\mathrm{s}^{-1}) \approx 1.52 \times 10^{15} \frac{4^{n^*} \xi_i(\mathrm{eV})}{n^* \Gamma(2n^*)} \left(20.5 \frac{\xi_i^{3/2}(\mathrm{eV})}{E[\mathrm{GV/m}]} \right)^{2n^*-1} \times \exp\left(-6.83 \frac{\xi_i^{3/2}(\mathrm{eV})}{E(\mathrm{GV/m})} \right). \quad (3)$$

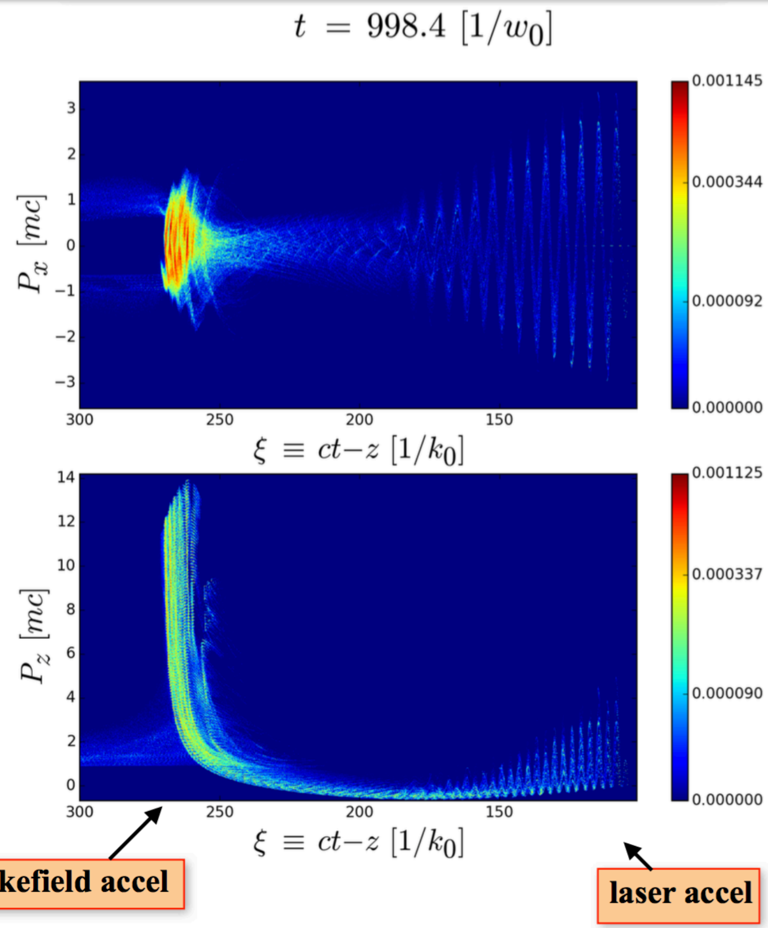
- Ammosov-Delone-Krainov (ADK) model
- Rates depend on field E and ionization potential ξ_i

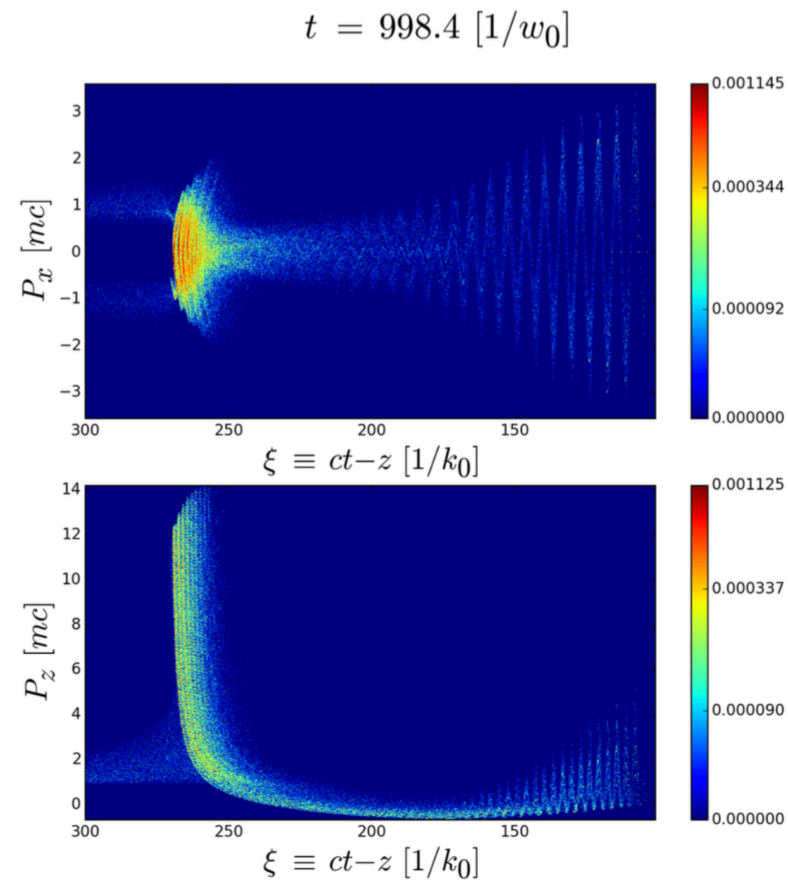
[†] Bruhwiler et al., Phys. of Plasmas, Vol. 10, 2022 (2013)

Ionization-Injection

- **Quasi-3D Parameters:**
  - Grid (z,r) = 1500 x 250 ; ppc: nø = 16, nrz = 1
  - Total particles: n ~ 10^6 ; modes m <= 1
  - Sim. time: ~ 1000 cpu-hours

- **Full-3D Parameters:**
  - Grid (x,y,z) = 1500 x 500 x 500 ; ppc = 1
  - Total particles: n ~ 10^8
  - Sim. Time: ~ 100,000 cpu-hours





Summary

- The quasi-3D geometry allows the ability to simulate LWFA regimes that are too computationally expensive for a full 3D Cartesian simulation
- Ionization-injected LWFA simulations have also been conducted in the quasi-3D geometry, with a hundred of times of speedup [Will be implemented in the 4.0 Framework in the Future]
- **LWFA simulations, which possess near-azimuthal symmetry by design, are ideal problems to be explored with Quasi-3D simulations, resulting even in hundreds of times the speedup in comparison to an equivalent 3D Cartesian simulation**

The End

Capabilities of a Fixed Energy Laser

Capabilities of a Fixed Energy Laser

We Explore the Implications of the Scaling Laws Given a Fixed Energy Laser

Optimal density and pulse length for a laser of fixed energy:

$$E_L = \alpha P \tau,$$

Assuming a matched spot size, we can adjust the relative pulse length as a free parameter:

$$\tau = \mathcal{F} 2 \sqrt{a_0} \omega_p^{-1}$$

We may recast the scaling laws equations as a function of the laser energy, pulse length, and amplitude:

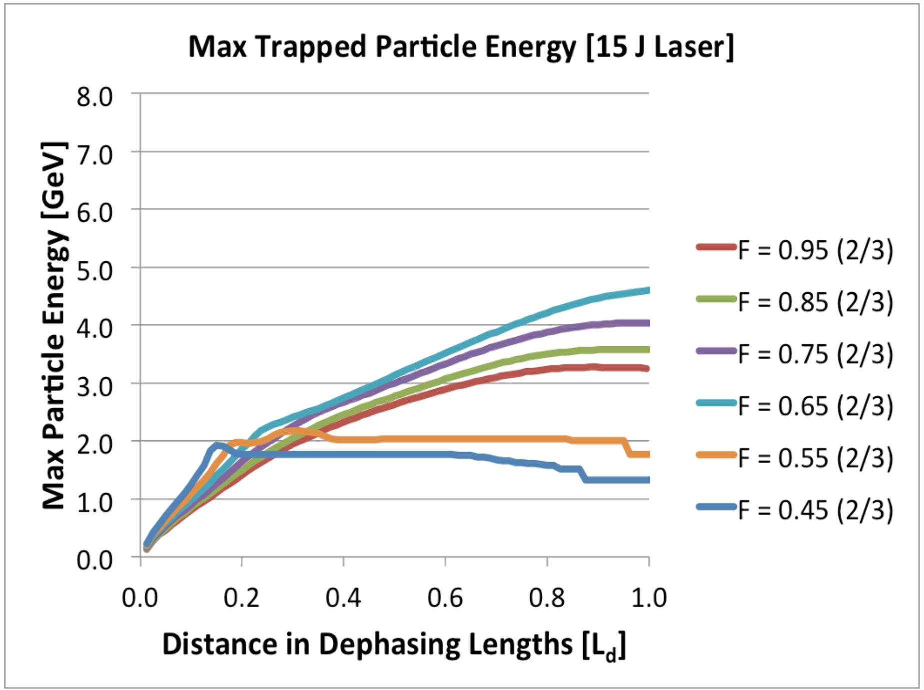
$$\Delta E = \frac{2}{3} \frac{m_e c^2}{\alpha^{2/3}} \left[\frac{4\omega_0}{\mathcal{A}} \right]^{2/3} \frac{E_L^{2/3}}{\mathcal{F}^{2/3} a_0^{4/3}}.$$

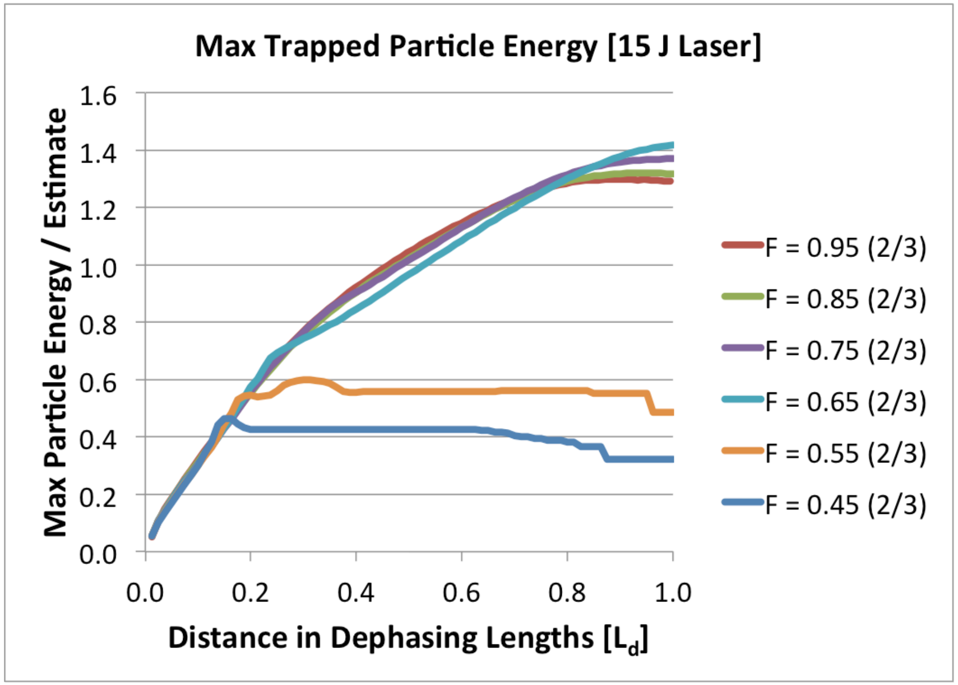
[A = 17 GW]

Logically, there is a lower bound to the pulse length that can be determined empirically

Capabilities of a Fixed Energy Laser

15 J Laser ($a_0 = 4.44$)

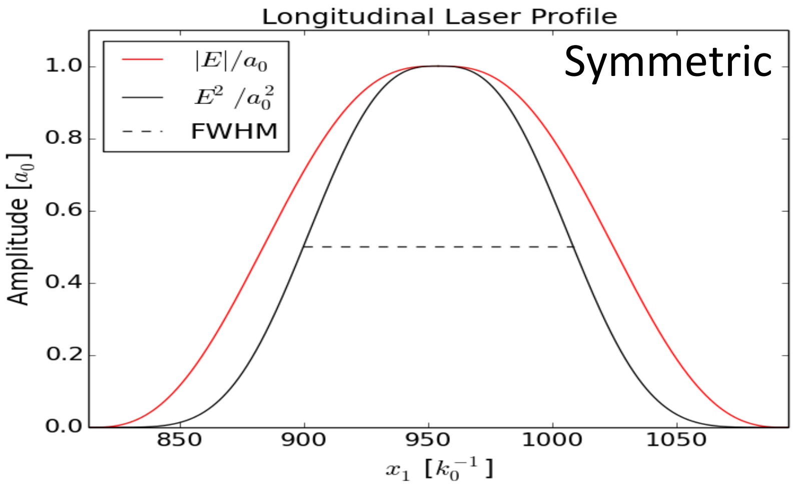


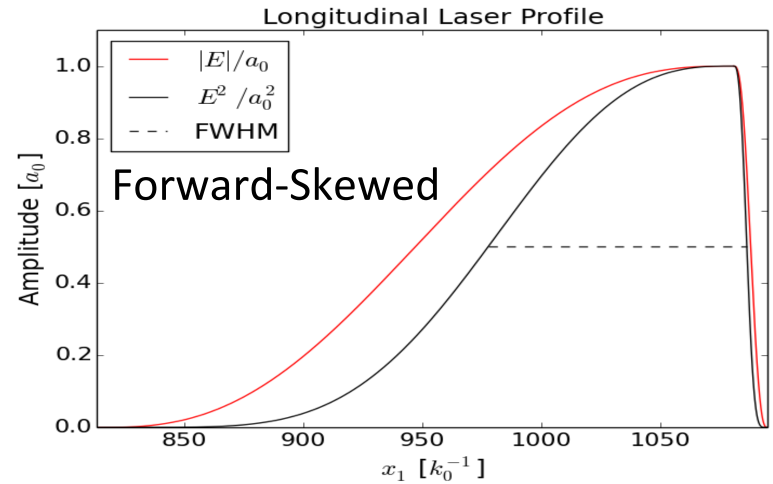


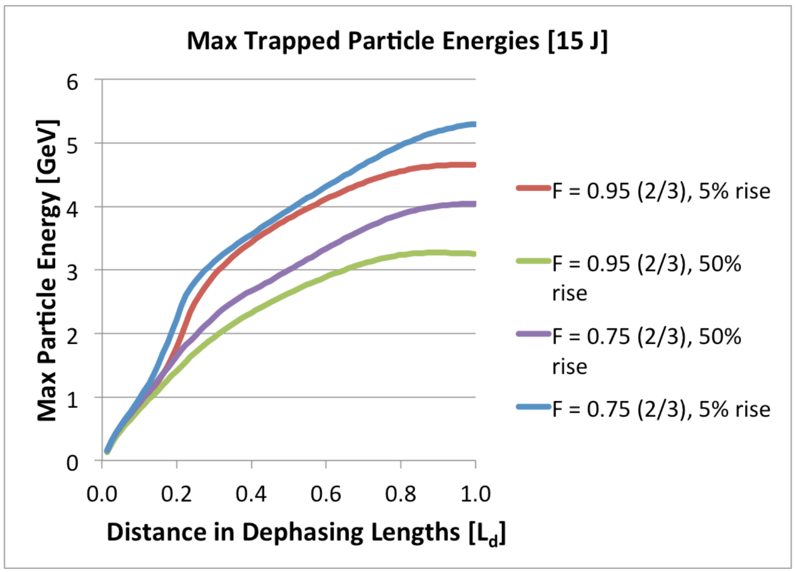
- By optimizing the pulse length of the 15 J case, we got an increase of energy **3.25 GeV -> 4.60 GeV**
- Even though the particles are self-injected in these simulations, this energy gain also applies to externally injected particles.

Capabilities of a Fixed Energy Laser

Longitudinal Profile Adjustment





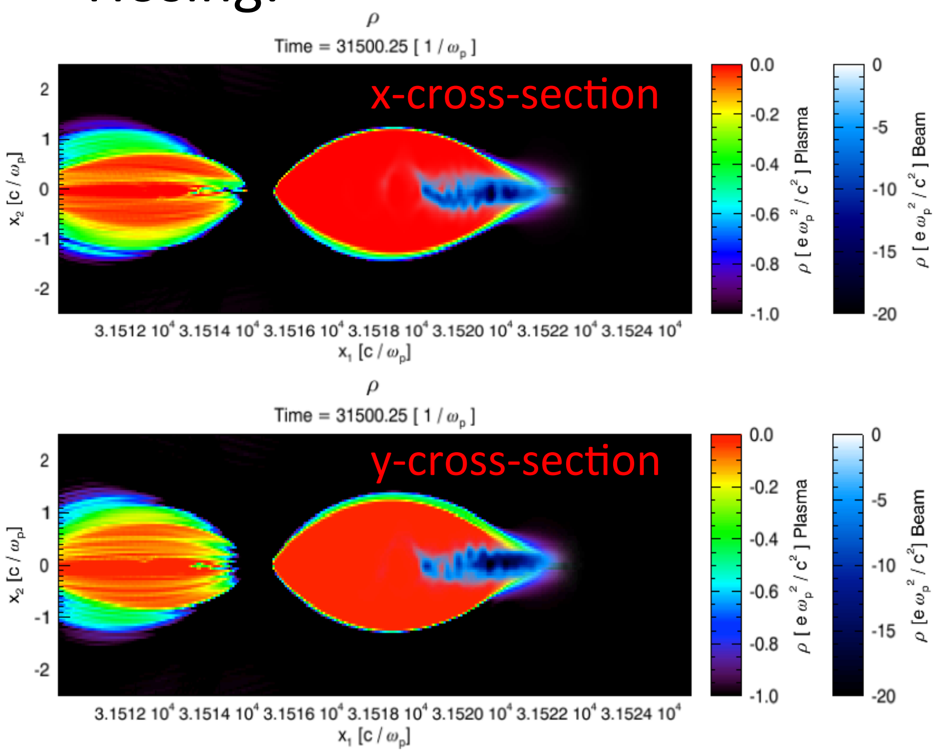


- Best results I found so far, by combining a skewed profile with optimized pulse length:
  - 15 J Laser : **5.3 GeV**
  - 30 J Laser : **8.1 GeV**
- Note that for the 15 J case, this is twice the estimated energy of 2.52 GeV using default parameters

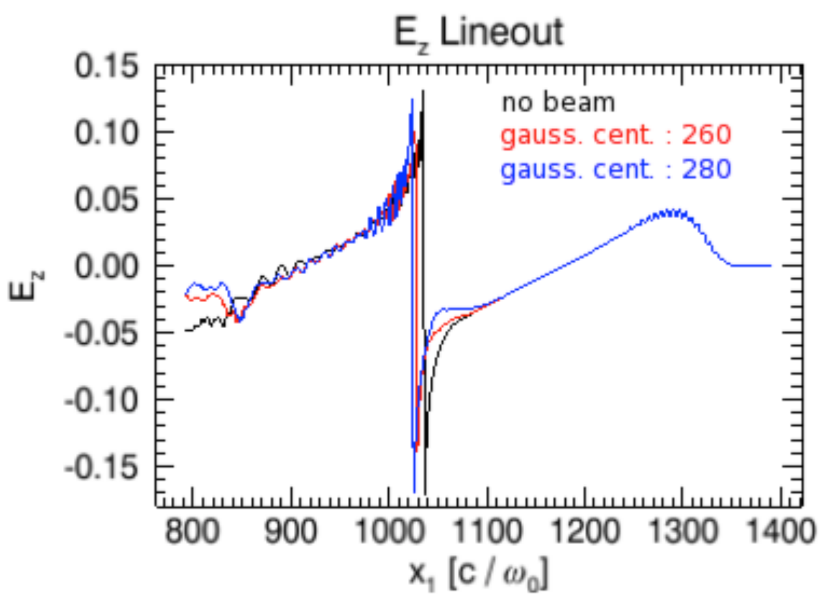
Other Potential Implementations

with the quasi-3D algorithm in OSIRIS

Hosing:



Beam Loading:



- The high speed and low computational cost of the simulations allow for quick and wide parameter scans